Pion Interferemetry from p+p to Au+Au in STAR

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Abstract. The geometric substructure of the particle-emitting source has been characterized via two-particle interferometry by the STAR collaboration for all energies and colliding systems at RHIC. We present systematic studies of charged pion interferometry. The collective nature of the source is revealed through the $m_T$ dependence of HBT radii for all particle types. Preliminary results suggest a scaling in the pion HBT radii with overall system size, as central Au+Au collisions are compared to peripheral collisions as well as with Cu+Cu and even with d+Au and p+p collisions, naively suggesting comparable flow strength in all systems. To probe this issue in greater detail, multidimensional correlation functions are studied using a spherical decomposition method. This allows clear identification of source anisotropy and, for the light systems, the presence of significant long-range non-femtoscopic correlations.

Keywords: HBT, femtoscopy, heavy ion collisions, intensity interferometry

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INTRODUCTION

Particle interferometry is an useful technique that provides information on the space-time properties of the particle emitting source and may be helpful in understanding the dynamics of the system created in high energy collisions by studying the transverse mass dependence ($m_T = \sqrt{k_T^2 + m_r^2}, k_T = \frac{1}{2}(p_{T1} + p_{T2})$) of HBT radii (for the latest review article see [1]). In this article femtoscopic results from a small system (p+p collisions) and a large system (Au+Au collisions) measured by the same experiment, at the same collision energy and detector acceptance are presented for the first time in high energy physics. The particular focus is on the $m_T$ dependence of HBT radii and an attempt to understand its origins for different initial sizes of the emitting source is made.

ANALYSIS DETAILS

The STAR Time Projection Chamber (TPC) [2] was used to reconstruct particles of interest. Particle identification was achieved by measuring momentum and specific ionization losses of charged particles in the gas of TPC ($dE/dx$ technique). A large data statistics in Au+Au, Cu+Cu and d+Au collisions allows to do an analysis for different centralities. Additionally, d+Au data set allows to extract p+Au collisions. It is performed by selecting events with a single neutron tagged in the Zero Degree Calorimeter (ZDC) in the deuteron beam direction.

In this study pions with transverse momentum $0.10 \text{ GeV/c} < p_T < 1.00 \text{ GeV/c}$ were used and the analysis was done for four bins of $k_T$ within a range of $[0.15, 0.60] \text{ GeV/c}$. 
Two-track effects due to splitting (one particle reconstructed as two tracks) and merging (two particles reconstructed as one track) were removed from the data.

The dependence of the correlation function on the transverse momentum is studied as a function of three components of pair relative momentum in a Pratt-Bertsch coordinate system [3, 4] in the longitudinally co-moving frame. The fit was performed using a method suggested by Bowler [5] and Sinyukov [6] assuming Gaussian parametrization of the source. For more details on analysis technique see [11].

SYSTEM EXPANSION AND MULTIPLICITY SCALING

One of the differences that may be expected between such a large system as Au+Au and a small system as p+p is the expansion. This can be studied in a model-dependent approach when the final RMS of the system is compared to the initial one. The first value is equal, with good accuracy, to $R_{side}$ calculated for the lowest $k_T$ range ([0.15, 0.25] GeV/c). The second one is calculated with Glauber model for nuclei and a proton initial size was taken from an $e^-$ scattering [12] as a reference. The result of this comparison for p+p, d+Au, Cu+Cu and Au+Au collisions at the same energy of the collision ($\sqrt{s_{NN}} = 200$ GeV) are combined on the left panel of Figure 1a.

As seen, the most central Au+Au collisions undergo an expansion by a factor of two while p+p collisions show no or a little expansion. Data points from peripheral d+Au collisions show similarity to p+p while central d+Au points exhibit an expansion like in peripheral Cu+Cu. Finally, central Cu+Cu expands similarly like peripheral Au+Au.

Figure 1b presents the HBT radii dependence on $(dN_{ch}/d\eta)^{1/3}$ ($dN_{ch}$ - number of charged particles at midrapidity) for different colliding systems and at different energies of the collisions. The motivation for studying such a relation is its connection to the final state geometry through the particle density at freeze-out. All STAR results, from p+p,
d+Au, Cu+Cu and Au+Au collisions, are combined on the left panel of this figure and, as seen, all radii exhibit a scaling with $(dN_{ch}/d\eta)^{1/3}$. On the right panel of this figure STAR radii, this time for different $k_T$ range, are plotted together with AGS/SPS/RHIC systematics [1]. It is impressive that the geometric radii ($R_{side}$ and $R_{long}$) follow the same curve for different collisions over a wide range of energies and, as it was checked, this observation is valid for all $k_T$ bins studied by STAR. It is a clear signature that the multiplicity is a scaling variable that drives geometric HBT radii at midrapidity. $R_{out}$ mixes space and time information. Therefore it is unclear whether to expect the simple scaling with the final state geometry. Although, because of the finite intercepts of the linear scaling [1, 7], results do not confirm predictions that freeze-out takes place at the constant density [8]. Additionally, this scaling was verified at midrapidity only, and some dependence on rapidity outside this region may be expected [9, 8] so it is not obvious if the scaling holds then.

As a result of this study, one can venture to predict the size of the source at midrapidity without knowing anything about the collision (like energy, $N_{part}$, impact parameter, etc.) except for the multiplicity [9, 8, 1]. This scaling is expected to persist for all systems that are meson dominated but is violated for low energy collisions that are dominated by baryons [9, 1, 10].

### TRANSVERSE MASS DEPENDENCE OF HBT RADI

In heavy ion collisions a decrease of HBT radii with an increase of $m_T$ is commonly associated with the transverse flow of a bulk matter [11]. Natural question would be whether this dependence looks different in smaller systems like p+p or d+Au and what is the origin of this dependence. On Figure 2a, the three dimensional radii from p+p and d(p)+Au collisions are plotted vs $m_T$. For these systems femtoscopic sizes decrease with the increase of the transverse mass and d+Au results show also the dependence on the centrality like it is observed in Au+Au collisions [11]. Additionally, the value of $R_{side}$ and $R_{long}$ for p+Au collisions is similar to p+p collisions while $R_{long}$ is more like in d+Au collisions. Although it has to be emphasized that due to the way of extracting p+Au events from d+Au sample p+Au results correspond rather to peripheral p+Au collisions so the size of the source is expected to be larger for central collisions. Therefore, results suggest that the size of the source in p+Au collisions is not the same as in p+p. Comparison of the peripheral d+Au collisions, that include about 15% of p+Au collisions, with and without extracted p+Au events show no significant difference but that may be due to a fact that the d+Au sample still includes n+Au events that cannot be excluded from the data.

In elementary particle collisions, resonance production contributes significantly to the $m_T$ dependence of the HBT radii [13], while in heavy ion collisions, flow effects dominate this dependence [14]. The other scenarios that can give the similar dependence are the Heisenberg uncertainty and the string fragmentation [15].

On Figure 2b the ratio of the three dimensional radii in Au+Au, Cu+Cu and d+Au collisions to p+p radii is plotted vs $m_T$. Surprisingly, these ratios look flat although it is expected that different origins drive the transverse mass dependences of the HBT radii in Au+Au and p+p collisions. If these expectations are correct the data show that one
FIGURE 2. a) $m_T$ dependence of HBT radii and $\lambda$ in p+p and d(p)+Au collisions at $\sqrt{s_{NN}} = 200$ GeV; b) Ratio of HBT radii from Au+Au, Cu+Cu and d+Au by p+p collisions at $\sqrt{s_{NN}} = 200$ GeV.

may not distinguish different physics between p+p and Au+Au collisions studying pion interferometry.

An alternative explanation of this phenomena came from a work done by Csörgő et al. [16]. Authors using a Buda-Lund hydrodynamic model, that successfully describes the momentum correlations in Au+Au collisions, were able to fit STAR p+p spectra and HBT radii. But in this case they claim that the transverse mass dependence of the femtoscopic sizes is not generated by the transverse flow, but by the temperature inhomogeneities of hadron-hadron collisions due to the freezing scale. Then the conclusion from this study would be that in p+p collisions the system has similar bulk properties as in Au+Au collisions.

Non-identical particle correlations like $\pi$-K or $\pi$-p in Au+Au collisions show a difference in then average emission points of two particles that is due to flow [17]. Therefore, femtoscopic study of particles with different masses in p+p collisions could be used to verify a flow hypothesis in small systems like p+p and d(p)+Au.

**EVIDENCE OF NON-FEMTOSCOPIC CORRELATIONS**

When doing femtoscopic analysis in p+p and d+Au collisions a problem with non-femtoscopic correlations has been observed. It is manifested in a non-vanished tail of the correlation function to unity, for large $Q$. In elementary particle collisions [15,18] these non-femtoscopic correlations were also observed and taken into account by adding an ad-hoc component to the parametrization of the correlation function that assumes that the correlation function for large $Q$ depends linearly on the three components of the two-
Using this parametrization the fit to the STAR p+p and d+Au collisions was performed and the femtoscopic radii turned out to be larger up to 30% in comparison to the standard parametrization. Figure 3a shows the projections of the 3D correlation function for the most peripheral d+Au collisions (that is STAR worst case) and the projections of the fit described above. It looks like the fit matches experimental data with good accuracy but more careful study is required to judge on the correctness of the new parametrization and will be performed with method described below.

A common approach to present 3D correlation function is to project it onto the three components of $\vec{Q}$ separately, as shown on Figure 3a. The disadvantage of this approach is that when doing such projections one has to constrain non-projected components to keep a signal but then the full information on the correlation function in the 3D space is lost. To eliminate this inconvenience a new approach of studying correlations was applied that is based on a decomposition of the correlation function into spherical harmonics (for detailed description of this method see [19]). In this method no cuts are performed on $\vec{Q}$’s components what allows to recognize symmetries in $\vec{Q}$-space to see, looking at 1D plots, relevant aspects of 3D correlation functions.

Figure 3b shows the first few components of the decomposition of the correlation function onto the spherical harmonics for peripheral d+Au collisions. The fitted correlation function, that includes a new term to account for non-femtoscopic effect, was decomposed using this method. As shown on Figure 3b the new parametrization fits the correlation function with good accuracy but with the spherical harmonic method it is seen that the fit is not correct. Distributions for $l=1$ are non-zero and $A_{10}$ shows a strong dependence on $|\vec{Q}|$. In a system like $\pi−\pi$ at midrapidity all odd components should vanish by symmetry. Additionally, the new parametrization does not fit the baseline of the correlation function that has an evidence in non-vanished $A_{20}$ and $A_{22}$ distributions.
This study shows that it is not sufficient to look at the Cartesian projections of the correlation function to judge about the quality of the fit and the correctness of the used parametrization. It is required to use spherical harmonic method to see the experimental data and the fit in the 3D space.

The analytic formulas of spherical harmonics are well-known so the $A_{2,0}$ and $A_{2,2}$ distributions may be parametrized and included in the fit. Such study was presented in [20] and it showed a good agreement with experimental data. Due to the lack of the space the results are not presented here, but the radii in p+p and d+Au collisions are changed up to 10% the most, although the $m_T$ scaling described in the previous section persists.

CONCLUSIONS

The results of pion interferometry for several energies and colliding systems at RHIC have been presented. In agreement with data at SPS and AGS, STAR indicates that the multiplicity is the scaling variable that determines the size of the source at freeze-out at midrapidity. The $m_T$ dependence of HBT radii seems to be independent of collision species or multiplicity. Finally, a problem with the baseline of the correlation function for low multiplicity collisions has been reported, and a promising tool based on the spherical harmonic decomposition of the correlation function has been used in order to address it. The physics of this structure remains under investigation. The advantage of this method in studying the correctness of the parametrization of the correlation function used in a fit has been shown.

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