Geometry and Dynamics in Heavy-Ion Collisions Seen by the Femtoscopy in the STAR Experiment

Sebastian Siejka
for the STAR Collaboration

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Faculty of Physics
Outline

1) Tools – femtoscopy, correlation functions and spherical harmonics

2) How does the source geometry depend on centrality and energy of the collision.
   Is it consistent across various systems?

3) What are the source dynamics? Is there a species dependence in the source?

4) Summary and conclusions
Few Words About Femtoscopy

Source

\( S(x, p) \)
Correlation function

\[ C(p_1, p_2) = \frac{P_2(p_1, p_2)}{P_1(p_1)P'_1(p_2)} \]
Few Words About Femtoscopy

**Single-particle distribution**

\[ P_1(p) = E \frac{dN}{d^3p} = \int d^4 x S(x, p) \]

**Two-particle distribution**

\[ P_2(p_1, p_2) = E_1 E_2 \frac{dN}{d^3p_1 d^3p_2} = \int d^4 x_1 S(x_1, p_1) d^4 x_2 S(x_2, p_2) \Phi(x_2, p_2 | x_1, p_1) \]

\( \Phi \) – pair mutual interaction

**Correlation function**

\[ C(p_1, p_2) = \frac{P_2(p_1, p_2)}{P_1(p_1) P_1'(p_2)} \]

**S(x,p) - emission function:** the distribution of source density probability of finding particle with \( x \) and \( p \)

Correlation function shows echo of emission function as seen through pair mutual interaction.
Types of Correlation Functions

**Identical particle combination**

- Quantum Statistics (QS)

- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

**Non-identical particle combination**

- Final State Interactions:
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UrQMD Au+Au; $R_{inv} = 3\, fm$

M. Gyulassy et al.

H. D. Boal et al.

S. E. Koonin et al.

R. Lednický

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UrQMD \( \text{Au} + \text{Au}; R_{\text{inv}} = 3 \text{ fm} \)

- M. Bleicher et al.

- M. Gyulassy et al.

- H. D. Boal et al.

- S. E. Koonin et al.

- R. Lednický

Source Dynamics – Spacetime Emission Asymmetry

### Time asymmetry

- $t_1 \neq t_2$
- $\Delta r = 0$
- $t_1 > t_2$ - Catching up
- $t_2 > t_1$ - Run away

### Space asymmetry

- $t_1 = t_2$
- $\Delta r \neq 0$
- $t_1 = t_2$
- $\Delta r \neq 0$

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R. Lednický, et al.,
Pions are emitted later and/or closer to the center than kaons.

J. Adams, et al.  
\[ C(\mathbf{q}) = \sum_{l,m} C_l^m(\mathbf{q}) Y_l^m(\theta, \phi) \]

\[ C_l^m(\mathbf{q}) = \int_\Omega C(q, \theta, \phi) Y_l^m(\theta, \phi) d\Omega \]

\[ \Omega \text{ – full solid angle} \]

\[ Y_l^m(\theta, \phi) \text{ – spherical harmonic function} \]

\[ q = |\mathbf{q}|, \theta, \phi \text{ – spherical coordinates} \]

- \( C_0^0 \) -> sensitive to the size of the emitting source (shapes same as correlation function)
- \( C_1^1 \) -> sensitive to the spacetime emission asymmetry

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P. Danielewicz and S. Pratt

A. Kisiel

P. Danielewicz and S. Pratt

A. Kisiel and D. A. Brown
Centrality Dependence (Non-Identical Particle Combinations)

\( \pi - K @ Au+Au 39 \text{ GeV} \)

- 0-10%
- 10-30%
- 30-70%

Unlike-sign
Like-sign

\( C_0^0[ GeV/c] \) -> sensitive to size of source

\( p - \bar{p} @ Au+Au 39 \text{ GeV} \)

Clear centrality dependence
\( R(0-10\%) > R(10-30\%) > R(30-70\%) \)

<table>
<thead>
<tr>
<th>Centrality</th>
<th>( R_{inv} p - \bar{p} ) [fm]</th>
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16th May 2018
Sebastian Siejka for the STAR Collaboration
Centrality Dependence (Identical Particle Combinations)

$p - p @ Au+Au 39 GeV$

\[ R_{inv} p - p [fm] \]

\begin{align*}
0-10\% & : & 4.00 & \pm 0.15 & \pm 0.02 \\
10-30\% & : & 3.61 & \pm 0.13 & \pm 0.17 \\
30-70\% & : & 2.72 & \pm 0.07 & \pm 0.07 \\
\end{align*}

\[ R_{inv} \bar{p} - \bar{p} [fm] \]

\begin{align*}
0-10\% & : & 3.83 & \pm 0.20 & \pm 0.03 \\
10-30\% & : & 3.68 & \pm 0.15 & \pm 0.11 \\
30-70\% & : & 2.95 & \pm 0.11 & \pm 0.08 \\
\end{align*}

No significant difference between $p - p$ and $\bar{p} - \bar{p}$ correlation functions.
Centrality Dependence (Identical Particle Combinations)

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\[ \bar{p} - \bar{p} @ Au+Au 39 GeV \]

Feed-down correction for residual correlations is in progress.

Radii from $p - p$ and $\bar{p} - \bar{p}$ systems differ from radii from $p - \bar{p}$ system $\rightarrow$ residual correlations contaminate correlation functions.

No significant difference between $p - p$ and $\bar{p} - \bar{p}$ correlation functions.
**Energy Dependence**

Energy dependence more pronounced for $p - p$ system than for $p - \bar{p}$ system.

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Energy and Centrality Dependence

$R_{inv}$ dependence

$\sqrt{S_{NN}}$ dependence

Feed-down correction may decrease significance of centrality dependence.

Significant centrality dependence.

$\sqrt{S_{NN}}$ dependence weak for all centralities.

STAR preliminary

0-10%

10-30%

30-70%

$p - p$
Energy and Centrality Dependence

No significant difference between $p - p$ and $\bar{p} - \bar{p}$ correlation functions at $\sqrt{S_{NN}} = 39$ GeV

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System Dependence

Like-sign 0-10% @ Au+Au 39 GeV

Unlike-sign 0-10% @ Au+Au 39 GeV

Clear system dependence

Like-sign: correlations dominated by Coulomb interaction
Coulomb strength depends on Bohr radius of the pair

\( K^- - p \) – lowest Bohr radius, strongest correlation

\( C_0^0 \) -> sensitive to size of source
Clear system dependence

Like-sign: correlations dominated by Coulomb interaction
Coulomb strength depends on Bohr radius of the pair

$K^- p$ – lowest Bohr radius, strongest correlation

Unlike-sign: interaction more complicated
Strong interaction not negligible in $K^- p$.

$C_0^0(K^- p)$ different shape due to strong interaction

$C_0^0$ -> sensitive to size of source
Asymmetry does not disappear for low energies.

\[ \pi - K \ @ \ Au+Au \ 39 \text{ GeV} \]

\[ C_1^1(k^*) \]

\[ \bullet \ 0-10\% \]

\[ \bullet \ 10-30\% \]

\[ \bullet \ 30-70\% \]

Clear signal of emission asymmetry

\[ \pi - K : \ Au+Au \ 0-10\% \]

\[ C_1^1(k^*) \]

\[ \bullet \ 39 \text{ GeV} \]

\[ \bullet \ 11.5 \text{ GeV} \]

\[ \bullet \ 7.7 \text{ GeV} \]

Like-sign

Unlike-sign

\[ \text{STAR preliminary} \]

not corrected for feed-down
stat. uncertainties only

\[ C_1^1 \rightarrow \text{sensitive to spacetime emission asymmetry} \]

16th May 2018

Sebastian Siejka for the STAR Collaboration
Like-sign particle combinations

\[ C_0^0(k^*) \]

\[ C_0^1(k^*) \]

\[ C_1^0(k^*) \]

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Lighter particle emitted closer to the center and/or later.

Unlike-sign particle combinations

\[ C_0^0(k^*) \]

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\[ C_1^1(k^*) \]

Lighter particle emitted closer to the center and/or later.

Heavier particle emitted closer to the center and/or later.
**Source Dynamics – System Dependence**

**Like-sign 0-10% @ Au+Au 39 GeV**

- `π⁺ K⁺`
- `π⁻ K⁻`
- `π⁺ p`
- `π⁻ p`
- `K⁺ p`
- `K⁻ p`

**Unlike-sign 0-10% @ Au+Au 39 GeV**

- `π⁺ K⁻`
- `π⁻ K⁺`
- `π⁺ p`
- `π⁻ p`
- `K⁺ p`
- `K⁻ p`

**C₀** -> sensitive to size of source

**C₁** -> sensitive to spacetime emission asymmetry

BES II will improve results.

`p – ¯p 0-10% @ Au+Au 39 GeV`

α peak

Heavier particles have stronger push by flow towards the edge of source than lighter particles. Heavier particles freeze-out earlier.

**Expected ordering of particles:**
Lighter particle is emitted closer to the centre and/or later.

No visible asymmetry between protons and antiprotons – similar masses.

A. Kisiel
Geometry:

- Visible centrality, system and energy dependence of source size at BES energies
- **No visible difference between proton-proton and antiproton-antiproton correlation functions at** $\sqrt{s_{NN}} = 39$ GeV
- Correlation functions contaminated by residual correlations – residual correction required
- Strong interaction not negligible in kaon-proton
Summary

Geometry:
• Visible centrality, system and energy dependence of source size at BES energies
• No visible difference between proton-proton and antiproton-antiproton correlation functions at $\sqrt{s_{NN}} = 39$ GeV
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Dynamics:
• Clear signal of emission asymmetry for particles with different masses at BES energies
• Asymmetry does not disappear for low energies
Summary

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Dynamics:
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• **Lighter particles are emitted closer to the center of the source and/or later than heavier particles** – flow gives heavier particles stronger push to the edge
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Thank you for your attention
Coulomb Interaction and Bohr Radius of the Pair

Pair mutual interaction:

$$\Phi_{-k^*}(r^*) = \sqrt{A_C(\eta)} \left[ e^{-ik^*r^*} F(-i\eta, 1, i\xi) + f_C(k^*) \frac{\tilde{G}(\rho, \eta)}{r^*} \right]$$

$A_C$ – Gamow factor
$\xi = k^*r^*(1 + \cos \theta^*)$
$\eta = \frac{1}{k^*a_C}$ where $a_C$ is the Bohr radius of the pair
$\rho = k^*r^*$
$F$ – confluent hypergeometric function
$\tilde{G}$ - combination of regular and singular s-wave Coulomb function
$f_C$ - Coulomb-modified strong interaction scattering amplitude
$\theta^*$ - angle between pair relative momentum $k^*$ and relative position $r^*$

<table>
<thead>
<tr>
<th>Pair</th>
<th>$\pi^+\pi^\pm$</th>
<th>$\pi^+K^\pm$</th>
<th>$\pi^\pm p$</th>
<th>$K^+K^\pm$</th>
<th>$K^\pm p$</th>
<th>$pp^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_C$, fm</td>
<td>$\pm 387.5$</td>
<td>$\pm 248.6$</td>
<td>$\pm 222.5$</td>
<td>$\pm 109.6$</td>
<td>$\pm 83.6$</td>
<td>$\pm 57.6$</td>
</tr>
<tr>
<td>$Q_C$, MeV/c</td>
<td>6.4</td>
<td>10.0</td>
<td>11.1</td>
<td>22.6</td>
<td>29.7</td>
<td>43.0</td>
</tr>
</tbody>
</table>

$a_C$ - pair Bohr radius including the sign of the interaction
$Q_C \equiv 2k^*_C = \frac{4\pi}{|a|}$ - characteristic width of Coulomb interaction

A. Kisiel

R. Lednicky
DIRAC Note 2004-06, CERN (27.11.2004)