Identical pion and kaon femtoscopy in EPOS 3 with and without the hadronic afterburner UrQMD

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Abstract. Femtoscopy is an effective instrument to study the size and dynamics of the system created in heavy-ion collisions. In particular, a decreasing dependence of system size on increasing pair momentum and particle mass could be interpreted as an evidence of the strong collective flow. Such phenomena are naturally modeled by hydrodynamics. The large data sample collected in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by the ALICE collaboration enables femtoscopic measurements for pions and kaons. In this paper, the ALICE data are compared with calculations within the EPOS 3 hadronic interaction model, which is based on a (3+1)D viscous hydrodynamical evolution and employs the UrQMD cascade to describe the hadronic phase. The femtoscopic radii for pions and kaons are considered as a function of pair transverse momentum/mass and collision centrality. The obtained results show the importance of the hadronic rescattering phase at LHC energies.

1. Introduction

At top Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) energies a color-deconfined QCD medium of high temperatures and densities, the quark-gluon plasma (QGP) [1,2], is created during heavy-ion collisions. The systematic study of many observables (transverse momentum spectra, elliptic flow, jets, etc.) measured at RHIC [3–5] and the LHC [6–10] confirmed the presence of strong collective motion and the hydrodynamic behavior of the system created in collisions.

The space-time scales of the interaction region of particles created in collisions at kinetic freeze-out (called “particle-emitting source”) can be investigated via the Bose–Einstein enhancement (Fermi-Dirac suppression) of the production of two identical mesons (baryons) at low relative momenta (quantum statistics correlations) [11,12]. The method of measurement of space-time characteristics of particle production using particle correlations is now known as “correlation femtoscopy”.

The investigation of the space-time scales of the particle-emitting source obtained via femtoscopy (“femtoscopic radii”) is one of the important cross-checks of the collective
(hydrodynamic) picture of heavy-ion collisions. Such radii are usually extracted as a function of event centrality and average pair transverse momentum \( k_T = \frac{|p_{T,1} + p_{T,2}|}{2} \). Hydrodynamic collectivity has a particular feature of involving all types of particles, including pions, kaons and protons, which are all subject to the same flow field. Therefore, the study of the pair transverse mass \( m_T = \sqrt{k_{T,1}^2 + m_{\pi,K}^2} \) dependence of pion and kaon source radii would be of particular interest. Recent calculations made within the (3+1)D hydrodynamical model coupled with a statistical hadronization code, THERMINATOR 2, showed an approximate scaling of the femtoscopic radii with transverse mass for pions, kaons and protons \[13\]. While the Hydro-Kinetic Model (HKM) \[14\], including a hydrodynamic phase as well as a hadronic rescattering stage, predicts violation of the \( m_T \) scaling between pions and kaons at LHC energies. Both models observe an approximate \( m_T \) scaling if there is no rescattering phase. The HKM suggests that rescattering has significantly different influence on pions and kaons and results in \( k_T \) scaling instead.

In this paper, the collisions of heavy-ions are studied for Pb ions at \( \sqrt{s_{NN}} = 2.76 \) TeV. The pion and kaon radii from EPOS 3.107 \[15–18\] with \( 6.3 \times 10^5 \) events and without \( 1.8 \times 10^5 \) events the UrQMD cascade \[19\] used to describe the later hadronic phase, are compared with the ALICE data \[10,20–23\]. The calculation was performed in centrality and \( k_T \) ranges corresponding to those chosen in the ALICE experiment \[10,20\]. Pions and kaons in EPOS 3 were selected in the same kinematic range as in the experiment.

2. EPOS 3 model

EPOS 3 is an event generator based on (3+1)D viscous hydrodynamical evolution starting from flux tube initial conditions, which are generated in the Gribov–Regge multiple scattering framework. An individual scattering (Pomeron) is identified with a parton ladder, eventually showing up as flux tubes/strings. Each parton ladder is composed of a pQCD hard process, plus initial and final state linear parton emission. Nonlinear effects are treated via saturation scales, depending on the energy and the number of participants connected to the given Pomeron. The initial stage is described in a multiple-scattering approach based on Pomerons and strings. The reaction volume is divided into a core and a corona parts \[18\]. The core is taken as the initial condition for the QGP evolution, for which one employs viscous hydrodynamics. The corona part is simply composed of hadrons from string decays. After hadronization of the fluid (core), these hadrons and the corona hadrons are fed into the UrQMD cascade \[24,25\], which describes hadronic interactions in a microscopic approach. The chemical and kinetic freeze-outs occur within this phase. The chemical freeze-out is expected to occur shortly after the phase transition from partonic to hadronic matter and is followed by the kinetic freeze-out. The UrQMD model \[19\] is a non-equilibrium transport approach. The interactions of hadrons include binary elastic and \( 2\rightarrow n \) inelastic scatterings, resonance creations and decays, string excitations, particle + antiparticle annihilations as well as strangeness exchange reactions \[26\]. The cross sections and branching ratios for the corresponding interactions are taken from experimental measurements (where available), balance relations and the additive quark model. The model describes the full phase-space evolution of all hadrons, including resonances, based on their hadronic interactions and their decay products.

3. Femtoscopic formalism

The femtoscopic correlation function (CF) is a ratio of the conditional probability to observe two particles with momenta \( p_1 \) and \( p_2 \) together, divided by the product of probabilities to observe each of them separately. Experimentally it is measured by dividing the distribution of relative momentum of a pair of particles detected in the same event \( A(p_1, p_2) \) by an equivalent distribution for a pair where each particle is taken from a different event \( B(p_1, p_2) \) \[27\].
$C(p_1, p_2) = A(p_1, p_2)/B(p_1, p_2)$. The CFs can be parametrized by various formulae depending on the origin of correlations between the considered particles. This paper focuses on the mutual two-particle correlations of identical charged mesons and the basis for femtoscopy is quantum statistics.

### 3.1. One-dimensional femtoscopy

Pions are most abundantly created particles, their multiplicities per-event are large enough to study precisely pion femtoscopic correlations in three dimensions and differentially in centrality and $m_T$. However, for heavier particles, such as kaons statistics limitations arise. Therefore, it is often possible to only measure one-dimensional CFs for those particles.

Assuming a Gaussian distribution of a particle source in the pair rest frame [13], the one-dimensional fit of the kaon CF is performed as

$$C(q_{inv}) = 1 + \lambda \exp \left( -R_{inv}^2 q_{inv}^2 \right),$$

where the parameters $R_{inv}$ and $\lambda$ describe the size of the source and the correlation strength, respectively.

The $R_{inv}$ and $\lambda$ parameters calculated in EPOS 3 with and without the UrQMD cascade phase are compared with the ALICE data in figure 1. Though there are no experimental data for the most peripheral collisions’ 50–100% range, it is presented here for EPOS 3 for completeness to see how femtoscopic parameters change from central to very peripheral collisions.

![Figure 1](image.png)

Figure 1. (color online) Experimental $K^\pm K^\pm$ invariant radii $R_{inv}$ (a) and correlation strengths $\lambda$ (b) shown versus $k_T$ are compared with the EPOS 3 model predictions with/without the UrQMD cascade.

Figure 1 (a) shows an excellent agreement of the EPOS 3 calculations with the experimental data when the UrQMD cascade is taken into account. The corresponding EPOS 3 $\lambda$ parameters (figure 1 (b)) are slightly larger than the experimental ones. The obtained radii decrease with increasing $k_T$ and for more peripheral collisions. All changes of the correlation strength $\lambda$ with $k_T$ and centrality are within errors. The EPOS 3 calculation without the UrQMD cascade gives the radii which are significantly smaller than the experimental ones and exhibit practically no $k_T$ dependence. The $\lambda$ parameters without the cascade are slightly larger than they are with the cascade. The observed importance of the hadronic rescattering phase agrees with the conclusion from the one-dimensional $K^\pm$ femtoscopic analysis in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [22,23].

### 3.2. Three-dimensional femtoscopy

One of the signs of collectivity are femtoscopic radii for different particle species when they follow the same scaling with pair transverse mass. As shown in [13,20], a common scaling of
pion and kaon $R_{\text{inv}}$ values does not exist, which has trivial kinematic origin. As a consequence, experimental values of $R_{\text{inv}}$ for pions and kaons are not good observables in the validation of hydrodynamic collectivity predictions. The correct observables are radii measured separately in three independent directions.

As explained above, three-dimensional kaon femtoscopy analysis is significantly more challenging than the corresponding measurement for pions. It became possible thanks to a large data sample collected by the ALICE collaboration [10].

Such analysis is performed in the Longitudinally Co-Moving System (LCMS), where the longitudinal direction is along the beam axis, the outwards direction is along the pair transverse momentum and the sideways direction is perpendicular to the other two (Bertsch-Pratt convention) [28,29] and where the total longitudinal pair momentum equals zero.

The CF in this case is decomposed into $(q_{\text{out}}, q_{\text{side}}, q_{\text{long}})$ and parametrized as

$$C(q) = 1 + \lambda \exp \left( -R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{long}}^2 q_{\text{long}}^2 \right),$$

where $R_{\text{out}}$, $R_{\text{side}}$, and $R_{\text{long}}$ are the Gaussian femtosopic radii. In figure 2 the radii in the

![Figure 2](image)

**Figure 2.** (color online) $\pi^+\pi^\pm$, $K^\pm K^\pm$ and $K^0 S K^0 S$ three-dimensional experimental and EPOS 3 radii versus $m_T$. The EPOS 3 radii for 30–50% bin are not presented due to lack of available data.

LCMS for pions and kaons are shown as a function of centrality and $m_T$. As can be seen, the radii universally grow with increasing event multiplicity and decrease with increasing $m_T$ in all directions. The slope of $R_{\text{long}}$ is steeper than for $R_{\text{out}}$ and $R_{\text{side}}$. This behavior is known as the “lengths of homogeneity” mechanism [30,31] and is a signature of the collective flow
of the system. A good agreement is observed for the EPOS 3 calculations with the UrQMD cascade and the experimental data for out and side projections for pions and for side and long projections – for kaons. The EPOS 3 calculation without the hadronic cascade does not describe the experimental radii at all. The difference is more remarkable for kaons and for more peripheral collisions. This result shows again the importance of the rescattering phase at ultra-relativistic energies similarly to the one-dimensional case.

A similar underestimation of the three-dimensional kaon radii was also seen in THERMINATOR 2 where hadronic rescattering was not included. In addition, the HKM calculations performed for the most central collisions (0–5%) agree with the kaon experimental radii only if the rescattering phase is included. The HKM calculations without the rescattering phase underestimate the experimental kaon radii. The same effect was also observed for pion radii.

![Figure 3.](image)

Figure 3. (color online) $R_{\text{out}}/R_{\text{side}}$ ratio for $\pi^{\pm}$, $K^{\pm}$, and $K_{S}^{0}$ and EPOS 3 model calculations versus $m_{T}$. EPOS 3 without UrQMD calculations for 30–50% bin are not presented due to lack of available data.

The ratio $R_{\text{out}}/R_{\text{side}}$ (figure 3) for pions is consistent with unity, slowly decreasing for more peripheral collisions and with increasing $m_{T}$. The measured ratio is slightly larger for kaons than for pions, which could be an indication of different space-time correlations for pions and kaons, and more prolonged emission duration for kaons. On the contrary, EPOS 3 tends to show $R_{\text{out}}/R_{\text{side}}$ larger for pions than for kaons. The possible explanation is that $R_{\text{out}}$ is underestimated in EPOS 3 for kaons as shown in figure 2.

4. Summary

The paper presented EPOS 3 calculations of femtoscopic radii for pions and kaons as a function of centrality and $k_{T}/m_{T}$ and compared them with the ALICE experimental data in Pb–Pb collisions at 2.76 TeV.

A decrease of the radii with increasing transverse mass and decreasing event multiplicity was observed both in the one- and three-dimensional analyses. The three-dimensional radius transverse components demonstrate a less steep $m_{T}$ dependence than the longitudinal component.

The measured ratio of transverse radii $R_{\text{out}}/R_{\text{side}}$ is larger for kaons than for pions indicating different space-time correlations. While EPOS 3 predicts an opposite trend explained by underestimation of the $R_{\text{out}}$ projection for kaons in EPOS 3.

The comparison of experimental radii with a model, wherein the hydrodynamic phase is followed by the hadronic rescattering phase, and pure hydrodynamical calculations shows that femtoscopic radii are well reproduced only if the hadronic rescattering phase is present.

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