HBT with an emphasis on exotic particle femtoscopy

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STAR latest analyses of two-particle correlations are presented, including measurements with heavy, exotic, strange and multi-strange hadrons (p,K,Λ,Ξ). These measurements yield insight into the dynamics of heavy-ion collisions. Species-dependent emission sizes and emission asymmetries are expected to arise as a consequence of collective expansion. Furthermore the correlation analyzes in heavy-ion collisions allow to study, otherwise hard to measure, strong interaction potential between different hadrons.

Keywords: heavy-ion, RHIC, STAR, femtoscopy, HBT

1 Introduction

Heavy-ion experiments have been pursuing the study of nuclear matter under the extreme conditions created in the collisions of large nuclei at high energies with a motivation to observe phase-transition into de-confined partonic matter as it was predicted by QCD calculations. Recent results from RHIC [1] indeed indicate that strongly interacting matter governed by partonic degrees of freedom was created. Measurements reveal that system undergoes rapid collective expansion with possible early thermalization of the constituents. The non-trivial space-time evolution of the system before and also after return into the state of confined nuclear matter is one of the main features of the heavy-ion physics.

Two-particle correlation femtoscopy[2] (often called HBT) is one of most direct ways of studying the space-time structure of the particle-emitting source and can shed a light onto the dynamics of the collision. Particles emitted with small relative momenta are correlated due to their final state interaction (FSI) and/or their interference due to quantum statistics (QS). The

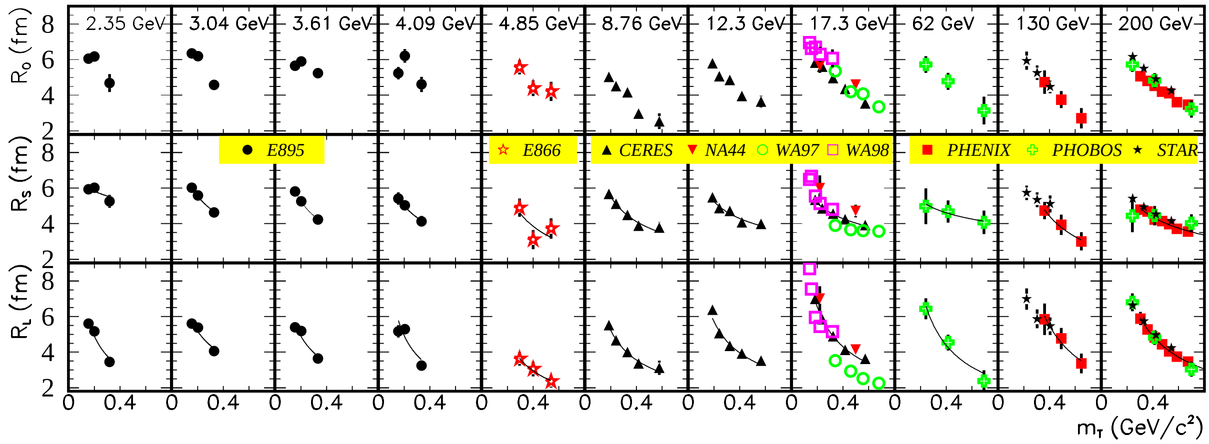

Figure 1: Collected data set of published m_t dependencies of pion HBT radii near mid-rapidity from Au+Au (Pb+Pb) collisions. Centrality selection is roughly top 10%. Figure from compilation [2].

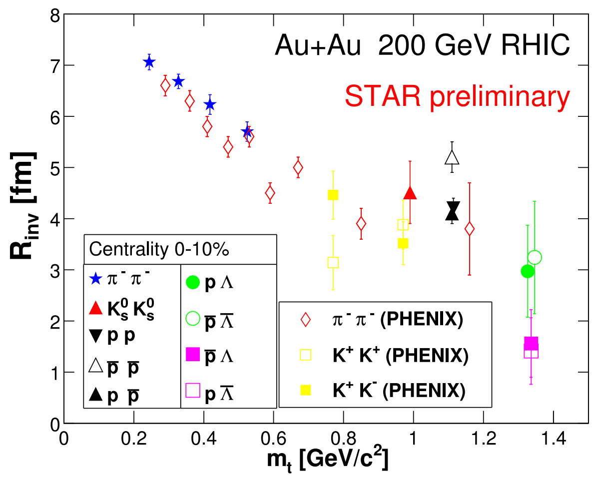

Figure 2: m_t dependence of HBT radii for different particle species measured by STAR experiment in 200 GeV Au+Au collisions. PHENIX data from [3].

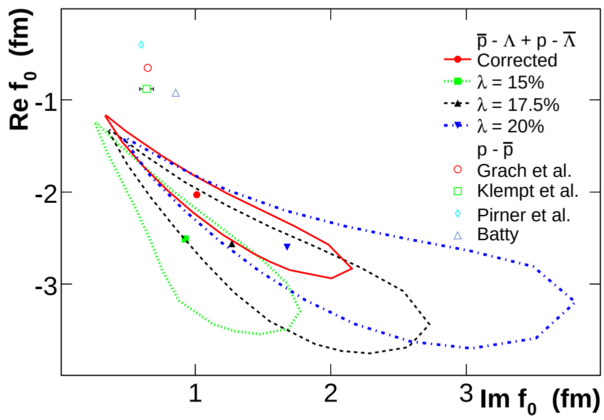

Figure 3: Spin-averaged s-wave scattering length for $p-\bar{\Lambda}+\bar{p}-\Lambda$ with one standard deviation contours compared to previous $p-\bar{p}$ measurements. Contours correspond to different correction methods. Figure from [4].

two-particle correlation function is defined as:

$$C^{ab}_{\vec{K}}(\vec{q}) = \frac{d^6N^{ab}/(dp_a^3 dp_b^3)}{(d^3N^a/dp_a^3)(d^3N^b/dp_b^3)} = \int d^3\vec{r} \cdot S^{ab}_{\vec{K}}(\vec{r}) \cdot |f(\vec{q},\vec{r})|^2, \quad (1)$$

where $\vec{K} = \frac{\vec{p}_a+\vec{p}_b}{2}$, $\vec{q} = \vec{p}_a - \vec{p}_b$ and $f(\vec{q},\vec{r})$ is the pair relative wavefunction, including the FSI and QS describing the propagation of the pair from a relative separation of $\vec{r}$ to the detector with relative momentum $\vec{q}$. The source function $S^{ab}_{\vec{K}}(\vec{r})$ is the probability of emitting a pair of particles with average momentum $\vec{K}$ at a distance $\vec{r}$ apart. Hence the correlation function (1) encodes the information about space-time configuration of the emitting source. It must be stressed, however, that $S^{ab}_{\vec{K}}(\vec{r})$ is not sensitive to the size of the entire source, but to the so called "homogeneity region" - part of the phase space occupied by outgoing particles whose velocities have a specific magnitude and direction [2].

2 Expansion dynamics and HBT observables

When the medium undergoes expansion it means that there is strong correlation between momenta of outgoing particles and their emission points. As a consequence, such models as hydro

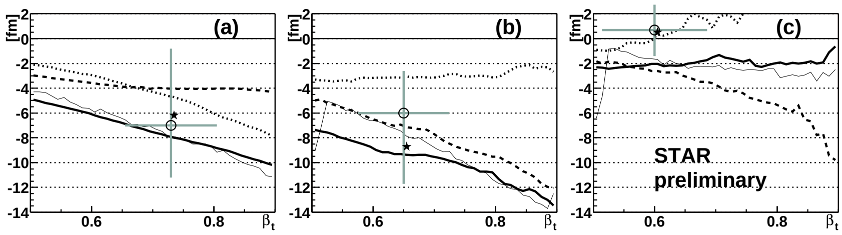

Figure 4: Comparison of the shift of the average emission point between (a) pion-kaon, (b) pion-proton and (c) kaon-proton. The real data (∘) are compared with model predictions: blastwave parametrization [5] (thin solid line) and RQMD(thick solid line). Figure from [6].

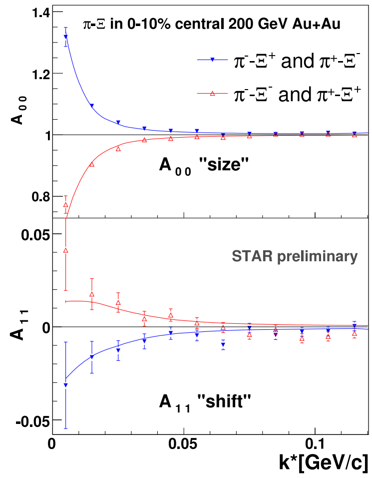

Figure 5: Fit of $\pi-\Xi$ correlation function in the most central 200 GeV Au+Au data. Data from [7].

and microscopic models, which include significant collective expansion, predict decrease of the measured radii (i.e. the size of the homogeneity region) with increasing transverse mass m_t of the particles. In Figure 1 is shown a collection of results on measured pion source sizes by different experiments for their largest colliding system and for the most central collisions. The $m_t = \sqrt{K_t^2 + m_\pi^2}$ dependence of HBT radii is generally attributed to the collective expansion. Further measurements [8] show that not only pions but also other particle species including strange and multi-strange particles significantly participate in the collective expansion. Thus the femtoscopic signals arising from it, such as the fall of pion HBT radii with m_t, should also be observed. Recent high statistics data collected at RHIC has allowed to carry out femtoscopic analyses with precision that was unreachable before and for particle pair types which were measured for the first time. In Figure 2 is presented m_t dependence of radii for different measured pairs of particles with close mass. It is of particular importance to note that these measurements include systems with different final state interaction and different systematical uncertainties. Using different particle species one can "turn on/off" Coulomb FSI and/or quantum statistics effects. In case of $K_S^0 - K_S^0$ and $p(\bar{p})-\Lambda(\bar{\Lambda})$ the Coulomb interaction is absent and in the latter case there is also no QS. The $p-\bar{\Lambda}$ and $\bar{p}-\Lambda$ analyses are an example of a way hadron interactions can be studied using femtoscopy, as presented by the STAR experiment in [4]. While in $p-\Lambda$ and $\bar{p}-\bar{\Lambda}$ strong interaction is known, allowing to perform standard femtoscopic measurement of the source size, $\bar{p}-\Lambda$ and $p-\bar{\Lambda}$ was measured for the first time and the interaction is unknown. However, assuming the same functional form of the interaction as in $p-\Lambda$, $\bar{p}-\bar{\Lambda}$ and treating the potential parameters (scattering lengths) as free parameters it was possible to extract spin-averaged scattering lengths as presented in Figure 3. The message from common scaling in Figure 2 is strengthened when considering different systematics involved in each measurement. From this point $p(\bar{p}) - p(\bar{p})$ analyses are especially of interest since these measurements are strongly affected by residual correlations originating from decays of Σ and Λ. This issue has been extensively treated in [9].

Femtoscopic measurements with non-identical particles are not only sensitive to the size of the system, but also to the relative difference in the space-time position of the emission of the two particle species [10]. Models that include collective expansion predict a relation between the average emission position and the mass of the particle such as that particles with higher m_t are emitted more on the outside of the expanding fireball [5]. This effect hence increases with a mass difference within the measured particle pair. Figure 4 shows that in heavy-ion collisions the average emission points of particles with different mass, such as pions, kaons and protons, are significantly shifted with respect to each other [11,6]. These measurements were recently extended by STAR experiment to include multi-strange baryons using $\pi-\Xi$ correlations. This exotic system is of particular interest as it includes an order of magnitude difference in mass plus $\Delta B = 1$ and $\Delta S = 2$ gap in baryon and strangeness quantum numbers respectively. The case of multi-strange baryon flow is of high importance since the collective behavior of these particles, suggested by large values of observed elliptic [1,8] flow, is believed to be coming predominantly from the early partonic stage. Recent results on $\pi-\Xi$ correlation function for different combination of charges are presented in Figure 5, where $2\vec{k^*} = \vec{q}$ in the pair cms. Spherical decomposition method [12,13], which has recently become a promising tool for 3-dimensional analyses of the correlation function, is used. As described in [13], the non-zero value of A_{11}-coefficient signalizes space-time shift in the average emission between pions and Ξs. Fit of the Coulomb interaction to the data yields value of the space-time shift $(5.6 \pm 1.)$ fm, including statistical errors only. This significantly large value is also in qualitative agreement with the collision evolution during which multi-strange baryons take part in the collective expansion of the matter.

3 Conclusions

STAR measurements on two-particle femtoscopy were presented, emphasizing results with heavy, strange and multi-strange hadrons. A species-independence of the m_t scaling of HBT radii together with extracted emission asymmetries among the particles were shown. These results provide an independent confirmation of a transversely expanding particle source in heavy-ion collisions. Results on $p-\bar{\Lambda}$, $\bar{p}-\Lambda$ show that non-identical correlations can be used to study otherwise hardly accessible hadron interactions.

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