Recent results of the femtoscopic measurements from RHIC and LHC

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Abstract. The two-particle correlations at low relative momenta (correlation femtoscopy) are sensitive to quantum statistics and allow to measure the space-time picture of the system evolution created in heavy-ion (HI) and particle collisions. The spatio-temporal parameters extracted from HI collisions describe the system at the last moment of the collision evolution — kinetic freeze-out and provide the essential information about the formation of the quark-gluon plasma. The measurements at many facilities showed the dependencies of the spatial scales from the event multiplicity and particle transverse mass, $m_T$. In this paper we show recent results obtained at RHIC and LHC energies and compare them to the theoretical expectations.

1. Introduction
The main goal of the ultrarelativistic heavy-ion experiments is to create and study the strongly interacting matter at high temperature or density with color degrees of freedom that was predicted by the quantum chromodynamics (QCD) and called quark-gluon plasma (QGP) [1–3]. The experiments at Relativistic Heavy Ion Collider (RHIC) showed that the matter formed in such collisions is a strongly coupled fluid of deconfined quarks and gluons (sQGP) [4–7] at high temperature and low chemical potential, $\mu_B$. The medium in the collision zone is expected to achieve local equilibrium and exhibit approximately hydrodynamic flow (transverse and longitudinal expansion) [8, 9]. The hydrodynamic approach successfully describes the momentum distributions of hadrons produced in heavy-ion collisions (HIC) [10, 11], however it gives a poor description of the spatial distributions of decoupling hadrons [12]. The study of the spatial extent may provide model constrains on the nuclear equation of state and the initial temperature [13].

The information about the space-time structure and the dynamical properties of the emitting source can be extracted using momentum correlations of particles at small relative velocities [14]. The increase of the source radii for more central collisions is attributed to the increasing volume of the emission region. In addition to the geometrical effects, the space-momentum correlations may be affected by the collective flow [15]. For instance, the systematic decrease of the source radii with mean transverse pair momentum, $k_T$, was attributed to the longitudinal and transverse flow [16]. The important check of the collective behavior is that all particle species created in the collision should follow the transverse mass scaling — the decrease of the femtoscopic radii with increasing transverse mass $m_T = \sqrt{k_T^2 + m^2}$. In this paper we present recent femtoscopic measurements of charged pions and kaons produced in HIC as a function of the $m_T$ performed at Large Hadron Collider (LHC) and top RHIC energies.
2. Correlation femtoscopy
The space-time structure and dynamical properties of the emitting source can be extracted using momentum correlations of particles at small relative momenta via measuring two-particle correlation function. Experimentally, the two-particle correlation function of identical particles with momenta \( p_1 \) and \( p_2 \) is defined as \( C(q) = A(q)/B(q) \), where \( A(q) \) is the measured distribution of the momentum difference, \( q = p_1 - p_2 \), of particles from the same event. The quantity \( B(q) \) is obtained by mixing particles from different events.

In order to extract the size of the emitting source one may fit the correlation function using the Bowler-Sinyukov formula:

\[
C(q) = N \left( 1 - \lambda + \lambda K(q)(1 + e^{-R_{inv}q^2}) \right),
\]

where \( N \) is the normalization factor, \( \lambda \) is the correlation strength, and \( R_{inv} \) is the one-dimensional size of the source. The \( q = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2} \) is the relative four-momentum of the particles from the pair. The quantity \( K(q) \) is the squared Coulomb wave function integrated over the source of the given radius. In order to study the length scales in the beam and transverse directions one may decompose the relative momentum \( q \) according to the Bertsch-Pratt (or “out-side-long”) convention [17, 18]. The momentum difference is calculated in the longitudinally co-moving system (LCMS), where the longitudinal pair momentum vanishes. The components of the relative momentum, \( q_{\parallel}, q_{\perp} \) and \( q_{s} \), correspond to the directions along the beam, transverse pair momentum, and the perpendicular to those two, respectively. In the three-dimensional case the Eq. 2 will be given by:

\[
C(q) = N \left( 1 - \lambda + \lambda K(q)(1 + e^{-R_{s}q_{\parallel}^2 - R_{s}q_{\perp}^2 - R_{s}q_{s}^2}) \right),
\]

where \( R_{s}, R_{s} \) and \( R_{s} \) are the spatial scales of the source. The ratio \( R_{s}/R_{s} \) is sensitive to the emission duration and the longitudinal component, \( R_{s} \), is sensitive to the system evolution time.

3. Femtosopic measurements at RHIC and LHC
The femtosopic measurements of \( \pi^+\pi^-, K^\pm K^\mp, K_S^0K_S^0, pp \) and \( \bar{p}p \) correlations from Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV were performed by ALICE Collaboration [19]. The femtosopic radii were extracted from one-dimensional correlation functions in terms of invariant relative momentum. Figure 1 shows the extracted source radii for different particle species as a function of \( m_T \). It is seen that in the overlapping transverse pair momentum regions, the femtosopic radii for pions, kaons and protons are consistent with each other within uncertainties. The line represents the hydrokinetic model prediction (HKM) [20]. The HKM values are specifically from \( K^\pm K^\mp \). The HKM incorporates realistic initial conditions, hydrodynamic evolution, microscopic transport and resonance decays [21, 22]. The measured charged kaon \( R_{inv} \) show very good agreement with the theoretical predictions.

Recently, the PHENIX Collaboration performed the three-dimensional analysis of the femtosopic radii of charged pions and kaons produced in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV [23]. Figure 2 shows the ratio of the transverse components of the extracted source radii, \( R_{o}/R_{s} \), of the \( \pi^+\pi^- \) and \( K^\pm K^\mp \) as a function of \( m_T \). This ratio is sensitive to the emission duration of particles. The values for kaons are larger than those for pions for all \( m_T \) ranges and collision centralities that indicates the longer emission duration time for kaons than for pions. In addition, the difference for \( R_{o} \) and \( R_{s} \) between charged pions and kaons at the same \( m_T \) is larger in more central collisions. It is shown that the \( m_T \) scaling breaks for these radii, but \( k_T \) scaling works well for all radii.

The HKM model reproduces the data for kaons well, but not for pions [25]. In addition to the HKM, the data for pions in most central collisions were compared with (3+1)-D viscous hydrodynamic model calculations [24]. This model employs a Glauber initial condition and \( \eta/s = 0.08 \). The model prediction follows the general trends in the data.
Figure 1. Comparison of the measured source radii with the HKM model measured by ALICE Collaboration for Pb-Pb collisions (0-5% centrality). Statistical (thin lines) and systematic (boxes) uncertainties are shown [19].

Figure 2. The ratio of $R_o$ and $R_s$ of the charged pions and kaons as a function of $m_T$ measured by PHENIX Collaboration in Au+Au collisions at top RHIC energy [23]. Solid and dashed lines correspond to the predictions from the hydrokinetic model for pions and kaons, respectively. The dash-dot lines correspond to the predictions from the viscous-hydrodynamic model (Bozek) [24].

4. Conclusion
The recent results of the two-particle femtoscopy of charged hadrons obtained by the ALICE and PHENIX Collaborations are presented. The one-dimensional source radii of charged pions, kaons and (anti)protons measured at the LHC energies exhibit the transverse mass scaling within uncertainties and consistent with the hydrodynamic model predictions. On the other hand, the measurements at top RHIC energy show the breaking of the $m_T$ scaling for pions and kaons for $R_o/R_s$. It is observed that the ratio $R_o/R_s$ is larger for kaons than that for pions. This indicates the different emission duration of $\pi$ and $K$. The hydrokinetic model fails to describe the data for pions in more central collisions. The presented results of recent femtoscopy measurements at top RHIC and LHC energies and their comparisons with the theoretical expectations show the non-trivial behavior of the created medium.

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