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

Diana Pawłowska[1,*] for the STAR Collaboration

[1]Faculty of Physics, Warsaw University of Technology,
Koszykowa 75, 00-662 Warsaw, Poland

Abstract. Relativistic heavy-ion collisions can study the properties of nuclear matter in high-energy experiments like the STAR experiment. One of the methods to learn about the properties of the bulk matter is the femtoscopy technique, which relies on information carried by the particles produced during the collisions. The emission source parameters, like space-time characteristics, can be extracted using the technique. High statistics data from RHIC make it possible to study the correlations between strange particles, like charged and neutral kaons. The pair-wise interactions between the identical kaons that form the basis for femtoscopy are quantum statistics and the Coulomb interaction for $K^{\pm}K^{\pm}$, and quantum statistics and the final-state interaction (FSI) through the $f_0(980)/a_0(980)$ threshold resonances for $K^0_S K^0_S$. The interactions between non-identical kaons pairs of $K^0_S K^{\pm}$ are essential, as the strong FSI is described only by the $a_0(980)$ resonance, which could be a four-quark state. These proceedings will present the femtoscopic measurements of strange particles with charged and neutral kaons correlations in Au+Au collisions at the RHIC energy.

1 Introduction

The main motivation to carry out the kaon femtoscopy study is that kaons are less affected by the feed-down from resonance decays. Kaons have a smaller cross-section on reaction with the hadronic matter and, what is also very important, they contain strange quarks. As it is known, one of the signatures of the Quark-Gluon Plasma (QGP) is the enhancement of the production of strange particles [1].
Comparison of femtoscopic results for all possible kaon combinations $K^{\pm}K^{\pm}$, $K^0_S K^0_S$, and $K^0_S K^{\pm}$ allows us to examine the a_0 resonance, which is suspected to be a four-quark state, e.g. a tetraquark [2]. All the systems should give the same emission source parameters of the homogeneity region and only final state interactions would cause the difference observed in correlations. Agreement between all kaon systems will shed light on the preceding assumption about the a_0 resonance.

2 Analysis methods

Experimentally, it is impossible to measure properties of the source directly with a size of about 1 fm and a lifetime of about 10^{-23} s. The relative momentum of particles produced during the heavy-ion collisions is used to learn about the source's characteristics. The equation (1) describes the correlation function:

*e-mail: diana.pawlowska.dokt@pw.edu.pl

$$CF(\vec{q}) = \int d^3r\, S(\vec{q},\vec{r})\, |\Psi(\vec{q},\vec{r})|^2, \tag{1}$$

where $S(\vec{q},\vec{r})$ is the emission function describing space-time properties of the source, $\Psi(\vec{q},\vec{r})$ is the pair wave function which contains information about all effects and interactions, and $\vec{q} = |\vec{p_1} - \vec{p_2}|$ is a relative momentum and $\vec{r} = |\vec{r_1} - \vec{r_2}|$ is relative distance between two particles. By measuring of pair relative momentum, space-time characteristics of the source like its size can be studied.

Theoretically, the $K^0_S K^0_S$ correlation function can be described analytically with a model derived by Lednicky-Lyuboshitz [3], which contains strong final state interaction (FSI):

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

where $F_1(z) = \int_0^z dx e^{x^2-z^2}/z$ and $F_2(z) = (1-e^{-z^2})/z$ are analytic functions, $f(k^*)$ is s-wave $K^0_S K^0_S$ scattering amplitude, which depends on masses and decay couplings of near-threshold resonances $f_0(980)$ and $a_0(980)$ (Table 1), $q_{inv} = \sqrt{(\vec{p_1} - \vec{p_2})^2 - (E_1 - E_2)^2}$ is pair relative momentum (k^* is a first particle momentum in pair rest frame), R_{inv} is the size of the particle-emitting source and λ is the correlation strength.

Table 1. The most common parameters describing $f_0(980)$ and $a_0(980)$ resonances used in the Lednicky-Lyuboshitz model.

	m_{f_0}[GeV/c^2]	$\gamma_{f_0 K\bar{K}}$	$\gamma_{f_0\pi\pi}$	m_{a_0}[GeV/c^2]	$\gamma_{a_0 K\bar{K}}$	$\gamma_{a_0\pi\pi}$
Antonelli [4]	0.973	2.763	0.5283	0.985	0.4038	0.3711
Achasov2001 [5]	0.996	1.305	0.2684	0.992	0.5555	0.4401
Achasov2003 [6]	0.996	1.305	0.2684	1.003	0.8365	0.4580
Martin [7]	0.978	0.792	0.1990	0.974	0.3330	0.2220

To show the importance of considering the strong FSI in the parameterization, the experimental data was fitted by a correlation function that only considers the effects of quantum statistics (QS). This fit assumed a spherical source size described by the Gaussian density distribution.

In the case of $K^0_S K^{\pm}$ analysis, the parametrization was also performed using the Lednicky-Lyuboshitz model, where the strong FSI is due to one resonance, $a_0(980)$, and all quantities have the same description as in the formula for $K^0_S K^0_S$:

$$CF(k^*) = 1 + \frac{\lambda}{4}\left[\left|\frac{f(k^*)}{R}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R}F_1(2k^*R) - \frac{2\Im f(k^*)}{R}F_2(2k^*R)\right]. \tag{3}$$

3 Description of experiment and data selection

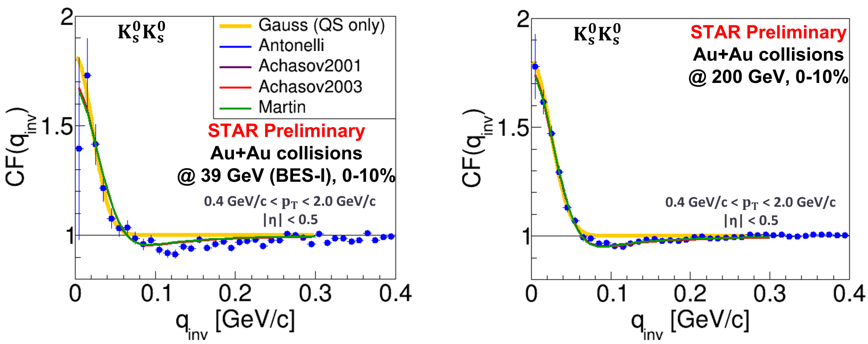
The femtoscopy method is successfully used in the case of the STAR experiment. Particle identification (PID) of charged particles is based on information from two detectors: the Time Projection Chamber (TPC) and Time of Flight (TOF) detector in the pseudorapidity range $|\eta| < 0.9$. TPC was used to measure the ionization energy loss of charged particles with a specific mass and momentum. For PID with TOF, the estimated time of flight was used to calculate the particle's mass and described as a function of the track length and momentum.

On the other hand, neutral particles like K^0_S were reconstructed using their decay products. Neutral kaons decay via the weak interaction into positive and negative daughters (π^+ and π^-). After reconstructing the secondary particles, neutral particles are identified based on the invariant mass applying cuts on their decay topology.

4 Results

4.1 Identical kaon femtoscopy

Figure 1 presents correlation functions for $K^0_S K^0_S$ combination for 0-10% most central Au+Au collisions at $\sqrt{s_{NN}}$ = 39 GeV and 200 GeV. These correlations are dominated by the QS effects and strong FSI which gives a characteristic dip structure around q_{inv} = 0.1 GeV/c. The parameterization, including only QS effects (Gaussian), does not describe this shape well, so it is crucial to take into account the strong interaction in the fitting procedure as well.

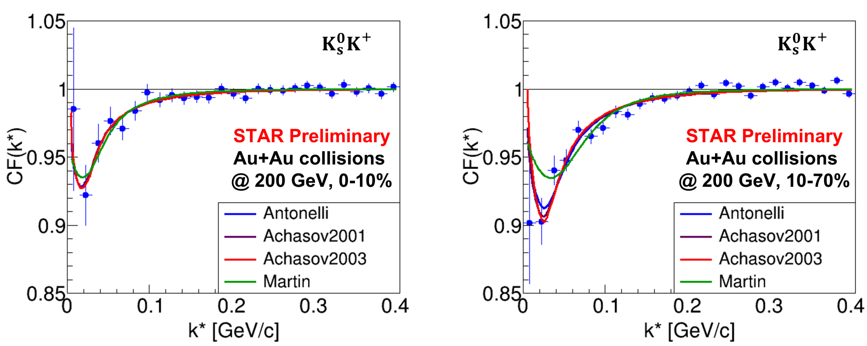


(a) (b)

Figure 1. $K^0_S K^0_S$ correlation functions for $\sqrt{s_{NN}}$ = 39 GeV (a) and 200 GeV (b) with Gaussian and Lednicky-Lyuboshitz parameterizations. Only statistical uncertainties are shown.

4.2 Non-identical kaon femtoscopy

Correlation functions for $K^0_S K^+$ system for central (0-10%) and noncentral (10-70%) Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV are presented in the Figure 2. The correlation functions are



(a) (b)

Figure 2. $K^0_S K^+$ correlation functions for $\sqrt{s_{NN}}$ = 200 GeV for central (a) and noncentral (b) collisions with Lednicky-Lyuboshitz parametrizations. Only statistical uncertainties.

characterized by dip structure due to near-threshold resonance $a_0(980)$, and the depth of this dip changes with the collision centrality. Three parametrizations Antonelli, Achasov2001, and Achasov2003 reflect this shape very well. Martin parametrization describes data worse for noncentral events.

4.3 Comparison of all kaon combinations

The comparison of the results from $K^\pm K^\pm$, $K^0_S K^0_S$, and $K^0_S K^\pm$ analyses for the top RHIC energy as a function of centrality is shown in Figure 3. The Antonelli parametrization gives the best agreement in the size of the particle emitting source among all combinations. Achasov's parametrizations lead to much larger source sizes for $K_S^0 K^\pm$ system, while the results with Martin are smaller for $K_S^0 K^\pm$. Antonelli parametrization favors the assumption that a_0 resonance could be the tetraquark.

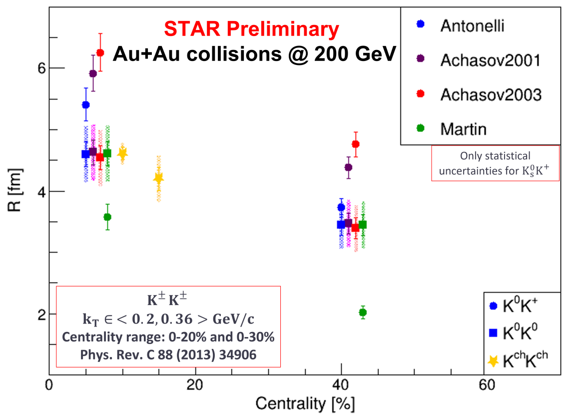


Figure 3. Centrality dependence of sizes of the $K^\pm K^\pm$ [8], $K_S^0 K_S^0$, and $K_S^0 K^\pm$ source at $\sqrt{s_{NN}} = 200$ GeV. For $K_S^0 K^\pm$ only statistical uncertainties are shown.

5 Summary

In summary, femtoscopic correlations with $K^\pm K^\pm$, $K_S^0 K_S^0$, and $K_S^0 K^\pm$ in Au+Au collisions at $\sqrt{s_{NN}} = 39$ and 200 GeV were presented. The extracted radii are compared among the three combinations for the first time. From the $K_S^0 K_S^0$ analysis, one can conclude that final state SI significantly affects these correlations due to two near-threshold resonances $a_0(980)$ and $f_0(980)$, and it is necessary to include this interaction in parametrization. Two-particle correlation in the $K_S^0 K^\pm$ system is reproduced by FSI due to the $a_0(980)$ resonance. Parametrization with $a_0(980)$ perfectly represents the signal region in the correlation function. The obtained source sizes are the biggest in the case of parametrization with the larger resonance mass (Achasov). For top RHIC energy, obtained source sizes for Antonelli parametrization are consistent among all the kaon combinations, which favors the assumption that $a_0(980)$ resonance could be a tetraquark.

Acknowledgement This work was supported by the Grant of National Science Centre, Poland, No: 2021/41/B/ST2/02409. Studies were funded by IDUB-POB-FWEiTE-1, IDUB-POB-FWEiTE-2 and IDUB-POB-FWEiTE-3 projects granted by Warsaw University of Technology under the program Excellence Initiative: Research University (ID-UB).

References

[1] M.I. Gorenstein, Heavy Ion Physics **14**, 141-148 (2001)
[2] E. Santopinto and G. Galatà, Physical Review C **75**, 045206 (2007)
[3] R. Lednicky and V.L.Lyuboshitz, Soviet Journal of Nuclear Physics **35**, 770 (1982)
[4] A. Antonelli, eConf **C020620**, THAT06 (2002)
[5] N.N. Achasov, V.V. Gubin, Physical Review D **63**, 094007 (2001)
[6] N.N. Achasov, A.V. Kiselev, Physical Review D **68**, 014006 (2003)
[7] A.D. Martin, E.N. Ozmutlu, E.J. Squires, Nuclear Physics B **121**, 514-530 (1977)
[8] STAR Collaboration, Physical Review C **88**, 34906 (2013)