Non-identical charged kaon femtoscopy in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by ALICE

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Abstract. We present the result of the femtoscopic analysis of non-identical charged kaon correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV obtained in ALICE at the LHC. One-dimensional $K^+K^-$ correlation functions were analyzed in three centrality classes and eight transverse momentum ranges. The femtoscopic correlations of $K^+K^-$ pairs are the result of Coulomb final-state interactions and formation of $a_0(980)$ and $f_0(980)$ resonances. The $K^+K^-$ correlation function was fit with the R. Lednicky and V. Luboshitz model [1]. For the first time, $f_0(980)$ mass and couplings were extracted from the $K^+K^-$ correlation functions fit with the constraint on the radii to be close to the corresponding radii from identical charged kaon correlations.

1. Introduction

Traditional femtoscopy is a tool for measuring the spatio-temporal characteristics of the particle emission region in the collision of ions and/or particles. Femtoscopy requires the determination of a correlation function which is affected by the final state interaction between the emitted particles. The technique is useful for determining the system size and its dependence on the transverse momentum and the event multiplicity. Recently, there has been great interest in measuring the parameters of the final state interactions using femtoscopy methods. This requires determining the femtoscopic correlations of non-identical kaons $K^0\bar{K}^\pm$ [2, 3]. An important addition to these studies will be the study of the $K^+K^-$ pair correlations. The amount of research in this area is rather scarce [4, 5]. The point here is that the interaction in the final state $K^+K^-$ is rather complex. It includes the Coulomb interaction and strong interaction through the resonances $f_0(980)$ (an $I=0$ isospin state) and $a_0(980)$ (an $I=1$ state). In this paper, results from the first study of $K^+K^-$ femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV obtained in the ALICE experiment at the LHC [6] are presented. The physics goals of the present study are: 1) fit of the $K^+K^-$ correlation function with the R. Lednicky and V. Luboshitz model [1], 2) extraction of $f_0(980)$ mass and coupling parameters from the $K^+K^-$ correlation function fit based on the published identical kaon results [7], and, 3) test of $a_0(980)$ mass and coupling parameters used in $K^0\bar{K}^\pm$ femtoscopy study [2, 3].

2. Data analysis

Most of the event and track selection criteria for the current analysis are the same as they were in the identical kaon one-dimensional femtoscopic analysis [7]. The data sample analyzed in this
contribution consists of about 40 million Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV collected with the ALICE detector [6] during the 2011 run of the LHC. Events were classified according to their centrality determined using the measured signal amplitudes in the V0 detectors. Charged particle tracking is performed using the Time Projection Chamber (TPC) and the Inner Tracking System (ITS). The ITS provides high spatial resolution in determining the primary (collision) vertex. The determination of particle momenta was performed using tracks reconstructed with the TPC and constrained to originate from the primary vertex. In order to reduce the number of secondaries, primary tracks were selected based on the distance of closest approach (DCA) to the primary vertex. Additional track selections based on the quality of the track momentum fit and the number of detected space points in the TPC were used. Pairs formed by primary particles sharing more than 5% of TPC clusters were rejected [7]. Particle identification (PID) was carried out using both the TPC and the Time-of-Flight (TOF) detector in the pseudorapidity range $|\eta| < 0.8$. For the TPC PID, a parametrized Bethe Bloch formula for a particle of given mass and momentum was used to calculate the specific energy loss ($\langle dE/dx \rangle$) in the detector. For PID with the TOF, the particle mass hypothesis was used to calculate the expected time of flight as a function of track length and momentum. The main contamination for $K^+K^-$ pairs is $e^+e^-$ contribution coming from $\gamma$ conversions. It should be noted that identification with the TOF was applied for smaller value of momentum to reduce this effect. And also the number of sigma standard deviations in the region where $e^+/e^-$ contamination is expected has been significantly reduced. To estimate the charged kaon purity at $p < 0.45$ GeV/c, the experimental $dE/dx$ distribution has been used. The estimated single kaon purity versus momentum $p$ is shown in Fig. 1 (a). The values of purity obtained decrease with increasing centrality. The resulting kaon pair purity for different centralities is shown in Fig. 1 (b). As seen from the figure, the contamination increases for more central collisions. The figure shows that the pair purity distribution is wider and its values are larger on average than for the single one. The value of the pair purity is higher than 99% for $K^+K^-$ pairs.

![Figure 1](attachment:image.png)

**Figure 1.** Single kaon purity versus single kaon momentum $p$ at 0–10%, 10–30%, and, 30–50% centralities (green triangles) (a). Points are slightly shifted along the X-axis for clarity. Charged kaon ($K^+K^-$) pair purity versus pair transverse momentum $k_T$ (b).
3. Analysis and Results

The correlation function of the K$^+K^-$ pair at a given pair relative momentum in the pair rest frame (PRF) $k^*$ and total pair three-momentum $P$ can be written as [1]:

$$C(k^*, P) = \int d^3r^* S^\alpha(r^*, P) \sum_{\alpha'} |\psi_{\alpha'}(r^*)|^2,$$

(1)

where $\alpha$ means K$^+K^-$ and sum over the intermediate channels $\alpha' = K^+K^-$, $K^0\overline{K}^0$. The K$^+K^-$ correlation functions were fit with a numerically calculated theoretical correlation function. The model proposed by R. Lednicky and V. Lyuboshitz [1, 8, 9] was used to calculate the theoretical correlation function $C_{FSI}$. It was assumed that K$^+K^-$ correlate in the final state due to the near-threshold resonances, $a_0(980)$ and $f_0(980)$, and due to the p-wave strong interaction through the $\phi$ meson resonance. In the one-dimensional analysis, we assume a spherically symmetric Gaussian distribution of the particle emitting points’ spatial separation $r^*$ in the PRF of size $R$:

$$S(r^*) \sim e^{\exp(-r^{*2}/4R^2)}.$$

(2)

The s-wave K$^+K^-$ scattering amplitude $f(k^*)$ is dominated by the near threshold s-wave isoscalar and isovector resonances $f_0(980)$ and $a_0(980)$ characterized by their masses $m_{f_0}$ and $m_{a_0}$ and respective couplings $\gamma_{f_0\to K+K^-}$, $\gamma_{f_0\to \pi\pi}$ and $\gamma_{a_0\to K+K^-}$, $\gamma_{a_0\to \pi\pi}$. Associating the amplitudes $f_1$ at isospin $I = 0$ and $I = 1$ with the resonances $r = f_0$ and $a_0$, respectively, one can write [10]:

$$f(k^*) = \frac{[f_0(k^*) + f_1(k^*)]}{2},$$

(3)

$$f_0(k^*) = \frac{\gamma_{f_0\to K+K^-}}{m_{f_0}^2 - s - i(\gamma_{f_0\to K+K^-} k_{\pi\pi}^* + \gamma_{f_0\to \pi\pi} k_{\pi\pi}^*)},$$

(4)

$$f_1(k^*) = \frac{\gamma_{a_0\to K+K^-}}{m_{a_0}^2 - s - i(\gamma_{a_0\to K+K^-} k_{\pi\pi}^* + \gamma_{a_0\to \pi\pi} k_{\pi\pi}^*)},$$

(5)

where $s = 4(m_{f_0}^2 + k_{\pi\pi}^2)$, $m_{a_0}$, $m_{f_0}$ are masses of the $a_0$ and $f_0$ resonances, respectively, and $k_{\pi\pi}$, $k_{\pi\pi}$ - mean momenta in the secondary decay channels (see Table 1).

The experimental two-particle correlation function is defined as $C(q) = A(q)/B(q)$, where $A(q)$ is the measured distribution of same-event pair momentum difference, $q = p_1 - p_2$, and $B(q)$ is the reference distribution of pairs from mixed events. This analysis presents correlation functions in eight pair transverse momentum bins $k_T$ ($k_T = |p_{T,1} + p_{T,2}|/2$): (0.2–0.3), (0.3–0.4), (0.4–0.5), (0.5–0.6), (0.6–0.7), (0.7–0.8), (0.8–1.0), and (1.0–1.3) GeV/c and three centrality bins 0–10%, 10–30%, 30–50%. The K$^+K^-$ correlation functions for these three of these eight $k_T$ bins are shown in Fig. 2. One can see the main features of the femtoscopic correlation function: the Coulomb attraction at a very small $q < 0.05$ GeV/c, the strong final-state interaction suppression due to the near-threshold resonances, $a_0(980)$ and $f_0(980)$ at $0.05 < q < 0.2$ GeV/c, and in the $q_{inv}$-interval around 0.25 GeV/c dominated by the narrow $\phi(1020)$ p-wave resonance.

The fit of the calculated correlation function to the experimental one would allow one to constrain the $f_0(980)$ and $a_0(980)$ masses and coupling parameters. The $a_0(980)$ parameters were fixed in $K_{\pi}^0K^\pm$ femtoscopic correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and pp collisions at $\sqrt{s} = 7$ TeV [2, 3]. Therefore only parameters of the $f_0(980)$ resonance are studied in this work. Parameters of the $a_0(980)$ resonance will be taken from the Achasov model [14]. Three possible sets of values of $f_0$ parameters proposed by theoretical models (Marin [11], Antonelli [12] and Achasov [13, 14], see Table 1) were tested. The corresponding radius and $\lambda$ parameters (correlation strength [7]) for K$^+K^-$ turned out to be absolutely inconsistent with
Table 1. The $a_0$ and $f_0$ masses and coupling parameters, all in GeV.

| Model       | $m_{f_0}^2$ | $m_{a_0}^2$ | $\gamma_{f_0 \to K^+K^-}$ | $\gamma_{f_0 \to \pi \pi}$ | $\gamma_{a_0 \to K^+K^-}$ | $\gamma_{a_0 \to \pi \pi}$ |
|-------------|-------------|-------------|-----------------------------|----------------------------|----------------------------|----------------------------|
| Martin [11] | .9565       | .9487       | .792                        | .199                       | .333                       | .222                       |
| Antonelli [12] | .9467     | .9698       | 2.763                       | .5283                      | .4038                      | .3711                      |
| Achasov1 [13] | .9920     | .9841       | 1.305                       | .2684                      | .5555                      | .4401                      |
| Achasov2 [14] | .9920     | 1.0060      | 1.305                       | .2684                      | .8365                      | .4580                      |

Figure 2. Examples of the correlation function fit with the Lednicky parametrization using new parameters for $f_0$ and Achasov [14] parameters for $a_0$. Statistical (vertical lines) and systematic (empty rectangles) uncertainties are shown.

these parameters for $K^+K^-$. Thus, it is necessary to select the parameters of the $f_0$ resonance so that the $K^+K^-$ radius and $\lambda$ parameters are consistent with the same parameters for $K^\pm K^\mp$.

Figure 2 shows examples of correlation function fit with the Lednicky parametrization using new parameters for $f_0$ and Achasov [14] parameters for $a_0$. The theoretical $K^+K^-$ correlation functions are smeared by the momentum resolution. Statistical and systematic uncertainties of the correlation function are shown. Systematic uncertainties were estimated using correlation functions obtained with different magnetic field orientation in the detector. As seen from Fig. 2, the new $f_0$ FSI parametrization gives an excellent description of the signal region of the data. The corresponding $\chi^2/ndf$ are in the range from 1 to 2. The radius and lambda parameters determined for $K^+K^-$ are compared to the corresponding parameters for $K^\pm K^\mp$. Figure 3 shows the radius (left panel) and $\lambda$ (right panel) parameter. From the point of view of theory,
there is no reason for the femtoscopic $K^+K^−$ radii to be different from $K^\pm K^\pm$ ones. $\lambda$ parameters for $K^+K^−$ tend to be a bit larger than those for $K^\pm K^\pm$. The values of $\lambda$ are seen to be about 0.7, i.e. less than the ideal value of unity, which can be due to the contribution of kaons from $K^*$ decays and from other long-lived resonances distorting the spatial kaon source distribution away from an ideal Gaussian which is assumed in the fit function.

![Figure 3. Examples of results for the $R$ (a) and $\lambda$ (b) parameters extracted in the presented $K^+K^−$ analysis using new parameters for $f_0$ and Achasov [14] parameters for $a_0$. Full points correspond to identical charged kaons [7] and open points are for $K^+K^−$. Statistical (vertical lines) and systematic (empty rectangles) uncertainties are shown.](image)

New parameters for $f_0(980)$ meson were extracted in the femtoscopic $K^+K^−$ analysis (see Eq. (4)) with constraint on radii to be close to the corresponding $K^\pm K^\pm$ radii. As a preliminary result, the mass and coupling parameters with statistical and systematical uncertainties associated with the $f_0$ meson are $m_{f_0} = 972 \pm 3 \pm 5\,\text{MeV}/c^2$, $\gamma_{f_0 \rightarrow K^+K^−} = 0.31 \pm 0.062 \pm 0.092\,\text{GeV}$, $\gamma_{f_0 \rightarrow \pi\pi} = 0.081 \pm 0.0162 \pm 0.024\,\text{GeV}$. The magnitude of the mass of the $f_0$ resonance is consistent within uncertainties with its PDG value ($m_{f_0} = 990 \pm 20\,\text{MeV}/c^2$). The ratio of two couplings is equal to $\gamma_{f_0 \rightarrow K^+K^−}/\gamma_{f_0 \rightarrow \pi\pi} = 3.83 \pm 1.07$. The value of the ratio is consistent with those shown in Table 1 and which are in the range from 4 to 5. Preliminarily estimates, the full width of the $f_0$ meson can be estimated as $\Gamma_{f_0} = 39.7 \pm 7.94 \pm 11.8\,\text{MeV}$.

4. Summary
Results of femtoscopic studies of non-identical charged kaon correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ with with the ALICE experiment at the LHC were presented. It was shown that the parameters of the $f_0(980)$ meson proposed by the Martin [11], Antonelli [12], and Achasov [13, 14] models do not allow one to describe the $K^+K^−$ experimental data well. For the first time, the $K^+K^−$ correlation function was fit using the $f_0(980)$ mass and couplings as free parameters and with the radii required to be close to the corresponding $K^\pm K^\pm$ ones. New preliminary values of the $f_0(980)$ meson mass and couplings were obtained from this fit. The measured width of $f_0(980)$ is about 40 $\text{MeV}/c^2$ and the mass is about 970 $\text{MeV}/c^2$, which is consistent with the PDG data [15]. It was tested that the $a_0(980)$ mass and coupling parameters used in $K^0\bar{K}^\pm$ femtoscopy study [2, 3] can describe the $K^+K^−$ experimental data well.
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