Femtoscopic measurements of two-kaon combinations in Au+Au collisions at the STAR experiment

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NATIONAL SCIENCE CENTRE | RESEARCH UNIVERSITY EXCELLENCE INITIATIVE
Femtoscopy - introduction

\[ CF(\vec{q}) = \frac{P_{12}(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1)P_2(\vec{p}_2)} = \int d^3r S(\vec{q}, \vec{r}) |\Psi(\vec{q}, \vec{r})|^2 = \frac{A(\vec{q})}{B(\vec{q})} \]

\[ \vec{p}_1, \vec{p}_2 - \text{single particle momentum} \]

\[ S(\vec{q}, \vec{r}) - \text{emission function} \]

\[ \Psi(\vec{q}, \vec{r}) - \text{pair wave function} \]

\[ \vec{q} = |\vec{p}_1 - \vec{p}_2| - \text{relative momentum} \]

\[ \vec{r} - \text{relative distance between two particles} \]

\[ \text{statistical} \quad \text{model} \quad \text{experiment} \]
Femtoscopy - introduction

\[ CF(\vec{q}) = \frac{P_{12}(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1)P_2(\vec{p}_2)} = \int d^3r \ S(\vec{q}, \vec{r}) |\Psi(\vec{q}, \vec{r})|^2 = \frac{A(\vec{q})}{B(\vec{q})} \]

\( \vec{p}_1, \vec{p}_2 \) - single particle momentum

\( S(\vec{q}, \vec{r}) \) – emission function
\( |\Psi(\vec{q}, \vec{r})|^2 \) – pair wave function
\( A(\vec{q}) \) - correlated
\( B(\vec{q}) \) - uncorrelated

Kaon correlation functions are sensitive to:

- \( K^\pm K^\pm \)
- Quantum Statistical effects (QS)
- Final State Interaction (FSI)
- Coulomb interaction (COUL)

- \( K_S^0 K_S^0 \)
- Quantum Statistical effects (QS)
- Final State Interaction (FSI)

- \( K_S^0 K^\pm \)
- Final State Interaction (FSI)
- strong interaction (SI)
Femtoscopy - introduction

**statistical model**

\[ CF(\hat{q}) = \frac{P_{12}(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1)P_2(\vec{p}_2)} = \int d^3 r \, S(\hat{q}, \vec{r}) |\Psi(\hat{q}, \vec{r})|^2 = \frac{A(\hat{q})}{B(\hat{q})} \]

- \( \vec{p}_1, \vec{p}_2 \) - single particle momentum
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- **\( K^\pm K^\pm \)**
- **\( K_s^0 K_s^0 \)**
- **\( K_s^0 K^\pm \)**

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Motivation

ALICE, Physics Letters B 774(2017) 64

Kaons provide complementary information to pions:
• contain strange quarks (larger production of strange particles is one of the signatures of QGP)
• less affected by the feed-down from resonance decays
• smaller cross section on reaction with the hadronic matter

Very interesting:
• compare femtoscopic results for all possible kaon combination ($K^\pm K^\pm$, $K^0_S K^0_S$, $K^0_S K^\pm$)
• $K^0_S K^\pm$ - $a_0$ could be a 4-quark state (a tetraquark)
Motivation

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Very interesting:
• compare femtoscopic results for all possible kaon combination ($K^\pm K^\pm$, $K_S^0 K_S^0$, $K_S^0 K^\pm$)
• $K_S^0 K^\pm$ - $a_0$ could be a 4-quark state (a tetraquark)
The STAR experiment

→ Excellent particle identification
→ Large, uniform acceptance at mid-rapidity

Datasets

<table>
<thead>
<tr>
<th>Energy $\sqrt{s_{NN}}$</th>
<th>Year</th>
<th>Mode</th>
<th>Statistics (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39 GeV</td>
<td>2010</td>
<td>Collider</td>
<td>~83</td>
</tr>
<tr>
<td>200 GeV</td>
<td>2010</td>
<td>Collider</td>
<td>~260</td>
</tr>
</tbody>
</table>

Au+Au collisions

Time Projection Chamber
PID: $dE/dx$
Tracking
$0 < \phi < 2\pi$, $|\eta| < 1$

Time-Of-Flight
Time resolution < 80 ps
PID: $m^2$

Au+Au collisions @ 39 GeV (BES-I)
Neutral kaon reconstruction

$K_S^0 \rightarrow \pi^+\pi^- (69.20 \pm 0.05)\%$

$K_S^0 \rightarrow \pi^0\pi^0 (30.69 \pm 0.05)\%$

Armenteros-Podolański plot
Parametrization - $K_s^0 K_s^0$

Gaussian density distribution (includes only QS effects):

$$CF(q_{inv}) = 1 + \lambda e^{-R_{inv}^2 q_{inv}^2}$$

$\lambda$ - the correlation strength, $R_{inv}$ - the size of the particle-emitting source.


$$CF(q_{inv}) = 1 + \lambda \left( e^{-R_{inv}^2 q_{inv}^2} + \frac{1}{2} \left| \frac{f(k^*)}{R_{inv}} \right|^2 + \frac{4Re f(k^*)}{\sqrt{\pi} R_{inv}} F_1(q_{inv} R_{inv}) - \frac{2Im f(k^*)}{\sqrt{\pi} R_{inv}} F_2(q_{inv} R_{inv}) \right)$$
Parametrization - $K_S^0 K_S^0$

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**Lednicky & Lyuboshitz model** includes strong FSI: [Sov.J.Nucl.Phys. 35, 770 (1982)]

$$CF(q_{inv}) = 1 + \lambda e^{-R_{inv}^2 q_{inv}^2} + \frac{1}{2} \left( \frac{f(k^*)}{R_{inv}} \right)^2 + \frac{4Re f(k^*)}{\sqrt{\pi} R_{inv}} F_1(q_{inv} R_{inv}) - \frac{2Re f(k^*)}{\sqrt{\pi} R_{inv}} F_2(q_{inv} R_{inv})$$

**QS effect**

**strong FSI through the $f_0(980)$ and $a_0(980)$ resonances**

$$F_1(z) = \int_0^z dx \frac{e^{x^2-z^2}}{z}, \quad F_2(z) = \frac{1-e^{x^2}}{z}$$

$$f(k^*) = \frac{1}{2} [f_0(k^*) + f_1(k^*)], \quad f_1(k^*) = \frac{\mathcal{Y}_r}{m_r-s-i\gamma_r k^* - i\gamma'_r k'_r}, \quad s = 4(m_K^2 + k^*^2)$$
# Parametrization - $K_S^0 K_S^0$

**Gaussian density distribution** (includes only QS effects): 
\[
CF(q_{\text{inv}}) = 1 + \lambda e^{-R_{\text{inv}}^2 q_{\text{inv}}^2}
\]
\(\lambda\) - the correlation strength, \(R_{\text{inv}}\) - the size of the particle-emitting source.

**Lednicky & Lyuboshitz model** includes **strong FSI**: [Sov.J.Nucl.Phys. 35, 770 (1982)]

\[
CF(q_{\text{inv}}) = 1 + \lambda \left( e^{-R_{\text{inv}}^2 q_{\text{inv}}^2} + \frac{1}{2} \left[ \frac{f(k^*)}{R_{\text{inv}}} \right]^2 + \frac{4 R f(k^*)}{\sqrt{\pi} R_{\text{inv}}} F_1(q_{\text{inv}} R_{\text{inv}}) - \frac{2 \Im f(k^*)}{\sqrt{\pi} R_{\text{inv}}} F_2(q_{\text{inv}} R_{\text{inv}}) \right]
\]

**QS effect**

**strong FSI through the $f_0(980)$ and $a_0(980)$ resonances**

\[
F_1(z) = \int_0^z dx \frac{e^{x^2-z^2}}{z}, \quad F_2(z) = \frac{1-e^{z^2}}{z}
\]
\[
f(k^*) = \frac{1}{2} [f_0(k^*) + f_1(k^*)], \quad f_1(k^*) = \frac{1}{m_r-s-i\gamma_r k_r^+ - i\gamma_{r'} k_{r'}^+}, \quad s = 4(m_K^2 + k^+)^2
\]

<table>
<thead>
<tr>
<th></th>
<th>(m_{f_0} [\text{GeV}/c^2])</th>
<th>(\gamma_{f_0 K\bar{K}})</th>
<th>(\gamma_{f_0 \pi\pi})</th>
<th>(m_{a_0} [\text{GeV}/c^2])</th>
<th>(\gamma_{a_0 K\bar{K}})</th>
<th>(\gamma_{a_0 \pi\pi})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antonelli [1]</td>
<td>0.973</td>
<td>2.763</td>
<td>0.5283</td>
<td>0.985</td>
<td>0.4038</td>
<td>0.3711</td>
</tr>
<tr>
<td>Achasov2001 [2]</td>
<td>0.996</td>
<td>1.305</td>
<td>0.2684</td>
<td>0.992</td>
<td>0.5555</td>
<td>0.4401</td>
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<td>0.8365</td>
<td>0.4580</td>
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<tr>
<td>Martin [4]</td>
<td>0.978</td>
<td>0.792</td>
<td>0.1990</td>
<td>0.974</td>
<td>0.3330</td>
<td>0.2220</td>
</tr>
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</table>

**$K_S^0 K_S^0$** femtoscopy at 39 GeV & 200 GeV

\[ q_{inv} = \sqrt{(p_{1T} - p_{2T})^2 - (E_1 - E_2)^2} \]

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13-19 June 2022
$K_S^0K_S^0$ femtoscopy at 39 GeV & 200 GeV

$0.4 \text{ GeV/c} < p_T < 2.0 \text{ GeV/c}$

$|\eta| < 0.5$

$q_{\text{inv}} = \sqrt{(p_1^2 - p_2^2) - (E_1 - E_2)^2}$
**K^0_S K^0_S** femtoscopy at 39 GeV & 200 GeV

FSI is needed to reproduce the dip structure

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**$K^0_S K^0_S$** femtoscopy at 39 GeV & 200 GeV

### STAR Preliminary

**Au+Au collisions**

- **@ 39 GeV (BES-I)**,
  - 0-10%
  - $0.4 \text{ GeV}/c < p_T < 2.0 \text{ GeV}/c$
  - $|\eta| < 0.5$

- **STAR Preliminary**
  - **0-70%**

**UrQMD**

**Therminator2**

$q_{inv} = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2}$

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**K^0_S K^0_S** femtoscopy at 39 GeV & 200 GeV

\[ q_{\text{inv}} = \sqrt{(p_1^2 - p_2^2) - (E_1 - E_2)^2} \]

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$K_S^0 K_S^0$ femtoscopy at 39 GeV & 200 GeV

Good agreement of the experimental points with the models

$Q_{inv} = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2}$

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**K^0_SK^0_S** femtoscopy – centrality dependence

- Visible centrality dependence
  
  \[ R_{0-10\%} > R_{10-70\%} \]

- Only Gaussian assumption leads to larger R, showing importance to include SI
**$K^0_S K^0_S$ femtoscopy – energy dependence**

- Visible energy dependence for both parametrization $R_{200\, GeV} > R_{39\, GeV}$
- Source sizes from models and FSI parametrizations consistent within the range of uncertainty
Parametrization - $K_S^0 K^\pm$


$$CF(k^*) = 1 + \frac{\lambda}{4} \left[ \frac{|f(k^*)|}{R} \right]^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R} F_1(2k^*R) - \frac{2\Im f(k^*)}{\sqrt{\pi}R} F_2(2k^*R)$$
**Parametrization - \( K_S^0 K^\pm \)**

**Lednicky & Lyuboshitz model** includes strong FSI: [Sov.J.Nucl.Phys. 35, 770 (1982)]

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\]

**strong FSI through the \( a_0(980) \) resonance**

\[
F_1(z) = \int_0^z dx \frac{e^{x^2} - x^2}{z}, \quad F_2(z) = \frac{1 - e^{x^2}}{z}
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\[
f(k^*) = \frac{\gamma_r}{m_r - s - i\gamma_r k^* - i\gamma'_r k'_r}, \quad s = 4(m_k^2 + k^{*2})
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$K_S^0 K^+$ femtoscopy at 200 GeV

$k^* = |\vec{p}_1| = |\vec{p}_2|$

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The $a_0$ FSI parametrization gives an excellent representation of the signal region of the data

$k^* = |\vec{p}_1| = |\vec{p}_2|$
$K_S^0 K^+$ femtoscopy at 200 GeV

<table>
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<tr>
<th></th>
<th>0-10%</th>
<th>10-70%</th>
<th>0-70%</th>
</tr>
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<tr>
<td>Antonelli [1]</td>
<td>0.60</td>
<td>1.66</td>
<td>1.04</td>
</tr>
<tr>
<td>Achasov2001 [2]</td>
<td>0.59</td>
<td>1.73</td>
<td>1.07</td>
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<tr>
<td>Achasov2003 [3]</td>
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<td>1.14</td>
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<td>1.65</td>
<td>1.16</td>
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$k^* = |\vec{p}_1| = |\vec{p}_2|$
$K_S^0 K^+$ femtoscopy – centrality dependence

- Visible centrality dependence $R_{0-10\%} > R_{10-70\%}$
- Achasov2003 parametrization (the larger $a_0$ mass) gives the larger size of the source
Comparison - $K_s^0 K_s^0$ and $K_s^0 K^+$ - 200 GeV

Antonelli favors $a_0$ resonance as a tetraquark

Only statistical uncertainties for $K_s^0 K^+$

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Comparison - $K_S^0K_S^0$ and $K_S^0K^+$ - 200 GeV

STAR Preliminary
Au+Au collisions @ 200 GeV

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eConf C020620, THAT06 (2002)
Comparison - $K_S^0 K_S^0$ and $K_S^0 K^+$ - 200 GeV

**STAR Preliminary**

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$R_{K^{±}K^{±}} = \sqrt{\frac{R_{out}^2 + R_{side}^2 + R_{long}^2}{3}}$

Diana Pawłowska (WUT)

STAR Preliminary

Au+Au collisions @ 200 GeV

Antonelli favors $a_0$ resonance as a tetraquark

eConf C020620, THAT06 (2002)
Summary

**K^0_S K^0_S femtoscopy**
- The strong final-state interaction has a significant effect on the K^0_S K^0_S correlation due to the near-threshold f_0(980) and a_0(980) resonances.
- The radii of the source depend on centrality and increase with increasing collision energy.
- Extracted source radii are comparable to those from models.

**K^0_S K^+ femtoscopy**
- The a_0(980) FSI parametrization gives very good representation of the shape of the signal region in CF.
- The parametrization with the larger a_0(980) mass and decay coupling gives larger size of the source.
- Comparison with K^0_S K^0_S.
  - Antonelli parametrization favors a_0(980) resonance as a tetraquark.
Summary

$K_S^0 K_S^0$ femtoscopy

• The strong final-state interaction has a significant effect on the $K_S^0 K_S^0$ correlation due to the near-threshold $f_0(980)$ and $a_0(980)$ resonances
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$K_S^0 K^+$ femtoscopy

• The $a_0(980)$ FSI parametrization gives very good representation of the shape of the signal region in CF
• The parametrization with the larger $a_0(980)$ mass and decay coupling gives larger size of the source
• Comparision with $K_S^0 K_S^0$
  • Antonelli parametrization favors $a_0(980)$ resonance as a tetraquark
Summary

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- The strong final-state interaction has a significant effect on the \( \text{K}_s^0 \text{K}_s^0 \) correlation due to the near-threshold \( f_0(980) \) and \( a_0(980) \) resonances
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\( \text{K}_s^0 \text{K}_s^+ \) femtoscopy
- The \( a_0(980) \) FSI parametrization gives very good representation of the shape of the signal region in CF
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- Comparison with \( \text{K}_s^0 \text{K}_s^0 \)
  - Antonelli parametrization favors \( a_0(980) \) resonance as a tetraquark

**Compatibility of source sizes for \( \text{K}_s^0 \text{K}_s^0, \text{K}_s^0 \text{K}_s^+ \) and \( \text{K}^\pm \text{K}^\pm \) pairs in the case of Antonelli**
Summary

$K_S^0 K_S^0$ femtoscopy

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- The $a_0(980)$ FSI parametrization gives very good representation of the shape of the signal region.
- The parametrization with the larger $a_0(980)$ mass and decay coupling gives larger size of the source.
- Comparison with $K_S^0 K_S^0$.
- Antonelli parametrization favors $a_0(980)$ resonance as a tetraquark.

Outlook

High statistic BES-II data give the ability to analyze neutral kaon femtoscopy for energies $\sqrt{S_{NN}} < 20$ GeV.

Compatibility of source sizes for $K_S^0 K_S^0$, $K_S^0 K^+$ and $K^\pm K^\pm$ pairs in the case of Antonelli.
Thank you for your attention!!