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Studying the $\mathrm{a}_0(980)$ tetraquark candidate using $\mathrm{K}^0_\mathrm{S}\mathrm{K}^\pm$ interactions in the LHC ALICE collaboration

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The $a_0(980)$ meson has been considered a tetraquark candidate for over 40 years, but its actual quark content remains in question. The ALICE Collaboration has carried out measurements of $\mathrm{K}^0_\mathrm{S}\mathrm{K}^\pm$ interactions with pp collisions at $\sqrt{s} = 7$ TeV and Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV to study the $a_0(980)$ using the method of two-particle femtoscopy. The $a_0(980)$ provides the final-state interaction between the kaons in the pair that is used in the femtoscopic analysis of these collisions. The measured femtoscopic source parameters are compared with source parameters extracted in identical-kaon measurements obtained in the same colliding systems. Using a simple geometric argument, our results are found to be compatible with the interpretation of the $a_0(980)$ having a tetraquark structure instead of that of a diquark.

Keywords: ALICE; LHC; pp scattering; two-kaon femtoscopy; tetraquark.

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1. Introduction

The work presented here is the experimental study of a low-lying meson that is considered a tetraquark candidate, *i.e.* the $a_0(980)$ meson, in order to establish whether or not it is indeed a four-quark state. The motivation to carry out this work is to test QCD, which allows for such a quark structure to exist in hadrons. There exist in the literature many QCD theoretical studies of the $f_0(500)$, $\mathrm{K}^*_0(700)$, $f_0(980)$ and $a_0(980)$ mesons. Jaffe first suggested that these mesons are part of a SU(3) tetraquark nonet using a quark model [1], and later Alford and Jaffe published a follow-up calculation reinforcing this work using lattice QCD calculations [2]. Since then, there have been a number of QCD studies of these mesons that fall in the categories of QCD-inspired models, for example Refs. [3–6], and lattice QCD calculations, for example Refs. [7–9].

There is no direct experimental evidence of the quark nature of the $f_0(500)$, $\mathrm{K}^*_0(700)$, $f_0(980)$ and $a_0(980)$ mesons, only interpretations of experiments that study their decay properties, for example Refs. [10, 11]. The femtoscopy method shown in the present work offers an alternative method of producing these mesons through final-state interactions and then analyzing them with femtoscopy. This method promises to give more direct signatures of their quark content, as will be shown in the present experimental study of the $a_0(980)$.

2. Two-particle femtoscopy

This section gives a brief summary of the definitions and methods used for two-particle femtoscopy relating to the present work. More detailed descriptions of this method can be found elsewhere [12–16].

Experimentally, if two particles are emitted from a pp or heavy-ion collision and detected in, for example, a particle tracking detector, the two-particle count rate is used to form the one-dimensional correlation function, $C(k^*)$, given by

$$C(k^*) = \frac{A(k^*)}{B(k^*)}, \tag{1}$$

where $A(k^*)$ is the measured distribution of particle pairs from the same event, i.e. the two-particle count rate, $B(k^*)$ is the reference distribution of particle pairs created from mixed events, and k^* is the magnitude of the momentum of each of the particles in their pair rest frame (PRF). Note that for particle pairs with identical masses, $k^* = Q_{\mathrm{inv}}/2$, where Q_{inv} is the invariant momentum difference of the pair.

Normally, two-particle femtoscopy is used to extract information about the space-time extent of the emitting particle source, *i.e.* the collision, from the experimental correlation function. In order to extract explicit spacial information and implicit time information about the particle source, the measured two-particle correlation function is, in general, fit with a one-dimensional formula that includes a quantum statistics term, for identical particles, and a parameterization which incorporates strong final-state interactions between the particles (FSI), for cases where they are important. If it is assumed that there is no Coulomb final-state interaction between the particles and the particles are bosons, the formula used in the present work, which was introduced by R. Lednicky and is based on the model by R. Lednicky and V.L. Lyuboshitz [13, 14] (see also Ref. [12] for more details), is

$$\begin{aligned} C(k^*) = 1 + \lambda e^{-4k^{*2}R^2} + \lambda\alpha\Bigg[\frac{1}{2}\left|\frac{f(k^*)}{R}\right|^2 \\ + \frac{2\mathcal{R}f(k^*)}{\sqrt{\pi}R}F_1(2k^*R) \\ - \frac{\mathcal{I}f(k^*)}{R}F_2(2k^*R) + \Delta C\Bigg], \end{aligned} \tag{2}$$

where

$$F_1(z) \equiv \frac{\sqrt{\pi}e^{-z^2}\,\mathrm{erfi}(z)}{2z}; \qquad F_2(z) \equiv \frac{1-e^{-z^2}}{z}. \tag{3}$$

In the above equations $f(k^*)$ is the s-wave scattering amplitude which depends on the types of particles being studied (see below), α is a factor that also depends on the types of particles, R is the radius parameter assuming a spherical Gaussian source distribution, and λ is the correlation strength. The correlation strength is equal to unity in the ideal case of perfect particle identification, a perfect Gaussian particle source and the absence of long-lived resonances that decay into the particles of interest. The term ΔC is a calculated correction factor that takes into account the deviation from the spherical wave assumption used in the inner region of the short-range potential in the derivation of Eq. (2) (see the Appendix in Ref. [12]).

The second term in Eq. (2) is the quantum statistics term for identical bosons, and the third term is the FSI term. One fits Eq. (2) to (1) to extract the parameters R and λ. Information on the emission time of the bosons by the source can be obtained by comparing the dependence of the extracted R parameters on kinematic variables, *e.g.* transverse momentum of the pairs, with models.

The main emphasis of the work presented here involves using femtoscopy with non-identical particles to study the resonance $a_0(980)$ with $\mathrm{K^0_S K^\pm}$ pairs. The quantum statistics term in Eq. (2) will thus not be present and the FSI term is divided by 2 since symmetrization of the two-boson wavefunction is no longer requred. Since this is a threshold resonance, it should be a reasonable assumption that the FSI described by $f(k^*)$ in Eq. (2) is primarily due to the $a_0(980)$ [12]. Thus $f(k^*)$ takes the following form:

$$f(k^*) = \frac{\gamma_{a0\to K\overline{K}}}{m_{a0}^2 - s - i(\gamma_{a0\to K\overline{K}}k^* + \gamma_{a0\to\pi\eta}k_{\pi\eta})}, \tag{4}$$

where m_{a0} is the mass of the a_0 resonance, and $\gamma_{a0\to K\overline{K}}$ and $\gamma_{a0\to\pi\eta}$ are the couplings of the a_0 resonance to the $\mathrm{K^0K^-}$ (or $\mathrm{\bar{K}^0K^+}$) and $\pi\eta$ channels, respectively. The a_0 decay couplings were obtained from Ref. [10]. Also, $s = 4(m_K^2 + k^{*2})$ and $k_{\pi\eta}$ denotes the momentum in the second decay channel ($\pi\eta$).

3. Details of the measurements

The present study is to apply the femtoscopy method with $\mathrm{K^0_S K^\pm}$ pairs in the LHC ALICE Collaboration [17] with the goal of extracting information about the quark content of the $a_0(980)$ meson from the extracted fit parameters, R and λ. The measurements use ALICE data from minimum-bias triggered $\sqrt{s} = 7$ TeV pp and 0-10% central-triggered $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb-Pb collisions. The ALICE experiment is designed to cover a wide acceptance of produced particles from LHC pp, Pb-Pb, and p-Pb collisions with good momentum resolution and particle identification [17]. These features make ALICE the ideal experiment to carry out femtoscopic studies.

Figure 1 shows $\mathrm{K^0_S K^\pm}$ correlation functions with FSI Lednicky equation fits from ALICE for $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb-Pb (left) and $\sqrt{s} = 7$ TeV pp collisions (right) from Refs. [18] and [19], respectively. The shapes of the correlation functions look qualitatively different, yet the Lednicky equation using the $a_0(980)$ as the FSI does a good job in fitting both of them. This supports the assumption that the $a_0(980)$ is responsible for the FSI in these measurements.

Figure 2 shows the resulting R and λ parameters that are extracted in these measurements, plotted versus k_T, i.e. the average transverse momentum of the kaon pair. It is seen that for the central Pb–Pb collision measurements $R \sim 5-6$ fm, decreasing with increasing k_T as was found for Pb–Pb $\mathrm{K^0_S K^0_S}$ measurements [20], whereas for the minimum-bias pp collisions $R \sim 1$ fm for increasing k_T as found for pp $\mathrm{K^0_S K^0_S}$ [21]. For λ, it is seen that $\lambda \sim 0.6$ for Pb–Pb, similar to what was found for both Pb–Pb and pp $\mathrm{K^0_S K^0_S}$ measurements [20, 21], whereas for pp $\lambda \sim 0.3$, which is significantly smaller taking into account the experimental uncertainties shown.

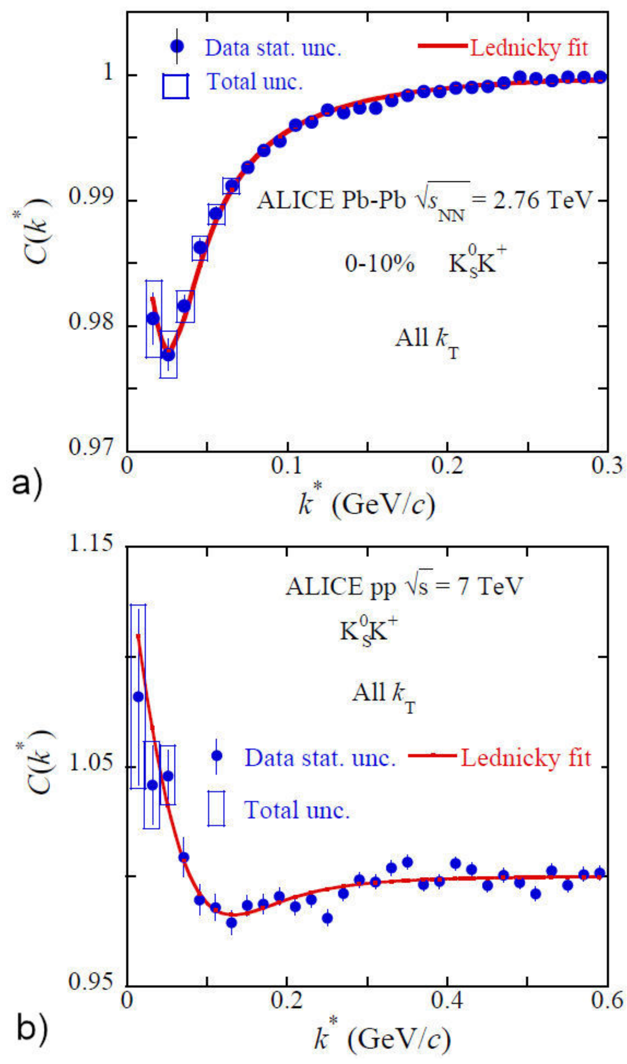

FIGURE 1. One-dimensional $K^0_S K^\pm$ correlation functions with FSI Lednicky equation fits from ALICE for $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb a) and $\sqrt{s} = 7$ TeV pp collisions b) from Refs. [18, 19], respectively. Statistical uncertainties are shown as error bars, and the algebraic sums of statistical and systematic uncertainties are shown as boxes.

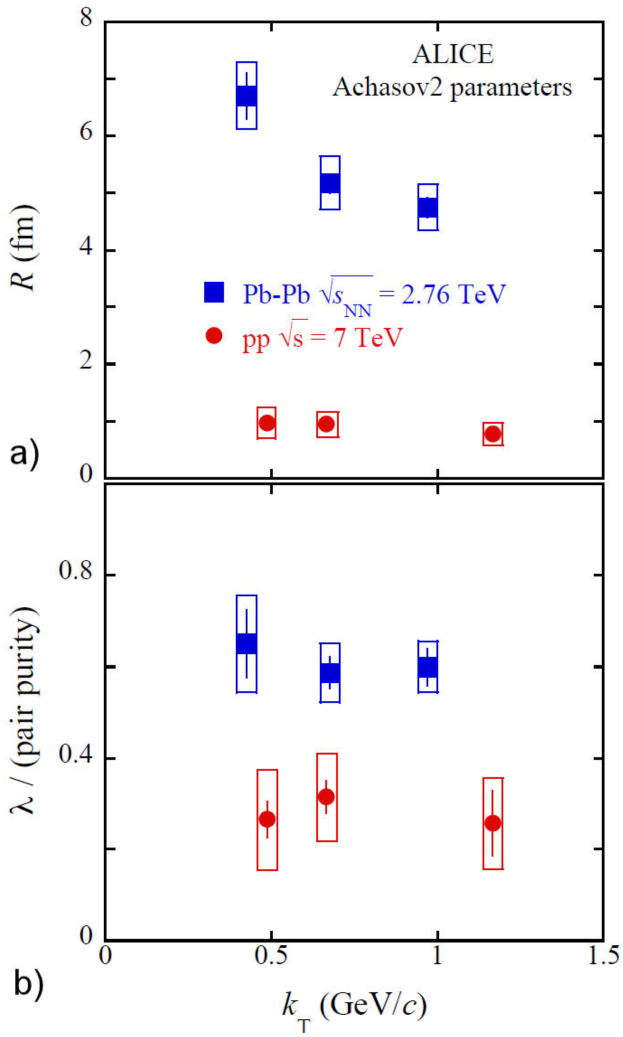

FIGURE 2. R and λ vs. k_T extracted from $K^0_S K^\pm$ femtoscopy in ALICE $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb and $\sqrt{s} = 7$ TeV pp collisions from Ref. [19]. Statistical uncertainties are shown as error bars, and the algebraic sums of statistical and systematic uncertainties are shown as boxes. "Achasov2 parameters" refers to the $a_0(980)$ decay couplings obtained from Ref. [10].

Three factors that can affect the value of the λ parameter are:

1) The experimental reconstruction purity of the kaons,

2) the extent to which a Gaussian describes the kaon source, and

3) the presence of kaons emitted from the decay of long-lived resonances which dilute the direct-kaon sample.

However, it can be shown that none of these factors can account for the differences seen in λ as described above [19].

A physics effect that could be responsible for this difference in λ values between the Pb–Pb and pp measurements shown in Fig. 2 is that the a_0 resonance may actually be a tetraquark state of the form $(q_1, \bar{q_2}, s, \bar{s})$, where q_1 and q_2 are u or d quarks. The strength of the FSI through a tetraquark a_0 would be decreased by the small size of the kaon source in pp, *i.e.* $R \sim 1$ fm, since $s - \bar{s}$ annihilation would be encouraged due to the close creation distance of the kaon pair. For a FSI through a diquark a_0, with the form $(q_1, \bar{q_2})$, the small source geometry in pp would not reduce its strength but would encourage a_0 formation since $s - \bar{s}$ annihilation would be required. For Pb-Pb and pp $K^0_S K^0_S$ measurements, λ would not be affected significantly by a tetraquark a_0 since the enhancement in the correlation function near $k^* \sim 0$ is dominated by the effect of quantum statistics [21]. For the large kaon source measured in Pb–Pb collisions to have $R \sim 6$ fm as seen in Fig. 2, the situation should be reversed, the large average distance between the kaons encouraging the formation of a tetraquark a_0 and being unfavorable for the formation of a diquark a_0. A larger $\lambda \sim 0.6$ is indeed measured in that case, as already mentioned above. Thus, from this simple geometric argument, the suggestion could be made that the present results are compatible with the $a_0(980)$ being a tetraquark state.

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