Conference of Fundamental Research and Particle Physics, 18-20 February 2015, Moscow, Russian Federation

Two-meson correlation femtoscopy in the SELEX experiment

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Abstract

The two-particle correlations at low relative momenta provide spatio-temporal information about the evolution of the system created in particle and heavy ion collisions. In this paper we discuss the basic concepts of the method and give a short review of recent experimental results obtained at Tevatron and LHC.

Keywords: Correlation femtoscopy, HBT intensity interferometry, Bose-Einstein correlations

1. Introduction

The correlation femtoscopy (also known as HBT intensity interferometry method) is a unique tool to measure spatial and temporal characteristics of the systems created in nuclear and particle collisions with accuracy of $\approx 10^{-15}$ m and $\approx 10^{-23}$ sec. In 1960 it was show that the correlations of identical pions are sensitive to source dimensions in antiproton-proton collisions \[1, 2\]. In the 1970s, these results were refined by Kopylov and Podgoretsky \[3–5\] and it was shown that momentum correlations are sensitive to the source-size measurements and final state interactions (Coulomb and strong interactions) as well. The analyses performed at Bevalac showed that intensity interferometry is capable of quantitatively determining spatial and temporal source dimensions and providing test of dynamical models \[6, 7\]. However, the HBT intensity interferometry refers only to identical-particle correlations. Later, Lednicky proposed to use term femtoscopy \[8, 9\] to denote any measurement that provide spatio-temporal information, including final state interactions (FSI). For more than 50 years this method is used to study dynamics of the source and its evolution in variety of facilities. It was shown that femtoscopic measurements also sensitive to the collective effects. For instance, the source radii extracted from relativistic heavy ion collisions describe the system at kinetic freeze-out, i.e. the last stage of the particle interactions. A decrease of the source radii with increasing transverse mass $m_T = \sqrt{k_T^2 + m^2}$, where $k_T = |\vec{p}_{T,1} + \vec{p}_{T,2}|/2$ is the average transverse momentum of the pair and $m$ is the mass of the particle, can be interpreted as one of the signatures of the formation of the deconfined quark matter \[10, 11\]. Moreover, this dependence was also observed in $p + p$ collisions in the STAR experiment \[12\] which may reflect the similarity of the underlying dynamics. These analyses usually study pions, however, the measurements with other
particles are needed in order to confirm the collective hydrodynamic behavior of the system created in nuclear and particle collisions. In this paper we will give a short review of the theoretical aspects of the correlation femtoscopy and recent results obtained at the LHC and Tevatron energies.

2. Correlation femtoscopy

The measurements of momentum correlations of the particles at small relative momentum are based on the correlation function, which relates the space-time separation of the particles to their momenta $\vec{p}_1$ and $\vec{p}_2$ at the emission time. The two-particle correlation function $C_2(\vec{p}_1, \vec{p}_2)$ can be constructed as a ratio of the pair- to single-particle cross sections:

$$C_2(\vec{p}_1, \vec{p}_2) = \frac{\sigma_0}{d^3\sigma/d^3\vec{p}_1 d^3\vec{p}_2} \frac{d^3\sigma}{d^3\vec{p}_1 d^3\sigma/d^3\vec{p}_2},$$

where $\sigma_0$ is defined by the normalization condition chosen for the integrals of the inclusive cross sections. In practice, the correlation function is constructed in terms of relative four-momentum $q = P_1 - P_2$ of two particles as a ratio:

$$C_2(q) = \frac{A(q)}{B(q)} D(q),$$

where $A(q)$ is the signal distribution, $B(q)$ it the reference or background distribution that ideally similar to $A(q)$ but does not contain femtoscopic correlations, and $D(q)$ is a correction factor that takes into account non-femtoscopic correlations that present in the signal and not fully accounted in the reference distribution. Since the ideal background should be identical to the signal distribution it has to meet all the conditions and selection criteria that were applied for the $A(q)$ such as, global event characteristics, acceptances and single particle distributions. One of simple ways to construct such a correlation distribution is to form pairs from different events within a single event class. This event-mixing technique [4] will describe in details the signal distribution in the high multiplicity environment. For elementary particle collision or in low-multiplicity events, event-mixing can violate total energy–momentum conservation [13] and lead to the presence of the non-femtoscopic effects in addition to the femtoscopic correlations. In these cases, the most common techniques are to form $B(q)$ from unlike-signed pairs, with excluded resonance regions, or to construct the background by using Monte Carlo generated pairs. For example, different Perugia tunes [24] of the PYTHIA event generator [23] provide a good description of the non-femtoscopic correlations and used by different experiments.

In order to extract the source radii one should fit the correlation function with the Bowler-Sinyukov formula [14, 15], assuming that the emitting source of identical bosons described by spherical Gaussian density function:

$$C(q) = N \left((1 - \lambda) + \lambda K(q) \left(1 + e^{-R^2 q^2}\right)\right) D(q),$$

where the factor $K(q)$ is the squared like-sign particle pair Coulomb wave-function integrated over a spherical Gaussian source, $R$ — size of the emitting source, $N$ is the normalization factor and $\lambda$ describes the correlation strength.

A detailed review of theoretical developments and experimental results may be found in [19].

3. Charged meson femtoscopic measurements

The momentum correlation analyses usually performed for identical pion pairs due to the big experimental statistics and show a collective hydrodynamic behavior of the system created in nuclear and elementary particle collisions. However, study kaons may provide a cleaner probe of the emitting source due to the smaller contamination of resonance decays to kaons compared to pions. In addition, since the charged kaon cross sections with nuclear matter are generally smaller than those for pions, the femtoscopic measurements of kaons may reflect the information about the different stage of the collision evolution. Moreover, kaon momentum correlation measurements may give an opportunity to test the hydrodynamic type of expansion by studying the dependencies of the source radii as a function of the transverse pair momentum for different particle species (so-called, $m_T$ scaling). Because of these reasons in this Letter we will focus on recent results of charged kaon HBT measurements obtained in elementary particle and hadron-induced collisions.
The first measurement of the charged kaon femtoscopy in hadronic collisions for more than one multiplicity and transverse pair momentum ranges was performed by the ALICE Collaboration at the LHC [16]. Figure 1 shows the extracted radii of charged kaons emitting source measured in 7 TeV pp collisions. The charged kaon correlation radii show an increase with multiplicity and are in agreement with the ππ [17] and $K_0^0 K_0^0$ radii. The radii decrease with increasing $m_T$ for the large multiplicity ranges (12–21, > 22). It was also observed that in the low multiplicity range (1–11) these radii increase with $k_T$.

Figure 1 also shows that the charged kaon femtoscopy radii for high multiplicity events (> 22) are slightly bigger than the pion radii from the same multiplicity class.

The other recent measurement of charged kaon femtoscopy correlations was performed by the SELEX Collaboration [20]. The $K^+ K^-$ femtoscopy analysis was performed for different transverse pair momentum ranges and for
different hadron-induced collisions (600 GeV/c $\Sigma$ $C(Cu)$, $\pi^-$ $C(Cu)$ and 540 GeV/c $pC(Cu)$) at the $\sqrt{s} \approx 34$ GeV with the same cuts, fitting procedures and detector setup. Figure 2 shows the one–dimensional femtoscopic source parameters radii $R$ and correlation strength $\lambda$. It is seen that the source radii decrease with increasing transverse pair momentum $k_T$ for all the beam types. The small difference of the source radii obtained for different beam types between is also observed. Since in these reactions the charged kaons may be produced via different production mechanisms the measurement gives an opportunity to check different hadronization models.

From Figures 1 and 2 one may notice that the measured charged kaon femtoscopic radii measured in different collision types are similar and weakly depend on the collision energy. The observed $k_T$ dependencies may have several origins such as, the final state rescattering between hadrons during the hadronization process [21], the hydrodynamic collective flow or the influence of the long-lived resonances [22]. It means that more experimental and theoretical inputs are needed in order to understand the particle hadronization mechanism.

4. Conclusion

The basic concepts of the correlation femtoscopy are shown. The most resent results of charged kaons correlations at low relative momenta obtained at the Tevatron (SELEX) and LHC (ALICE) experiments are presented. The extracted HBT radii $R$ measured by ALICE decrease with the transverse pair momentum $k_T$ for high multiplicities (> 12) meanwhile for the low multiplicity events (1–11) the measured $\pi\pi$ and $K^+K^+$ radii show the slight increase of the radii with increasing the $k_T$. The first charged kaon femtoscopic analysis of different hadron-induced collisions performed in the SELEX experiment shows the decrease of the emitting source radii with $k_T$ for $\Sigma^-$ $C(Cu)$, $\pi^-C(Cu)$ and $pC(Cu)$ interactions. The one-dimensional HBT radii were shown to follow the similar transverse pair momentum behavior for different collision types and energies.

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