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# $K^0_S K^0_S$ correlations in pp collisions at $\sqrt{s} = 7$ TeV from the LHC ALICE experiment ☆

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ABSTRACT

Identical neutral kaon pair correlations are measured in $\sqrt{s} = 7$ TeV pp collisions in the ALICE experiment. One-dimensional $K^0_S K^0_S$ correlation functions in terms of the invariant momentum difference of kaon pairs are formed in two multiplicity and two transverse momentum ranges. The femtoscopic parameters for the radius and correlation strength of the kaon source are extracted. The fit includes quantum statistics and final-state interactions of the $a_0/f_0$ resonance. $K^0_S K^0_S$ correlations show an increase in radius for increasing multiplicity and a slight decrease in radius for increasing transverse mass, $m_T$, as seen in $\pi\pi$ correlations in pp collisions and in heavy-ion collisions. Transverse mass scaling is observed between the $K^0_S K^0_S$ and $\pi\pi$ radii. Also, the first observation is made of the decay of the $f'_2(1525)$ meson into the $K^0_S K^0_S$ channel in pp collisions.



## 1. Introduction

In this Letter we present results from a $K^0_S K^0_S$ femtoscopy study by the ALICE experiment [1,2] in pp collisions at $\sqrt{s} = 7$ TeV from the CERN LHC. Identical boson femtoscopy, especially identical charged $\pi\pi$ femtoscopy, has been used extensively over the years to study experimentally the space–time geometry of the collision region in high-energy particle and heavy-ion collisions [3]. Recently, the ALICE and CMS collaborations have carried out charged $\pi\pi$ femtoscopic studies for pp collisions at $\sqrt{s} = 7$ TeV [4,5]. These studies show a transverse momentum dependence of the source radius developing with increasing particle multiplicity similar to the one observed in heavy-ion collisions, where the transverse momentum of a particle is defined as $p_T = \sqrt{p_x^2 + p_y^2}$, where $p_x$ and $p_y$ are the components of the particle momentum transverse to the direction of the initial colliding beams. The main motivations to carry out the present $K^0_S K^0_S$ femtoscopic study to complement this $\pi\pi$ study are 1) to extend the transverse pair momentum range of the charged $\pi\pi$ studies which typically cuts off at about 0.8 GeV/$c$ due to reaching the limit of particle identification, whereas $K^0_S$'s can easily be identified to 2 GeV/$c$ and beyond, 2) since $K^0_S$ is uncharged, $K^0_S K^0_S$ pairs close in phase space are not suppressed by a final-state Coulomb repulsion as is the case of charged $\pi\pi$ pairs, 3) $K^0_S K^0_S$ pairs close in phase space are additionally enhanced by the strong final-state interaction due to the $a_0/f_0$ resonance giving a more pronounced signal, and 4) one can, in principle, obtain complementary information about the collision interaction region by using different types of mesons [6–8]. The physics advantage of items 1) and 4) is to study the transverse mass scaling of the source size which is considered a signature of collective behaviour in heavy-ion collisions [3], where transverse mass is defined as $m_T = \sqrt{p_T^2 + m_0^2}$, where $m_0$ is the particle rest mass. By definition, $m_T$ scaling occurs when the source sizes from different particle species fall on the same curve vs. $m_T$. Thus, comparing results from $\pi\pi$ and $K^0_S K^0_S$ at the same $m_T$ would be a good test of this scaling. Item 3) can be used as an advantage since the final-state interaction of $K^0_S K^0_S$ via the $a_0/f_0$ resonance can be calculated with a reasonable degree of precision. Previous $K^0_S K^0_S$ studies have been carried out in LEP $e^+e^-$ collisions [9–11], HERA ep collisions [12], and RHIC Au–Au collisions [13]. Due to statistics limitations, a single set of femtoscopic source parameters, i.e. radius, $R$, and correlation strength, $\lambda$, was extracted in each of these studies. The present study is the first femtoscopic $K^0_S K^0_S$ study to be carried out a) in pp collisions and b) in more than one multiplicity and transverse pair momentum, $k_T$, range, where $k_T = |\vec{p}_{T1} + \vec{p}_{T2}|/2$ and $\vec{p}_{T1}$ and $\vec{p}_{T2}$ are the transverse momenta of the two $K^0_S$'s from the pair.

## 2. Description of experiment and data selection

The data analyzed for this work were taken by the ALICE experiment during the 2010 $\sqrt{s} = 7$ TeV pp run at the CERN LHC.

Particle identification and momentum determination were performed with particle tracking in the ALICE Time Projection Chamber (TPC) and ALICE Inner Tracking System (ITS) [1,2]. The TPC was used to record charged-particle tracks as they left ionization trails in the Ne–$CO_2$ gas. The ionization drifts up to 2.5 m from the central electrode to the end caps to be measured on 159 padrows, which are grouped into 18 sectors; the position at which the track crossed the padrow was determined with resolutions of 2 mm and 3 mm in the drift and transverse directions, respectively. The ITS

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was used also for tracking. It consists of six silicon layers, two innermost Silicon Pixel Detector (SPD) layers, two Silicon Drift Detector (SDD) layers, and two outer Silicon Strip Detector (SSD) layers, which provide up to six space points for each track. The tracks used in this analysis were reconstructed using the information from both the TPC and the ITS; such tracks were also used to reconstruct the primary vertex of the collision. For details of this procedure and its efficiency see Ref. [2].

A minimum-bias trigger was used for this analysis. Event triggering was accomplished using several sets of detectors. The forward scintillator detectors, VZERO, are placed along the beam line at +3 m and −0.9 m from the nominal interaction point. They cover a region $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. They were used in the minimum-bias trigger and their timing signal was used to reject the beam–gas and beam–halo collisions. The minimum-bias trigger required a signal in either of the two VZERO counters or one of the two inner layers of the SPD. Within this sample, events were selected based on the measured charged-particle multiplicity within the pseudorapidity range $|\eta| < 1.2$. Events were required to have a primary vertex within 1 mm of the beam line and 10 cm of the centre of the 5 m long TPC. This provides almost uniform acceptance for particles with $|\eta| < 1$ for all events in the sample. It decreases for $1.0 < |\eta| < 1.2$. In addition, we require events to have at least one charged particle reconstructed within $|\eta| < 1.2$.

Event multiplicity, $N_{\rm ch}$, was defined as the number of charged particles falling into the pseudorapidity range $|\eta| < 0.8$ and transverse momentum range $0.12 < p_{\rm T} < 10$ GeV/$c$. The two event multiplicity ranges used in this analysis, 1–11 and >11, correspond to mean charged particle densities, $\langle {\rm d}N_{\rm ch}/{\rm d}\eta\rangle$, of 2.8 and 11.1, respectively, with uncertainties of ∼10%. Events from the Monte Carlo event generator PYTHIA [14,15] were used to estimate $\langle {\rm d}N_{\rm ch}/{\rm d}\eta\rangle$ from the mean charged-particle multiplicity in each range as was done for Table I of Ref. [4], which presents ALICE $\pi\pi$ results for pp collisions at $\sqrt{s} = 7$ TeV, event multiplicity having been determined in the same way there as in the present work.

The decay channel $K^0_s \to \pi^+\pi^-$ was used for particle identification, with a typical momentum resolution of ∼1% [16]. The distance of closest approach (DCA) of the candidate $K^0_s$ decay daughters was required to be $\leqslant 0.1$ cm. Fig. 1 shows invariant mass distributions of candidate $K^0_s$ vertices for the four multiplicity–$k_{\rm T}$ ranges used in this study (see below) along with a Gaussian + linear fit to the data. The invariant mass at the peaks was found to be 0.497 GeV/$c^2$, which is within 1 MeV/$c^2$ of the accepted mass of the $K^0_s$ [17]. The average peak width was $\sigma = 3.72$ MeV/$c^2$ demonstrating the good $K^0_s$ momentum resolution obtained in the ALICE tracking detectors. A vertex was identified with a $K^0_s$ if the invariant mass of the candidate $\pi^+\pi^-$ pair associated with it fell in the range 0.490–0.504 GeV/$c^2$. As seen in Fig. 1, the ratio of the $K^0_s$ signal to signal + background, $S/(S+B)$, in each of the four ranges is determined to be 0.90 or greater. The minimum $K^0_s$ flight distance from the primary vertex was 0.5 cm. Additional cuts on the $K^0_s$ were made in $\eta$ and $p_{\rm T}$, i.e. $|\eta| < 0.8$ and $0.4 < p_{\rm T} < 3.5$ GeV/$c$. A cut was imposed to prevent $K^0_s K^0_s$ pairs from sharing the same decay daughter. Minimum bias events with two or more $K^0_s$'s were selected for use in the analysis. Three or more $K^0_s$'s occurred in 19% of the events, and all pair combinations of these which satisfied cuts were used.

## 3. Results

Fig. 2 shows a $K^0_s K^0_s$ correlation function, $C(Q_{\rm inv})$, in the invariant momentum difference variable $Q_{\rm inv} = \sqrt{Q^2 - Q_0^2}$, where $Q^2$ and $Q_0^2$ are the squared 3-momentum and energy differences between the two particles respectively, for all event multiplicities and $k_{\rm T}$. The experimental $C(Q_{\rm inv})$ is defined as

$$C(Q_{\rm inv}) = a\frac{N_{\rm R}(Q_{\rm inv})}{N_{\rm B}(Q_{\rm inv})} \tag{1}$$

where $N_{\rm R}(Q_{\rm inv})$ is the number of "real" $K^0_s K^0_s$ pairs from the same event, $N_{\rm B}(Q_{\rm inv})$ is the number of "background" $K^0_s K^0_s$ pairs constructed by mixing of $K^0_s$ candidates from ten adjacent events in the same $k_{\rm T}$ and event multiplicity range as the real pairs, and $a$ is a normalization constant which is adjusted to set the large-$Q_{\rm inv}$ value of $C(Q_{\rm inv})$ to be in the vicinity of unity. Only events with two or more $K^0_s$'s were used in event mixing. As a test, background formed using only single-$K^0_s$ events was found to agree with the default one within the statistical uncertainties. Bins in $Q_{\rm inv}$ were taken to be 20 MeV/$c$ which is greater than the average resolution of $Q_{\rm inv}$ resulting from the experimental momentum resolution. Also, the enhancement region in $Q_{\rm inv}$ of the correlation functions for source sizes of ∼ 1 fm is ∼ 200 MeV/$c$. Thus

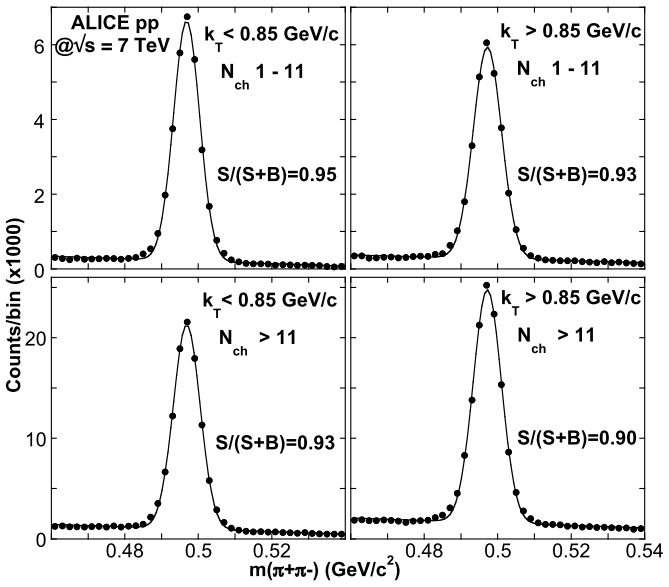


**Fig. 1.** Invariant mass distributions of $\pi^+\pi^-$ pairs in the four multiplicity–$k_{\rm T}$ ranges used in the study. $K^0_s$ used in this analysis were identified by the cut 0.490 GeV/$c^2 < m <$ 0.504 GeV/$c^2$. Also shown is a Gaussian + linear fit to the data points.

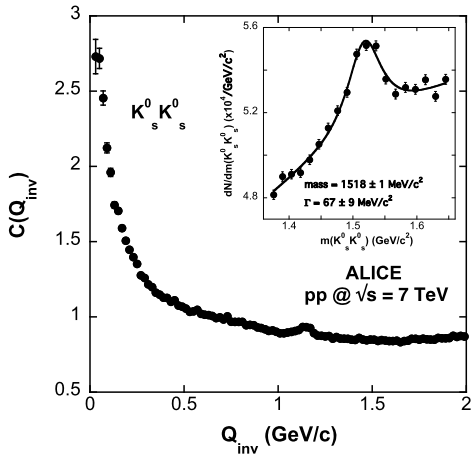


**Fig. 2.** Inclusive (all event multiplicities and $k_{\rm T}$) $K^0_s K^0_s$ $Q_{\rm inv}$ correlation function. Plotted in the insert to the figure is the invariant $K^0_s K^0_s$ mass distribution, $dN/dm(K^0_s K^0_s)$, in the vicinity of the small peak at $Q_{\rm inv} \approx 1.15$ GeV/$c$.

the smearing of the correlation function by the experimental momentum resolution has a negligible effect on the present measurements. The three main features seen in this correlation function are 1) a well-defined enhancement region for $Q_{\rm inv} < 0.3$ GeV/$c$, 2) a non-flat baseline for $Q_{\rm inv} > 0.3$ GeV/$c$, and 3) a small peak at $Q_{\rm inv} \approx 1.15$ GeV/$c$.

Considering feature 3) first, fitting a quadratic + Breit–Wigner function to the invariant $K^0_sK^0_s$ mass distribution, $dN/dm(K^0_sK^0_s)$, around this peak, where $m(K^0_sK^0_s) = 2\sqrt{(Q_{\rm inv}/2)^2 + m^2_K}$, we obtain a mass of $1518 \pm 1 \pm 20$ MeV/$c^2$ and full width ($\Gamma$) of $67 \pm 9 \pm 10$ MeV/$c^2$ (giving the statistical and systematic errors, respectively). This is plotted in the insert to Fig. 2. Comparing with the Particle Data Group meson table [17], this peak is a good candidate for the $f'_2(1525)$ meson ($m = 1525 \pm 5$ MeV/$c^2$, $\Gamma = 73^{+6}_{-5}$ MeV/$c^2$). This is the first observation of the decay of this meson into the $K^0_sK^0_s$ channel in pp collisions. A similar invariant mass plot to that shown in Fig. 2 was made using PYTHIA for comparison since it contains the $f'_2(1525)$ meson. No similar peak was seen above background, thus showing that PYTHIA underestimates the production of this meson in the present system.

In order to disentangle the non-flat baseline from the low-$Q_{\rm inv}$ femtoscopic enhancement, PYTHIA was used to model the baseline. PYTHIA contains neither quantum statistics nor the $K^0_sK^0_s \to a_0/f_0$ channel, but does contain other kinematic effects which could lead to baseline correlations such as mini-jets and momentum and energy conservation effects [4]. PYTHIA events were reconstructed and run through the same analysis method as used for the corresponding experimental data runs to simulate the same conditions as the experimental data analysis. The PYTHIA version of the invariant mass distributions shown for experiment in Fig. 1 yielded similar $S/(S+B)$ values. As a test, the $K^0_sK^0_s$ background obtained from event mixing using PYTHIA events was compared with that from experiment. Since the background pairs do not have femtoscopic effects, these should ideally be in close agreement. A sample plot of the experimental to PYTHIA ratio of the background vs. $Q_{\rm inv}$ is shown in Fig. 3 for the range $N_{\rm ch}$ 1–11, $k_{\rm T} < 0.85$ GeV/$c$. The average of the ratio is normalized to unity. It is found that PYTHIA agrees with the $Q_{\rm inv}$-dependence of the experimental backgrounds within 10%, even though PYTHIA underpredicts the overall scale of $K^0_sK^0_s$ production by about a factor of 2. Since only ratios of PYTHIA $K^0_sK^0_s$ distributions are used in disentangling the experimental non-flat baseline, the overall scale factor cancels out. The method of determining the systematic error of using PYTHIA for this purpose is discussed later. The Monte Carlo event generator PHOJET [18,19] was also studied for use in modelling the baseline. When it was compared with the experimental data using the same method shown for PYTHIA in Fig. 3, it was found to not represent the shape of the experimental background as well as PYTHIA, differing from experiment by >20%. It was thus decided to not use PHOJET for this study.

$K^0_sK^0_s$ correlation functions in $Q_{\rm inv}$ were formed from the data in four ranges: two event multiplicity (1–11, > 11) ranges times two $k_{\rm T}$ (< 0.85, > 0.85 GeV/$c$) ranges. About $3 \times 10^8$ experimental minimum bias events were analyzed yielding $6 \times 10^6$ $K^0_sK^0_s$ pairs. About $2.3 \times 10^8$ PYTHIA minimum bias events used for the baseline determination were also analyzed. This was found to give sufficient statistics for the PYTHIA correlation functions such that the impact of these statistical uncertainties on the measurement of the source parameters was small compared with the systematic uncertainties present in the measurement.

The femtoscopic variables $R$ and $\lambda$ were extracted in each range by fitting a model correlation function to the double ratio of the experimental correlation function divided by the PYTHIA correlation function, $C_{\rm DR}(Q_{\rm inv}) = [C(Q_{\rm inv})]_{\rm exp}/[C(Q_{\rm inv})]_{\rm PYTHIA}$, where $C(Q_{\rm inv})$ is calculated via the ratio given in Eq. (1). The model correlation function used in the fitting was the Lednicky correlation function [13], $C_{\rm L}(Q_{\rm inv})$, based on the model by R. Lednicky and V.L. Lyuboshitz [20]. This model takes into account both quantum statistics and strong final-state interactions from the $a_0/f_0$ resonance which occur between the $K^0_sK^0_s$ pair. The $K^0_s$ spatial distribution is assumed to be Gaussian with a width $R$ in the parametrization and so its influence on the correlation function is from both the quantum statistics and the strong final-state interaction. This is the same parametrization as was used by the RHIC STAR collaboration to extract $R$ and $\lambda$ from their $K^0_sK^0_s$ study of Au–Au collisions [13]. The correlation function is

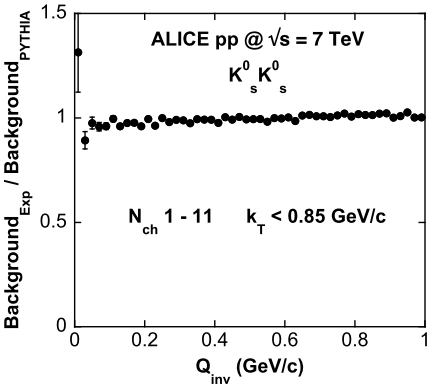


**Fig. 3.** Ratio of $K^0_sK^0_s$ experimental background to PYTHIA background vs. $Q_{\rm inv}$ for the range $N_{\rm ch}$ 1–11, $k_{\rm T} < 0.85$ GeV/$c$. The average of the ratio is normalized to unity.

$$C_{\rm L}(Q_{\rm inv}) = \lambda C'(Q_{\rm inv}) + (1-\lambda) \tag{2}$$

where

$$C'(Q_{\rm inv}) = 1 + e^{-Q^2_{\rm inv}R^2} + \alpha\left[\left|\frac{f(k^*)}{R}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R}F_1(Q_{\rm inv}R) - \frac{2\Im f(k^*)}{R}F_2(Q_{\rm inv}R)\right] \tag{3}$$

and where

$$F_1(z) = \int_0^z dx\,\frac{e^{x^2-z^2}}{z}; \qquad F_2(z) = \frac{1-e^{-z^2}}{z}. \tag{4}$$

$f(k^*)$ is the s-wave $K^0\bar{K}^0$ scattering amplitude whose main contributions are the s-wave isoscalar and isovector $f_0$ and $a_0$ resonances [13], $R$ is the radius parameter and $\lambda$ is the correlation strength parameter (in the ideal case of pure quantum statistics $\lambda = 1$). $\alpha$ is the fraction of $K^0_sK^0_s$ pairs that come from the $K^0\bar{K}^0$ system which is set to 0.5 assuming symmetry in $K^0$ and $\bar{K}^0$ production [13]. As seen in Eq. (3), the first term is a Gaussian function for quantum statistics and the second term describes the final-state resonance scattering and both are sensitive to the radius parameter, $R$, giving enhanced sensitivity to this parameter. The scattering amplitude, $f(k^*)$, depends on the resonance masses and decay couplings which have been extracted in various experiments [13]. The uncertainties in these are found to have only a small effect on the extraction of $R$ and $\lambda$ in the present study. An overall normalization parameter multiplying Eq. (2) is also fit to the experimental correlation function.

Fig. 4 shows the experimental and PYTHIA $K^0_sK^0_s$ correlation functions for each of the four multiplicity–$k_{\rm T}$ ranges used. Whereas the experimental correlation functions show an enhancement for

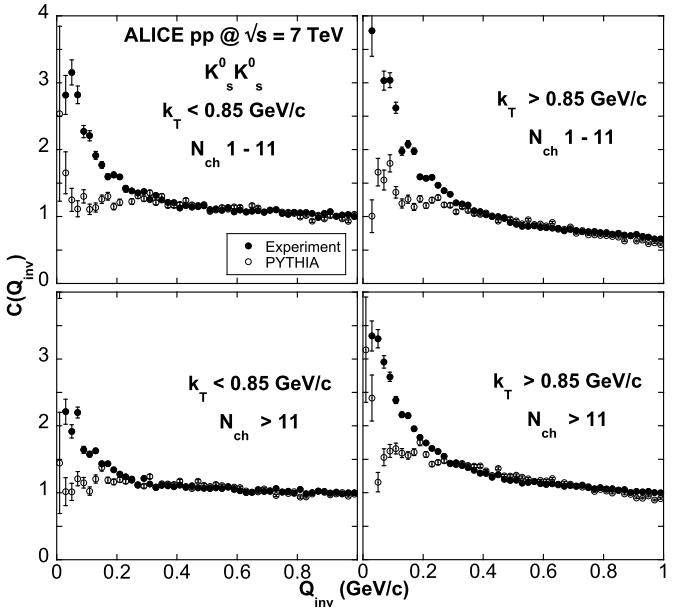


**Fig. 4.** Experimental and PYTHIA $K^0_s K^0_s$ correlation functions for the four multiplicity–$k_T$ ranges.

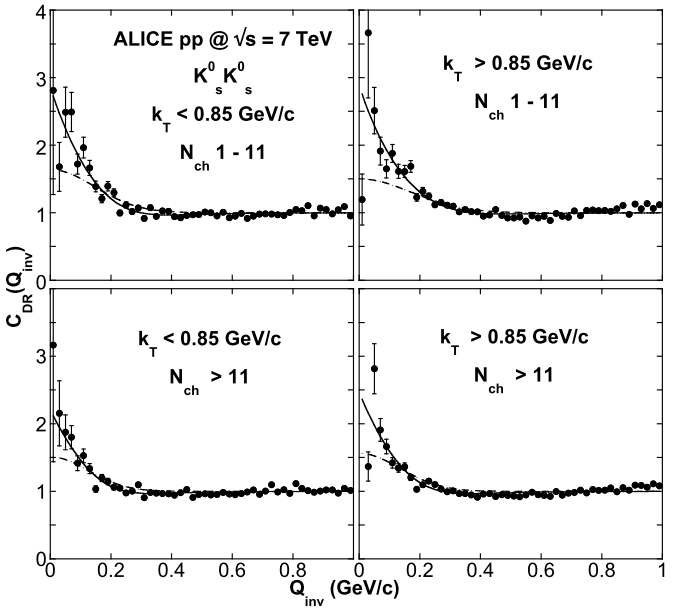


**Fig. 5.** Experimental $K^0_s K^0_s$ correlation functions divided by PYTHIA correlation functions for the four multiplicity–$k_T$ ranges with femtoscopic fits using the full Lednicky parametrization (solid lines) and the contribution due to quantum statistics (dashed lines).

$Q_{\rm inv} < 0.3$ GeV/$c^2$, the PYTHIA correlation functions do not show a similar enhancement. This is what would be expected if the experimental correlation functions contain femtoscopic correlations since PYTHIA does not contain these. PYTHIA is seen to describe the experimental baseline rather well in the region $Q_{\rm inv} > 0.4$ GeV/$c^2$ where it is expected that effects of femtoscopic correlations are insignificant. Fig. 5 shows $C_{\rm DR}(Q_{\rm inv})$, the experimental correlation functions divided by the PYTHIA correlation functions from Fig. 4, along with the fits with the Lednicky parametrization from Eqs. (2)–(4) (solid lines). Also shown for reference is the contribution of the quantum statistics part in Eq. (3) (dashed lines), which are seen to account for roughly one-half of the overall value

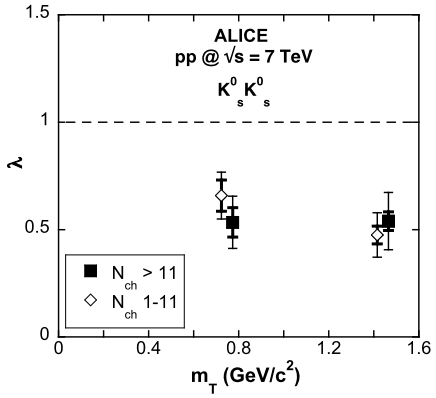


**Fig. 6.** $\lambda$ parameters extracted by fitting the Lednicky parametrization to $K^0_s K^0_s$ correlation functions as shown in Fig. 5. Statistical (darker lines) and total uncertainties are shown. The $N_{\rm ch} > 11$ points are offset by 0.05 GeV/$c^2$ for clarity.

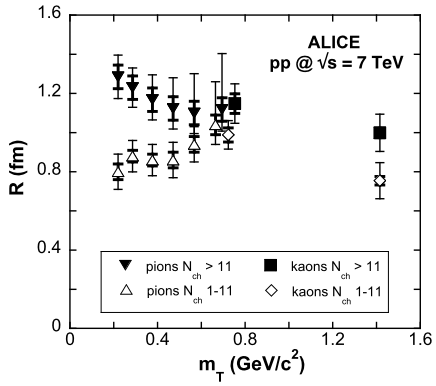


**Fig. 7.** $R$ parameters extracted by fitting the Lednicky parametrization to $K^0_s K^0_s$ correlation functions as shown in Fig. 5. Also shown for comparison are $R$ parameters extracted in the same event multiplicity ranges from a $\pi\pi$ femtoscopic study by ALICE [4] in pp collisions at $\sqrt{s} = 7$ TeV. Statistical (darker lines) and total uncertainties are shown. The highest $m_{\rm T}$ pion $N_{\rm ch} > 11$ point and lower $m_{\rm T}$ kaon $N_{\rm ch} > 11$ point have been shifted by 0.03 GeV/$c^2$ for clarity.

of the correlation functions. The full Lednicky model fits are seen to qualitatively describe the correlation functions within the error bars, which are statistical.

Figs. 6 and 7 and Table 1 present the results of this study for $\lambda$ and $R$ parameters extracted by fitting the Lednicky parametrization to $K^0_s K^0_s$ correlation functions as shown in Fig. 5. The source parameters are plotted versus the average $m_{\rm T} = \sqrt{\langle k_{\rm T}\rangle^2 + m_{\rm K}^2}$ to observe whether $m_{\rm T}$ scaling is present (as discussed earlier) and statistical + systematic error bars are shown. The statistical uncertainties include both the experimental and the PYTHIA statistical uncertainties used to form the correlation functions, as shown in Fig. 4.

The largest contributions to the systematic uncertainties are 1) the non-statistical uncertainty in using PYTHIA to determine the baseline and 2) the effect of varying the $Q_{\rm inv}$ fit range by ±10%. These were found to be on the order of or greater than the size of the statistical uncertainties, as can be seen in Table 1. The method used to estimate the systematic uncertainty of using PYTHIA was to set the PYTHIA $K^0_s K^0_s$ background distribution equal to the experimental background distribution in the ratio of correlation functions, e.g. forcing the ratio plotted in Fig. 3 to be exactly unity for all $Q_{\rm inv}$. The ratio of correlation functions then becomes the ratio of the experimental to PYTHIA real pair distributions, which is then fit with the Lednicky parametrization to extract the source parameters. Parameters extracted from these correlation functions were

**Table 1**
$K^0_s K^0_s$ source parameters from Lednicky fits for $\sqrt{s} = 7$ TeV pp collisions. Statistical and systematic uncertainties are shown.

| $k_T$ range (GeV/$c$) | $N_{ch}$ range | $\langle k_T \rangle$ (GeV/$c$) | $\langle dN_{ch}/d\eta \rangle$ | $\lambda$ | $R$ (fm) |
|---|---|---|---|---|---|
| $< 0.85$ | 1–11 | 0.52 | 2.8 | $0.66 \pm 0.07 \pm 0.04$ | $0.99 \pm 0.04 \pm 0.04$ |
| $> 0.85$ | 1–11 | 1.32 | 2.8 | $0.48 \pm 0.04 \pm 0.06$ | $0.75 \pm 0.02 \pm 0.07$ |
| $< 0.85$ | $> 11$ | 0.52 | 11.1 | $0.53 \pm 0.07 \pm 0.05$ | $1.15 \pm 0.05 \pm 0.05$ |
| $> 0.85$ | $> 11$ | 1.32 | 11.1 | $0.54 \pm 0.04 \pm 0.09$ | $1.00 \pm 0.02 \pm 0.07$ |

**Table 2**
$K^0_s K^0_s$ source parameters comparing $\alpha = 0.5$ (quantum statistics + FSI) and $\alpha = 0$ (quantum statistics only) fits to Fig. 5 using Eqs. (2)–(4). Statistical uncertainties are shown.

| $k_T$ range (GeV/$c$) | $N_{ch}$ range | $\lambda$ ($\alpha = 0.5$) | $R$ (fm) ($\alpha = 0.5$) | $\lambda$ ($\alpha = 0$) | $R$ (fm) ($\alpha = 0$) |
|---|---|---|---|---|---|
| $< 0.85$ | 1–11 | $0.64 \pm 0.07$ | $0.96 \pm 0.04$ | $1.36 \pm 0.15$ | $1.35 \pm 0.07$ |
| $> 0.85$ | 1–11 | $0.50 \pm 0.04$ | $0.81 \pm 0.02$ | $1.07 \pm 0.09$ | $1.05 \pm 0.04$ |
| $< 0.85$ | $>11$ | $0.51 \pm 0.07$ | $1.12 \pm 0.05$ | $0.97 \pm 0.15$ | $1.64 \pm 0.11$ |
| $> 0.85$ | $>11$ | $0.56 \pm 0.05$ | $1.03 \pm 0.02$ | $0.89 \pm 0.10$ | $1.37 \pm 0.07$ |

then averaged with those from Fig. 5 and are given in Figs. 6 and 7 and Table 1. This method is similar to that used in estimating systematic uncertainties in other $K^0_s K^0_s$ measurements [10,12]. Other systematic uncertainties were also studied, including the effects of varying the $K^0_s$ candidate invariant mass acceptance window, using different sets of resonance masses and decay couplings in the scattering amplitude, $f(k^*)$, used in fitting $C_L(Q_{inv})$ in Eq. (3), and momentum resolution effects (as discussed earlier). These were found to be smaller than the statistical uncertainties. The effects of all systematic uncertainties studied on $R$ and $\lambda$ were added in quadrature to calculate the total systematic uncertainties given in Table 1.

To see the effect of the $a_0/f_0$ final-state interaction (FSI) term in the Lednicky parametrization, the correlation functions in Fig. 5 were fit with Eqs. (2)–(4) for two cases: 1) quantum statistics + FSI terms, i.e. $\alpha = 0.5$ in Eq. (2), and 2) quantum statistics term only, i.e. $\alpha = 0$ in Eq. (3). Case 2) corresponds to a Gaussian parametrization for $R$ and $\lambda$. The results of these fits are shown in Table 2. Including the FSI term in the fit is seen to significantly reduce both $R$ and $\lambda$, i.e. $R$ by $\sim 30\%$ and $\lambda$ by $\sim 50\%$. The FSI is thus seen to enhance the correlation function for $Q_{inv} \to 0$ making $\lambda$ appear larger and making the enhancement region narrower. This results in an apparent larger $R$ and $\lambda$ when fitting with the pure Gaussian quantum statistics model. A reduction in $R$ and $\lambda$ when including the FSI term was also observed, but to a lesser extent, in the STAR Au–Au $K^0_s K^0_s$ study [13]. A larger effect of the $a_0/f_0$ resonance on the correlation function in pp collisions compared with Au–Au collisions is expected since the two kaons are produced in closer proximity to each other in pp collisions, enhancing the probability for final-state interactions.

Within the uncertainties, the $m_T$ dependence of $\lambda$ is seen in Fig. 6 to be mostly flat with $\lambda$ lying at an average level of $\sim 0.5$–$0.6$, similar to that found in the ALICE $\pi\pi$ results for pp collisions at $\sqrt{s} = 7$ TeV [4]. In $\pi\pi$ studies the $\lambda$ value smaller than 1 has been shown at least in part to be due to the presence of long-lived meson resonances which distort the shape of the source so that the Gaussian assumption, which the fitting functions are based on, is less valid [21]. This same explanation is possible for the present $\lambda$ parameters extracted from the $K^0_s K^0_s$ correlation functions. For example, the $\phi$ and K* mesons with full widths of $\Gamma \sim 4$ and $\Gamma \sim 50$ MeV/$c^2$, respectively, could act as long-lived resonances compared with the extracted source scale of $R \sim 1$ fm, the larger scales being unresolved in the first few $Q_{inv}$ bins but still depressing the overall correlation function.

In Fig. 7 the dependence of the extracted radius parameters on the transverse mass and event multiplicity are shown. Also shown for comparison are $R$ parameters extracted in the same event multiplicity ranges from a $\pi\pi$ femtoscopic study by ALICE [4] in 7 TeV pp collisions. Looking at the $m_T$ dependence first, the $K^0_s K^0_s$ results alone suggest a tendency for $R$ to decrease with increasing $m_T$ for both multiplicity ranges. The $\pi\pi$ measurements also show this decreasing trend for the high multiplicity range, but show the opposite trend for the low multiplicity range, $R$ increasing slightly for increasing $m_T$. Taken with the $\pi\pi$ results the $K^0_s K^0_s$ results for $R$ extend the covered range of $m_T$ to $\sim 1.3$ GeV/$c$, which is more than twice the range as for $\pi\pi$. The lower $m_T$ points for $K^0_s K^0_s$ which are in close proximity in $m_T$ to the highest $m_T$ points for $\pi\pi$ are seen to overlap within errors, showing $m_T$ scaling. The $m_T$ dependence of $R$ combining both particle species is seen to be weak or non-existent within the error bars. Looking at the multiplicity dependence, a tendency for $R$ to increase overall for increasing event multiplicity is seen for both $\pi\pi$ and $K^0_s K^0_s$ measurements as is observed in $\pi\pi$ heavy-ion collision studies [22].

The multiplicity–$m_T$ dependence of the pion femtoscopic radii in heavy-ion collisions is interpreted as a signature for collective hydrodynamic matter behaviour [3]. Such dependences have also been discussed in $e^+e^-$ collisions [23,24]. The corresponding measurements in pp collisions at $\sqrt{s} = 7$ TeV also show a multiplicity–$m_T$ dependence [4,5]. However, important differences with heavy-ion collisions remain, for example at low multiplicities the pion $R$ seems to increase with increasing $m_T$ rather than decreasing as with heavy-ion collisions, as already mentioned earlier. The interpretation of these pp results for pions is still not clear, although model calculations exist that attempt to explain them via a collective phase created in high-multiplicity pp collisions [25–27]. If such a collective phase is hydrodynamic-like, the $m_T$ dependence of the radii should extend to heavier particles such as the $K^0_s$ as well, as shown in Ref. [27]. The measurements presented in this Letter provide a cross-check of the collectivity hypothesis. The interpretation is, however, complicated by the fact that in such small systems particles coming from the decay of strong resonances play a significant role [28]; simple chemical model calculations show that this influence should be relatively smaller for kaons than for pions. So far, no model calculations are known in the literature for any KK correlations in pp collisions for $m_T \geqslant 0.7$ GeV/$c^2$, but the results measured in the present study should act as a motivation for such calculations.

## 4. Summary

In summary, identical neutral kaon pair correlations have been measured in $\sqrt{s} = 7$ TeV pp collisions in the ALICE experiment. One-dimensional $K^0_s K^0_s$ correlation functions in terms of

the invariant momentum difference of kaon pairs were formed in two multiplicity and two transverse momentum ranges. The femtoscopic kaon source parameters $R$ and $\lambda$ have been extracted. The fit includes quantum statistics and final-state interactions of the $a_0/f_0$ resonance. $K^0_sK^0_s$ correlations show an increase in $R$ for increasing multiplicity and a slight decrease in $R$ for increasing $m_T$ as seen in $\pi\pi$ correlations in the pp system and in heavy-ion collisions. Within uncertainties, $m_T$ scaling is also observed for the $K^0_sK^0_s$ and $\pi\pi$ radii.

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