Bose-Einstein correlations of charged and neutral kaons in pp and Pb–Pb collisions at the LHC with the ALICE experiment

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Abstract. Due to the effects of quantum statistics and final state interactions, momentum correlations of two or more particles at small relative velocities, i.e. at small relative momenta in their center-of-mass system, are sensitive to the space-time characteristics of the production processes at the level of fm ($10^{-15}\text{ m}$). Kaons are the perfect tool to study Bose-Einstein correlations due to the fact that they are less influenced by resonance decays and therefore probe more effectively directly produced particles. In conjunction with femtoscopic measurements of pions and protons, they can also reveal properties of collective dynamics in heavy-ion collisions. We report on the results of Bose-Einstein correlations of charged and neutral kaons in pp collisions at $\sqrt{s} = 7\text{ TeV}$ and in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76\text{ TeV}$ by the ALICE experiment at the LHC. The results are compared with existing data from Bose-Einstein correlations of identical pions at LHC energies, and of kaons in pp collisions. A comparison of experimental data with theoretical expectations is also carried out.

1. Introduction

Femtoscopic correlations are the tool to measure directly the spatial and temporal scales of the extremely small and short-lived systems created in particle or nuclear collisions with accuracy of 1 fm. The method is based on the Bose-Einstein or Fermi-Dirac symmetric properties of quantum states and uses quantum correlations between identical particles due to symmetrization or antisymmetrization of the wave functions [1]. The source radii extracted from two-particle correlations at low relative momenta describe the system at kinetic freeze-out, i.e. the last stage of particle interactions. Pion femtoscopy, which is the most common femtoscopic analysis, has shown signatures of hydrodynamic flow in heavy-ion collisions, manifesting as a decrease in the source radii with increasing transverse mass $m_T = \sqrt{k_T^2 + m^2}$ [2], where $k_T = |\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|/2$ is the average transverse momentum of the pair. This behavior can be interpreted as one of the signatures of the formation of a deconfined quark matter in these collisions [3]. However, a necessary condition for collective behavior is for all particles created in the collision, not just pions, to experience hydrodynamic flow. We report on the results of femtoscopic studies of $\pi^\pm\pi^\mp$, $K^\pm K^\mp$, $K^0\bar{K}^0$, pp, and pp correlations from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76\text{ TeV}$ by the ALICE experiment at the LHC [4]. The femtoscopic radii are extracted from one-dimensional correlation functions in terms of the invariant momentum difference for a range of collision centralities and $m_T$ values.
2. Data analysis

The dataset analyzed in this contribution is from Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) at the LHC measured by the ALICE detector [5]. About 8 million events from 2010 and about 40 million events from 2011 were used. Events were classified according to their centrality determined using the measured amplitudes in the V0 detectors. Charged particle tracking is performed using the Time Projection Chamber (TPC) and the Inner Tracking System (ITS). The ITS allows for high spatial resolution in determining the primary (collision) vertex. The determination of the momenta of the particles was performed using tracks reconstructed with the TPC and constrained to 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. In the neutral kaon analysis, the secondary daughter tracks used global (TPC and ITS) track reconstruction. 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 was used to calculate the specific energy loss (\( <dE/dx> \)) in the detector expected for a particle with a given mass and momentum. 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.

3. Results

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. The charged kaon correlation functions were fitted using the Bowlar-Sinyukov formula \( C(q) = N \left[ 1 - \lambda + \lambda K(q) (1 + \exp (-R^2 q^2)) \right] \), where \( K(q) \) factor approximates the influence of the Coulomb interaction on the correlation function. The neutral kaon correlation functions were fitted by \( C(q) = [1 - \lambda + \lambda C'(q)] \), where \( C'(q) = 1 + e^{-q^2 R^2} + C_{\text{strongFSI}}(q,R) \) and \( C_{\text{strongFSI}} \) is the strong final state interaction (FSI) contribution to the \( K_S^0 K_S^0 \) correlation function due to the near-threshold resonances, \( f_0(980) \) and \( a_0(980) \).

![Figure 1](image)

**Figure 1.** Left: \( \lambda \) parameters (\( \lambda_{pp} + \lambda_{pA} \) in case of (anti)proton pairs) vs. \( m_T \) for the three centralities considered for \( \pi^+\pi^- \), \( K^+K^- \), \( K_S^0K_S^0 \), pp, and \( p\bar{p} \) [4]. Right: \( R_{\text{avg}} \) parameters versus \( m_T \) for the three centralities considered for \( \pi^+\pi^- \), \( K^+K^- \), \( K_S^0K_S^0 \), pp, and \( p\bar{p} \) [4]. Left and right: Statistical (thin lines) and systematic (boxes) uncertainties are shown.

Fig. 1(left panel) shows the extracted \( \lambda \) parameters as a function of \( m_T \) for several centralities.
The values of $\lambda$ are less than unity due to long-lived resonances which dilute the correlation functions and also lead to non-Gaussian shapes of the correlation functions, especially in the one-dimensional case. Results for kaons and protons are consistent with each other at similar $m_T$. The values of $\lambda$ for pions are lower than for kaons due to the stronger influence of resonances. An additional cause could be a partial coherence of pions. Fig. 1(right panel) shows the extracted $R_{inv}$ parameters as a function of $m_T$ for several centralities. For overlapping $m_T$, the radius parameters are mostly consistent with each other within uncertainties, though the pion radii are generally larger than the kaon radii. The radius parameters show increasing size with increasing event multiplicity as would be expected from a simple geometric picture of the collisions. They also show a decreasing size with increasing $m_T$ as would be expected in the presence of collective radial flow [3]. Both of these dependencies can be seen in previous $\pi^\pm\pi^\pm$ femtoscopic measurements [2] and also reinforce the interpretation that collective flow is present in these collisions for pions, kaons (neutral and charged), and protons alike. Deviations from exact $m_T$-scaling of $R_{inv}$ can be explained as a consequence of the increase of the Lorentz factor with decreasing particle mass. In a hydrodynamic model [6], scaling is observed for the three-dimensional radii measured in the Longitudinally Co-Moving System (LCMS). The transformation from LCMS to the Pair Rest Frame (PRF) involves a boost along the outward direction only, where the boost value is proportional to the transverse velocity of the pair and inversely proportional to the particle mass (for similar $m_T$). Thus, a smaller mass leads to an increase in the boosted $R_{out}$ and, subsequently, $R_{inv}$ in the PRF. Indeed, we observe such an effect in the data, as the pion radii are systematically higher than the kaon radii at the same $m_T$.

Figure 2. Comparison of the HKM model (see text) with measured kaon $\lambda$ (a) and $R_{inv}$ (b) parameters for 0-5% centrality [4]. Statistical (thin lines) and systematic (boxes) uncertainties are shown.

A comparison of a hydrodynamic flow and kinetics model, HKM [7], with the measured $R_{inv}$ and $\lambda$ parameters for 0-5% centrality is shown in Fig. 2. The HKM values in Fig. 2 are extracted from $K^\pm K^\pm$, but the predictions for $K^0_S K^0_S$ and $K^\pm K^\pm$ are consistent with each other. The $R_{inv}$ predicted by the HKM are in a very good agreement with the experimental kaon data. The experimental data for the neutral kaons are again slightly higher than for the charged kaons, but this difference is still within systematic uncertainties. The HKM predicts a decrease of $\lambda$ with increasing $k_T$, which is in accordance with both sets of kaon data, however, the model slightly overpredicts the experimental data. It is shown in [7] that the most important resonances for KK pairs, $K^*(890)$ and $\phi(1020)$, do not significantly influence the $\lambda$ parameter (due to their low contribution), and the discrepancy between the
model and the experimental data can be explained by the lower experimental kaon purity and deviations of the experimental correlation function shape from a Gaussian distribution. The $K^\pm K^\pm$ correlation radii in Fig. 3 show an increase with multiplicity in agreement with the $\pi^+\pi^-$ radii, at 900 GeV and 7 TeV, and the $K_S^0 K^0_S$ radii, as was observed for $\pi\pi$ correlations in heavy-ion collisions. These radii also decrease with increasing $m_T$ for the large multiplicity bins $11 < N_{ch} < 22$ and $N_{ch} > 22$. Such tendency was found for pions and neutral kaons $K_S^0 K^0_S$ in pp collisions and pions in heavy-ion collisions at LHC energies. In the low multiplicity bin $1 < N_{ch} < 11$ charged kaons show a completely different $m_T$ dependence of the radii: these radii increase with $m_T$. This effect is qualitatively similar to that of pions. The $m_T$ dependence at high multiplicity show a decreasing size with increasing $m_T$ as would be expected by models incorporating some collective expansion even in small systems [9].

4. Summary

Results from femtoscopic studies of $\pi^+\pi^\pm$, $K^\pm K^\pm$, $K_S^0 K^0_S$, pp, and $pp$ correlations from Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE at the LHC have been presented. The femtoscopic radii and $\lambda$ parameters were extracted from one-dimensional correlation functions in terms of the invariant momentum difference. It was found that the emission source sizes of kaons and protons measured in these collisions exhibit transverse mass scaling within uncertainties, which is consistent with hydrodynamic model predictions assuming collective flow. The deviation from the scaling for pions can be explained as a consequence of the increase of the Lorentz factor with decreasing particle mass during the transformation from LCMS to PRF systems [6]. The extracted $\lambda$ parameters are found to be less than unity, as is expected due to long-lived resonances and non-Gaussian correlation functions. The predictions of the hydrokinetic model (HKM) for the one-dimensional femtoscopic radii for charged and neutral kaons and protons coincide well with the observations. The $m_T$ dependence in pp collisions at high multiplicity is expected by models incorporating some collective expansion even in small systems. K.M. acknowledges partial support by the RFBR-CNRS grants No 14-02-93107 and 14-02-93108.

References

[1] G. Goldhaber, S. Goldhaber, W. Lee, A. Pais, *Phys. Rev.* 120 (1960) 325.
[2] M. A. Lisa, S. Pratt, R. Soltz and U. Wiedemann, *Ann. Rev. Nucl. Part. Sci.* 55, 357 (2005).
[3] S. V. Akkelin, Yu. M. Sinyukov, *Phys. Lett.* B 356, 525-530 (1995).
[4] J. Adam et al. [ALICE Collaboration], arXiv:1506.07884 [nucl-ex].
[5] K. Aamodt et al. [ALICE Collaboration], *JINST* 3, S08002 (2008).
[6] A. Kisiel, M. Galazyn, and P. Bozek, arXiv:1409.4571 [nucl-th].
[7] V.M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov, arXiv:1404.4501 [hep-ph].
[8] B. Abelev et al. [ALICE Collaboration], *Phys. Rev. D* 87, 052016 (2013).
[9] Yu.M. Sinyukov and V.M. Shapoval, *Phys. Rev. D* 87 094024 (2013); K. Werner et al. arXiv:1104.2405 [hep-ph]