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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 the pp system 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.

*See Appendix A for the list of collaboration members

1 Introduction

In this paper 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 collaboration has carried out a charged $\pi\pi$ femtoscopic study for pp collisions at $\sqrt{s} = 7$ TeV. This study shows a transverse momentum dependence of the source radius developing with increasing particle multiplicity similar to the one observed in heavy-ion collisions [4]. 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. The physics advantage of items 1) and 4) is to study transverse mass scaling, of the source size which is considered a signature of collective behaviour in heavy-ion collisions [3]. If m_T scaling is present, the source sizes from different species should fall on the same curve vs. m_T. Thus, comparing results from $\pi\pi$ and $K^0_s K^0_s$, particularly at very different 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 [5, 6, 7], HERA ep collisions [8], and RHIC Au–Au collisions [9]. Due to statistics limitations, a single set of femtoscopic source parameters, i.e. radius, R, and correlation strength, λ, 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 two transverse momenta of the $K^0_s K^0_s$ 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. About 3×10^8 minimum bias events were analyzed.

K^0_s 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 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].

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

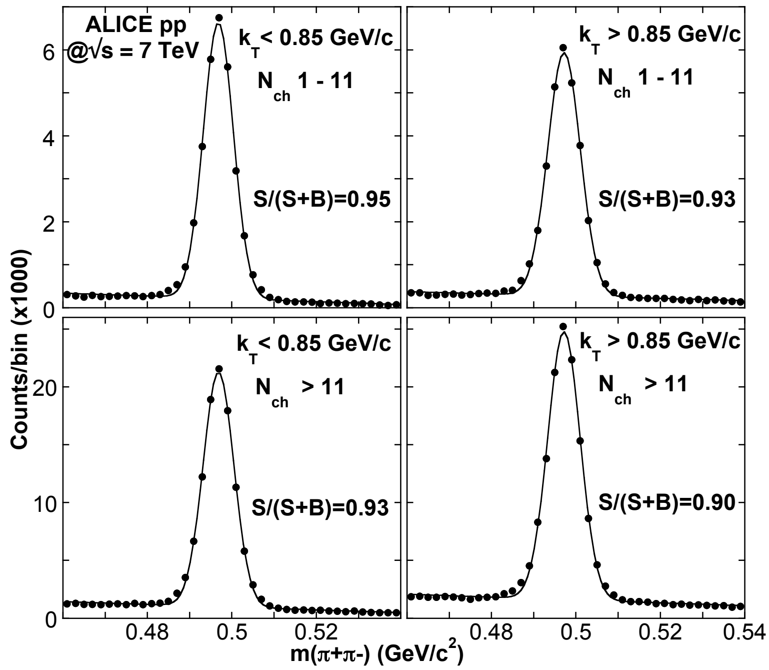

Fig. 1: Invariant mass distributions of $\pi^+\pi^-$ pairs in the four multiplicity–k_T ranges used in the study. K_s^0 used in this analysis were identified by the cut 0.490 GeV/$c^2 < m <$ 0.504 GeV/c^2. Also shown is a Gaussian+linear fit to the data points.

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 $|\eta| < 1.2$.

The decay channel $K_s^0 \to \pi^+\pi^-$ was used for particle identification, with a typical momentum resolution of $\sim 1\%$ [10]. The distance of closest approach (DCA) of the candidate K_s^0 decay daughters was required to be ≤ 0.1 cm. Figure 1 shows invariant mass distributions of candidate K_s^0 vertices for the four multiplicity–k_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_s^0 [11]. The average peak width was $\sigma = 3.72$ MeV/c^2 demonstrating the good K_s^0 momentum resolution obtained in the ALICE tracking detectors. A vertex was identified with a K_s^0 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 Figure 1, the ratio of the K_s^0 signal to signal+background, $S/(S+B)$, in each of the four ranges is determined to be 0.90 or greater. The minimum K_s^0 flight distance from the primary vertex was 0.5 cm. Minimum bias events with two of more K_s^0's were selected for use in the analysis, with 19% having greater than two K_s^0's. A cut was imposed to prevent $K_s^0K_s^0$ pairs from sharing the same decay daughter.

3 Results

Figure 2 shows a $K_s^0K_s^0$ correlation function in the invariant momentum difference variable $Q_{\rm inv} = \sqrt{Q^2 - Q_0^2}$, where Q and Q_0 are the 3–momentum and energy differences between the two particles respectively, for all event multiplicities and k_T. The correlation function was formed from the ratio of "real" $K_s^0K_s^0$ pairs from the same event to "background" $K_s^0K_s^0$ pairs constructed by event mixing of ten adjacent events. 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_{inv} of the

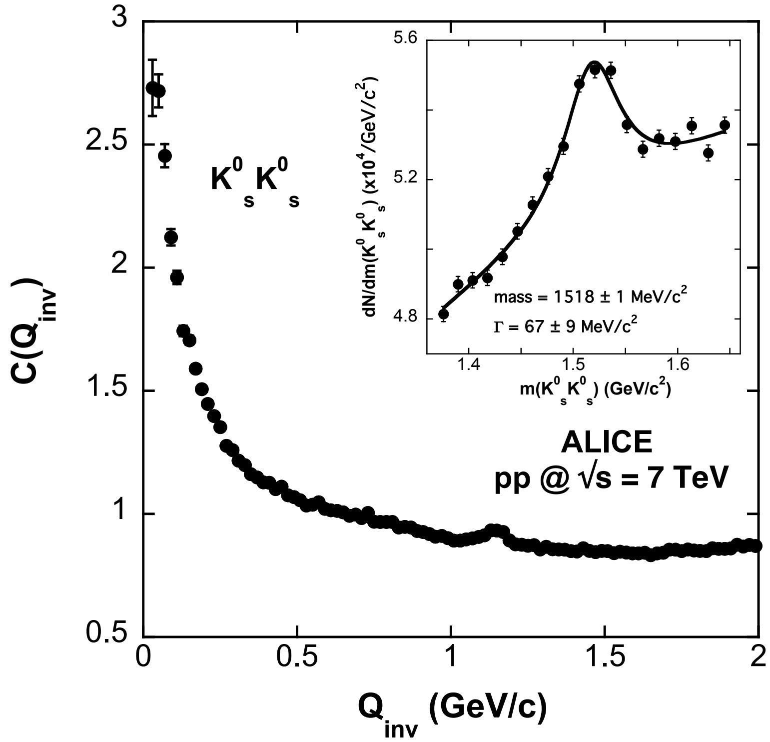

Fig. 2: Inclusive (all event multiplicities and k_T) $K^0_sK^0_s$ Q_{inv} correlation function. Plotted in the insert to the figure is the invariant $K^0_sK^0_s$ mass distribution, $dN/dm(K^0_sK^0_s)$, in the vicinity of the small peak at $Q_{inv} \approx 1.15$ GeV/c.

correlation functions for source sizes of ~ 1 fm is ~ 200 MeV/c. Thus 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 $Q_{inv} < 0.3$ GeV/c, 2) a non-flat baseline for $Q_{inv} > 0.3$ GeV/c and 3) a small peak at $Q_{inv} \approx 1.15$ 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 $m(K^0_sK^0_s) = 2\sqrt{(Q_{inv}/2)^2 + m_K^2}$, we obtain a mass of $1518 \pm 1 \pm 20$ MeV/c^2 and full width (Γ) of $67 \pm 9 \pm 10$ MeV/c^2 (giving the statistical and systematic errors, respectively). This is plotted in the insert to Figure 2. Comparing with the Particle Data Group meson table [11], 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.

In order to disentangle the non-flat baseline from the low-Q_{inv} femtoscopic enhancement, the Monte Carlo event generator PYTHIA [12, 13] was used to model the baseline. PYTHIA contains neither quantum statistics nor the $K^0_sK^0_s \rightarrow a_0/f_0$ 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 Figure 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_{inv} is shown in Figure 3 for the range N_{ch} 1-11, $k_T < 0.85$ GeV/c. The average of the ratio is normalized to unity. It is found that PYTHIA agrees with the experimental backgrounds within 10%. The Monte Carlo event generator PHOJET [14, 15] was also studied for use in modeling the baseline, but it was found to not agree as well with experiment as PYTHIA, and thus was not used.

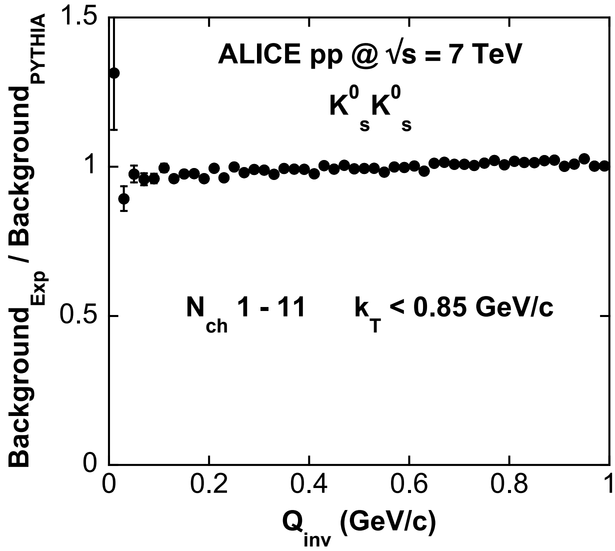

Fig. 3: Ratio of $K^0_sK^0_s$ experimental background to PYTHIA background vs. Q_{inv} for the range N_{ch} 1-11, $k_{\mathrm{T}} < 0.85$ GeV/c. The average of the ratio is normalized to unity.

$K^0_sK^0_s$ correlation functions in Q_{inv} were formed from the data in four ranges: two event multiplicity (1-11, > 11) ranges times two k_{T} (< 0.85, > 0.85 GeV/c) ranges. Event multiplicity was defined as the number of charged particles falling into the pseudorapidty range $|\eta| < 0.8$ and transverse momentum range $0.12 < p_{\mathrm{T}} < 10$ GeV/c. The two event multiplicity ranges used, 1-11 and > 11, correspond to mean charged particle densities, $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$, of 2.8 and 11.1, respectively, with uncertainties of $\sim 10\%$. PYTHIA events were used to estimate $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ from the mean charged–particle multiplicity in each range as was done for Table I of Reference [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. This is convenient since the $K^0_sK^0_s$ source parameters from the present work are compared with those from the $\pi\pi$ measurement below. About 3×10^8 minimum bias events were analyzed yielding about 6×10^6 $K^0_sK^0_s$ pairs. A similar number of 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 λ were extracted in each range by fitting the experimental correlation function divided by the PYTHIA correlation function with the Lednicky parametrization [9] based on the model by R. Lednicky and V.L. Lyuboshitz [16]. 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 spacial 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 λ from their $K^0_sK^0_s$ study of Au–Au collisions [9]. The correlation function is

$$C(Q_{\mathrm{inv}}) = \lambda C'(Q_{\mathrm{inv}}) + (1-\lambda) \tag{1}$$

where,

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

and where

$$F_1(z) = \int_0^z dx \frac{e^{x^2-z^2}}{z} \; ; F_2(z) = \frac{1-e^{-z^2}}{z}. \tag{3}$$

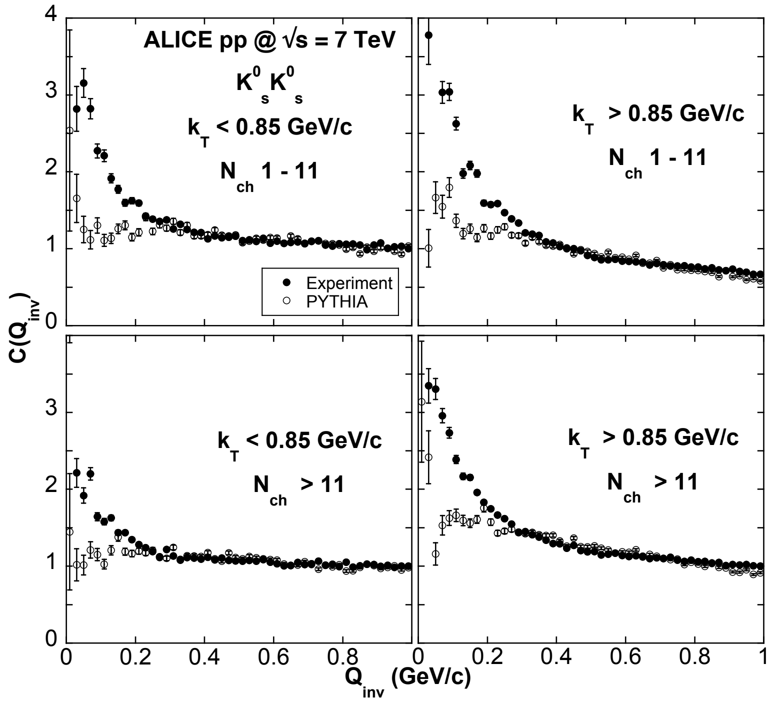

Fig. 4: Experimental and PYTHIA $K^0_s K^0_s$ correlation functions for the four multiplicity–k_T ranges.

$f(k^*)$ is the s–wave $K^0\overline{K^0}$ scattering amplitude whose main contributions are the s–wave isoscalar and isovector f_0 and a_0 resonances [9], R is the radius parameter and λ is the correlation strength parameter (in the ideal case of pure quantum statistics $\lambda = 1$). α is the fraction of $K^0_s K^0_s$ pairs that come from the $K^0\overline{K^0}$ system which is set to 0.5 assuming symmetry in K^0 and $\overline{K^0}$ production [9]. As seen in Eq. (2), the first term is the usual Gaussian from 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 [9]. The uncertainties in these are found to have only a small effect on the extraction of R and λ in the present study. An overall normalization parameter multiplying Eq. (1) is also fit to the experimental correlation function.

Figure 4 shows the experimental and PYTHIA $K^0_s K^0_s$ correlation functions for each of the four multiplicity–k_T ranges used. Whereas the experimental correlation functions show an enhancement for $Q_{\rm inv} < 0.3$ 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. Figure 5 shows the experimental correlation functions divided by the PYTHIA correlation functions from Figure 4 along with the fits with the Lednicky parametrization from Eqs. (1)-(3). The fits are seen to qualitatively describe the correlation functions within the error bars, which are statistical.

Figures 6 and 7 and Table 1 present the results of this study for λ and R parameters extracted by fitting the Lednicky parametrization to $K^0_s K^0_s$ correlation functions as shown in Figure 5. The source parameters are plotted versus $m_T = \sqrt{\langle k_T \rangle^2 + m_K^2}$ to observe whether m_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 Figure 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 $\pm 10\%$. These

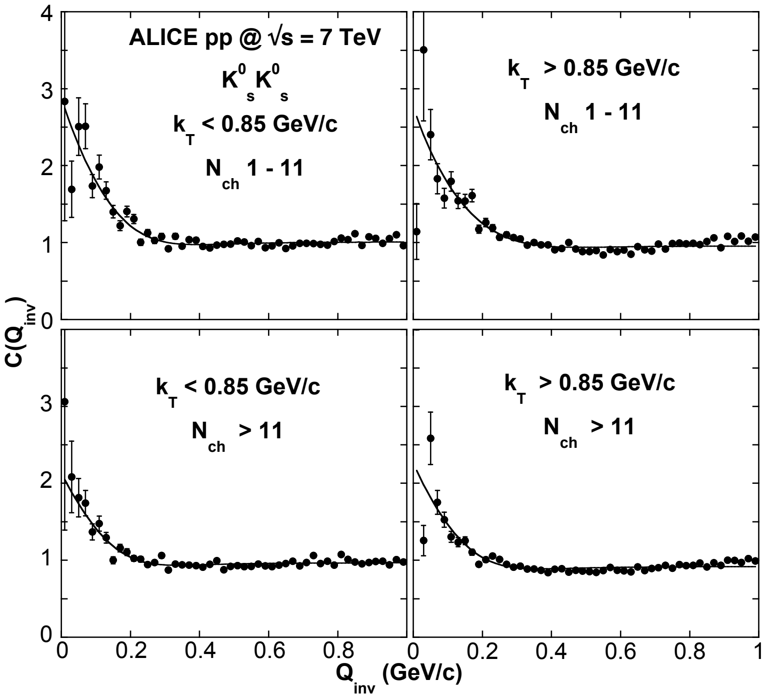

Fig. 5: Experimental $K^0_s K^0_s$ correlation functions divided by PYTHIA correlation functions for the four multiplicity–k_T ranges with femtoscopic fits using the Lednicky parametrization.

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 Figure 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 then averaged with those from Figure 5 and are given in Figures 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 [6, 8].

To see the effect of the a_0/f_0 final-state interaction (FSI) term in the Lednicky parametrization, the correlation functions in Figure 5 were fit with Eqs. (1)-(3) 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. (2). Case 2) corresponds to the usual Gaussian parametrization for R and λ. 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 λ, i.e. R by $\sim 30\%$ and λ by $\sim 50\%$. The FSI is thus seen to enhance the correlation function for $Q_{\rm inv} \to 0$ making λ appear larger and making the enhancement region narrower resulting in an apparent larger R. A reduction in R and λ 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 [9]. 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 λ is seen in Figure 6 to be mostly flat with λ 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 λ 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 [17]. This same explanation is possible for the

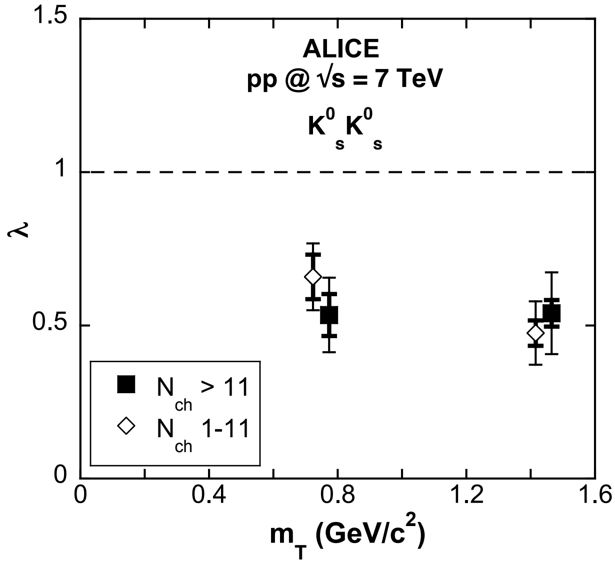

Fig. 6: λ parameters extracted by fitting the Lednicky parametrization to $K^0_sK^0_s$ correlation functions as shown in Figure 5. Statistical (darker lines) and total errors are shown. The $N_{ch} > 11$ points are offset by 0.05 GeV/c^2 for clarity.

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

k_T range (GeV/c)	N_{ch} range	$\langle k_T \rangle$ (GeV/c)	$\langle dN_{ch}/d\eta \rangle$	λ	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: $K^0_sK^0_s$ source parameters comparing $\alpha = 0.5$ (quantum statistics+FSI) and $\alpha = 0$ (quantum statistics only) fits to Figure 5 using Eqs. (1)-(3). Statistical errors are shown.

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

present λ parameters extracted from the $K^0_sK^0_s$ correlation functions. For example, the ϕ 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 Figure 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 $K^0_sK^0_s$ 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

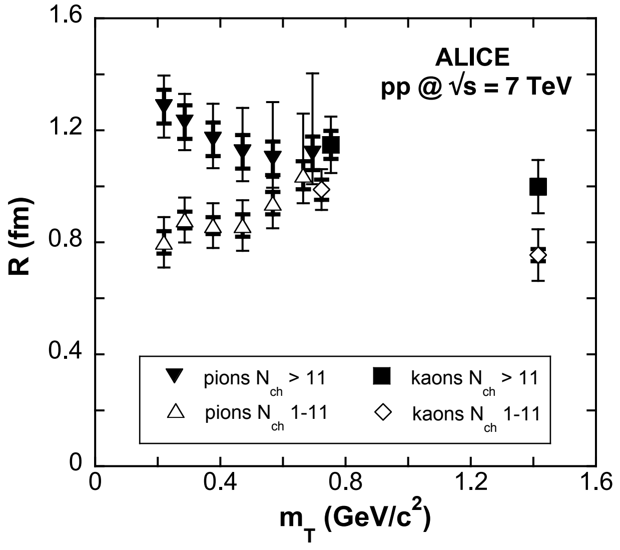

Fig. 7: R parameters extracted by fitting the Lednicky parametrization to $K_s^0K_s^0$ correlation functions as shown in Figure 5. Also shown for comparison are R parameters extracted in the same event multiplicity ranges from a $\pi\pi$ femtoscopic study by ALICE [4] in pp collisions at $\sqrt{s} =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

the opposite trend for the low multiplicity range, R increasing slightly for increasing m_T. Taken with the $\pi\pi$ results the $K_s^0K_s^0$ results for R extend the covered range of m_T to ~ 1.3 GeV/c, which is more than twice the range as for $\pi\pi$. The lower m_T points for $K_s^0K_s^0$ 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 nonexistent 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 $K_s^0K_s^0$ measurements as is observed in $\pi\pi$ heavy-ion collision studies [18].

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]. The corresponding measurements in pp collisions at $\sqrt{s} = 7$ TeV show similar behaviour [4]. However, important differences with heavy-ion collisions remain, for example the low–multiplicity m_T dependence of R in pp for pions 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 [19, 20, 21]. If such a collective phase is hydrodynamic–like, the m_T dependence of the radii should extend to heavier particles such as the K_s^0 as well, as shown in Ref. [21]. The measurements presented in this paper provide a crucial 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 [22]; 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 $m_T \geq 0.7$ 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 $K_s^0K_s^0$ 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 λ 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. The universality of the m_T dependence of the extracted radii, i.e. m_T scaling, is also observed within uncertainties for the $K^0_sK^0_s$ and $\pi\pi$ radii.

References

[1] K. Aamodt *et al.* [ALICE Collaboration], JINST **3**, S08002 (2008).

[2] K. Aamodt *et al.* [ALICE Collaboration], Eur. Phys. J. C **68**, 345 (2010).

[3] M. A. Lisa, S. Pratt, R. Soltz and U. Wiedemann, Ann. Rev. Nucl. Part. Sci. **55**, 357 (2005).

[4] K. Aamodt *et al.* [ALICE Collaboration], Phys. Rev. D **84**, 112004 (2011) arXiv:1101.3665 (2011).

[5] P. Abreu *et al.* [DELPHI Collaboration], Phys. Lett. **B379**, 330-340 (1996).

[6] S. Schael *et al.* [ALEPH Collaboration], Phys. Lett. **B611**, 66-80 (2005).

[7] G. Abbiendi *et al.* (OPAL Collaboration), Eur. J. Phys. C**21**, 23 (2001).

[8] S. Chekanov *et al.* [ZEUS Collaboration], Phys. Lett. **B652**, 1-12 (2007).

[9] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. **C74**, 054902 (2006).

[10] K. Aamodt *et al.* [ALICE Collaboration], Eur. Phys. J. C **71**, 1594 (2011) [arXiv:1012.3257 [hep-ex]].

[11] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).

[12] T. Sjostrand, L. Lonnblad, S. Mrenna and P. Skands, arXiv:hep-ph/0603175 (March 2006).

[13] P. Z. Skands, arXiv:0905.3418 (2009).

[14] R. Engel, Z. Phys. C **66**, 203 (1995).

[15] R. Engel and J. Ranft, Phys. Rev. D **54**, 4244 (1996) [arXiv:hep-ph/9509373].

[16] R. Lednicky and V. L. Lyuboshitz, Sov. J. Nucl. Phys. **35**,770 (1982).

[17] T. J. Humanic, Phys. Rev. C **76**, 025205 (2007).

[18] K. Aamodt *et al.* [ALICE Collaboration], Phys. Lett. **B696**, 328 (2011) [arXiv:1012.4035 [nucl-ex]].

[19] P. Bozek, Acta Phys. Polon. **B41**, 837 (2010). [arXiv:0911.2392 [nucl-th]].

[20] K. Werner, K. Mikhailov, I. Karpenko, T. Pierog, [arXiv:1104.2405 [hep-ph]].

[21] D. Truesdale and T. J. Humanic, J. Phys. G: Nucl. Part. Phys. **39**, 015011(2012).

[22] A. Kisiel, Phys. Rev. C **84**, 044913 (2011) [arXiv:1012.1517 [nucl-th]].

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Christensen[71], P. Christiansen[28], T. Chujo[114], S.U. Chung[84], C. Cicalo[96], L. Cifarelli[21,29,9], F. Cindolo[97], J. Cleymans[79], F. Coccetti[9], F. Colamaria[27], D. Colella[27], G. Conesa Balbastre[64], Z. Conesa del Valle[29], P. Constantin[82], G. Contin[20], J.G. Contreras[8], T.M. Cormier[119], Y. Corrales Morales[25], P. Cortese[26], I. Cortés Maldonado[1], M.R. Cosentino[67], F. Costa[29], M.E. Cotallo[7], E. Crescio[8], P. Crochet[63], E. Cruz Alaniz[56], E. Cuautle[55], L. Cunqueiro[65], A. Dainese[19,93], H.H. Dalsgaard[71], A. Danu[50], D. Das[89], I. Das[42], K. Das[89], S. Dash[40], A. Dash[108], S. De[116], G.O.V. de Barros[107], A. De Caro[24,9], G. de Cataldo[98], J. de Cuveland[35], A. De Falco[18], D. De Gruttola[24], H. Delagrange[102], A. Deloff[100], V. Demanov[87], N. De Marco[94], E. Dénes[60], S. De Pasquale[24], A. Deppman[107], G. D Erasmo[27], R. de Rooij[45], M.A. Diaz Corchero[7], D. Di Bari[27], T. Dietel[54], S. Di Liberto[95], A. 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Gangadharan[15], P. Ganoti[74], C. Garabatos[85], E. Garcia-Solis[10], I. Garishvili[68], J. Gerhard[35], M. Germain[102], C. Geuna[11], A. Gheata[29], M. Gheata[50,29], B. Ghidini[27], P. Ghosh[116], P. Gianotti[65], M.R. Girard[118], P. Giubellino[29], E. Gladysz-Dziadus[104], P. Glässel[82], R. Gomez[106], A. Gonschior[85], E.G. Ferreiro[12], L.H. González-Trueba[56], P. González-Zamora[7], S. Gorbunov[35], A. Goswami[81], S. Gotovac[103], V. Grabski[56], L.K. Graczykowski[118], R. Grajcarek[82], A. Grelli[45], C. Grigoras[29], A. Grigoras[29], V. Grigoriev[69], A. Grigoryan[121], S. Grigoryan[59], B. Grinyov[2], N. Grion[92], P. Gros[28], J.F. Grosse-Oetringhaus[29], J.-Y. Grossiord[109], R. Grosso[29], F. Guber[44], R. Guernane[64], C. Guerra Gutierrez[91], B. Guerzoni[21], M. Guilbaud[109], K. Gulbrandsen[71], T. Gunji[113], A. Gupta[80], R. Gupta[80], H. Gutbrod[85], Ø. Haaland[14], C. Hadjidakis[42], M. Haiduc[50], H. Hamagaki[113], G. Hamar[60], B.H. Han[16], L.D. Hanratty[90], A. Hansen[71], Z. Harmanova[34], J.W. Harris[120], M. Hartig[52], D. Hasegan[50], D. Hatzifotiadou[97], A. Hayrapetyan[29,121], S.T. Heckel[52], M. Heide[54], H. Helstrup[31], A. Herghelegiu[70], G. Herrera Corral[8], N. Herrmann[82], B.A. Hess[115], K.F. Hetland[31], B. Hicks[120], P.T. Hille[120], B. Hippolyte[58], T. Horaguchi[114], Y. Hori[113], P. Hristov[29], I. Hřivnáčová[42], M. Huang[14], T.J. Humanic[15], D.S. Hwang[16],

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Kim[16] , D.J. Kim[37] , S. Kirsch[35] , I. Kisel[35] , S. Kiselev[46] , A. Kisiel[29,118] , J.L. Klay[4] , J. Klein[82] , C. Klein-Bösing[54] , M. Kliemant[52] , A. Kluge[29] , M.L. Knichel[85] , A.G. Knospe[105] , K. Koch[82] , M.K. Köhler[85] , A. Kolojvari[117] , V. Kondratiev[117] , N. Kondratyeva[69] , A. Konevskikh[44] , A. Korneev[87] , R. Kour[90] , M. Kowalski[104] , S. Kox[64] , G. Koyithatta Meethaleveedu[40] , J. Kral[37] , I. Králik[47] , F. Kramer[52] , I. Kraus[85] , T. Krawutschke[82,30] , M. Krelina[33] , M. Kretz[35] , M. Krivda[90,47] , F. Krizek[37] , M. Krus[33] , E. Kryshen[75] , M. Krzewicki[85] , Y. Kucheriaev[88] , C. Kuhn[58] , P.G. Kuijer[72] , I. Kulakov[52] , J. Kumar[40] , P. Kurashvili[100] , A. Kurepin[44] , A.B. Kurepin[44] , A. Kuryakin[87] , V. Kushpil[73] , S. Kushpil[73] , H. Kvaerno[17] , M.J. Kweon[82] , Y. Kwon[123] , P. Ladrón de Guevara[55] , I. Lakomov[42] , R. Langoy[14] , S.L. La Pointe[45] , C. Lara[51] , A. Lardeux[102] , P. 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