Femtoscopy via Lévy sources with PHENIX at RHIC

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Abstract

Charged pion two-particle correlation functions were measured in 0–30% centrality $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions with the PHENIX experiment at RHIC. The measured correlation functions can be statistically well described based on the assumption of Lévy-shaped source distributions. In this proceedings paper we present the Lévy parameters of the measured correlation functions: correlation strength parameter λ , Lévy index α and Lévy scale parameter R as a function of pair transverse mass m_T , in 31 bins from 228 to 871 MeV, separately for positive and negative pion pairs. We discuss the physical interpretation of the m_T dependence of the parameters.

1 Introduction

In ultra-relativistic collisions of heavy ions, strongly coupled Quark Gluon Plasma (sQGP) is formed [1–4] for a very short amount of time, and after a quark-hadron freeze-out, hadrons are created. The measurement of Bose-Einstein correlations (i.e. femtoscopy) can be used to gain knowledge about the space-time geometry of the particle emitting source, as originally observed by [5,6], and in radio and optical astronomy by R. Hanbury Brown and R. Q. Twiss (HBT) [7]. In an interaction-free case, the two-particle Bose-Einstein correlation functions are related to the Fourier transform of the source function $(S(x, k), \text{ describing the probability density of particle creation at the space-time point x and with four-momentum x):$

$$C_2^{(0)}(Q,K) \simeq 1 + \left| \frac{\tilde{S}(Q,K)}{\tilde{S}(0,K)} \right|^2,$$
 (1)

where $\tilde{S}(q,k) = \int S(x,k)e^{iqx}d^4x$ is the Fourier-transformed of S, and $Q = p_1 - p_2$ is the momentum difference, $K = (p_1 + p_2)/2$ is the average momentum, and we assumed, that $q \ll K$ holds for the investigated kinematic range. Usually, correlation functions are measured versus Q, for a well-defined K-range, and then properties of the correlation functions are analyzed as a function of the average K of each range. In an expanding Gaussian source, then $1 + \exp{-(QR)^2}$ correlations are thus measured, where the observed Gaussian radius R is a homogeneity length, depending on the average momentum K or the related transverse mass m_T . The approximate dependence of $R^{-2} \propto a + bm_T$ is observed, rather universally (for various collision systems, collision energies and particle types) [8,9], which can be interpreted as a consequence of hydrodynamical expansion [10, 11]. See Ref. [12] (and references therein) for details.

It is important to note, that a significant fraction of pions are secondary, coming from decays. Hence the source will have two components: a core of primordial pions, stemming from the hydrodynamically expanding sQGP, and a halo, consisting of the decay products of long lived resonances (such as η , η' , K_S^0 , ω): $S = S_{\text{core}} + S_{\text{halo}}$. These two components have characteristically different sizes (≤ 10 fm for the core, > 50 fm for the halo, based on the half-lives of the above mentioned resonances). In particular, the halo component is so narrow in momentum-space, that it cannot be resolved experimentally. This leads to the following apparent correlation function:

$$\lim_{q \to 0} C_2^{(0)}(Q, K) = 1 + \lambda(K), \tag{2}$$

where $\lambda = N_{\text{core}}/(N_{\text{core}} + N_{\text{halo}})$ was introduced, being related related to the fraction of primordial pions among all (primordial plus decay) pions. One of the motivations for measuring λ is that it is related [23] to the η' meson yield, expected [24] to increase in case of chiral $U_A(1)$ symmetry restoration in heavy-ion collisions (due to the expected

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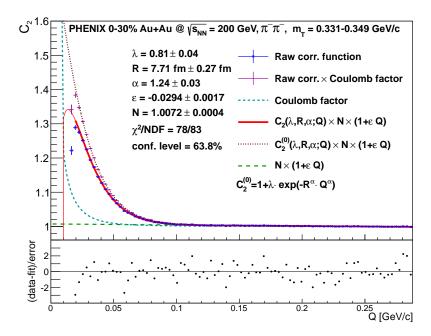


Figure 1: Example fit of to a $\pi^-\pi^-$ correlation function, for $m_T = 0.331 - 0.349 \text{ GeV}/c^2$. The fit shows the measured correlation function and the complete fit function, while a "Coulomb-corrected" fit function $C^{(0)}(Q)$ is also shown, with the data multiplied by $C^{(0)}/C^{\text{Coul}}$.

in-medium mass decrease of the η'). Note that a study [25] reported the compatibility of existing $\lambda(m_T)$ data and predictions based on a decreased in-medium η' mass.

Experimental results show [13, 14], that the source function does not always exhibit a Gaussian shape. In an expanding hadron resonance gas, increasing mean free paths lead to a Lévy-flight, anomalous diffusion, and hence to spatial Lévy distributions [15–17] This leads to a correlation function of

$$C_2^{(0)}(Q,K) = 1 + \lambda(K) \cdot e^{-(QR(K))^{\alpha(K)}},$$
(3)

where α is the (K-dependent) Lévy-exponent, which is conjectured [18] to be identical to the critical exponent η , conjectured to take a value of 0.5 or even lower, identivally to the universality class of the 3D Ising model (possibly with random external fields) [18–22]. Since the exploration the search for the QCD critical endpoint is one of the major goals of experimental heavy ion physics nowadays, we gain additional motivation for the measurement and analysis of of Bose-Einstein correlation functions.

Hence, in the following we utilize a generalization of the usual Gaussian shape of the Bose-Einstein correlations, namely we analyze our data using Lévy stable source distributions. In this proceedings paper we omit the discussion of final-state interactions, in particupar the effect of the Coulomb interaction. The handling of this is described in detail in Ref. [12].

2 Results

We analyzed $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions from the 2010 running period of the PHENIX experiment, selecting about 2.2 billion 0 – 30% centrality events from the recorded 7.3 billion Minimum Bias events. Note that in the original conference presentation, the Minimum Bias data were presented (shown also e.g. in Ref. [27]). In this paper we present the final data from Ref. [12], which yield the same conclusion. Two-particle correlation functions of $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs (versus the momentum difference length in the longitudinally comoving system, Q) were measured 31 m_T bins ranging from 228 to 871 MeV/ c^2 (where m_T denotes the transverse momentum variable related to the average momentum K). We fitted these correlation functions with the Coulomb-effect incorporated, based on Lévy-shaped sources, as described in the previous section and in Ref. [12]. Additionally, we introduced a linear background, as indicated in Fig. 1, where an example fit is shown. The fits in all m_T bins and for both charges yield statistically acceptable descriptions of the measured correlation functions, indicating that the fit parameters of R, α and λ indeed represent the measurements.

The m_T dependence of the fit parameters is shown in Fig. 2. We may observe that α is approximately constant

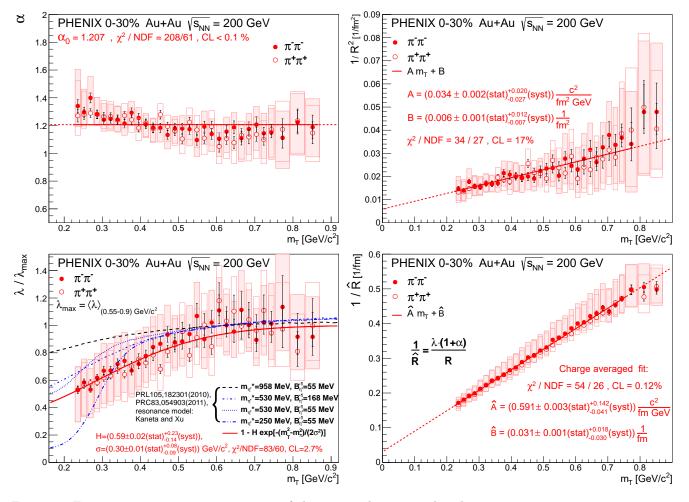


Figure 2: Fit parameters versus average m_T of the pair with statistical and symmetric systematic uncertainties shown as bars and boxes, respectively.

(within systematic uncertainties), and takes an average value of 1.207, being far from the Gaussian assumption of $\alpha = 2$, but also far from the conjectured $\alpha = 0.5$ value at the critical point. The results are furthermore incompatible with the exponential assumption of $\alpha = 1$. We also see, that despite being far from the hydrodynamic limit of Gaussian distributions, the hydro prediction of $1/R^2 \simeq a + bm_T$ still holds. The correlation function strength λ is shown after a normalization by $\lambda_{\max} = \langle \lambda \rangle_{m_T=0.5-0.7 \text{GeV}/c^2}$. This clearly indicates a decrease at small m_T , which may be explained by resonance effects, and is in particular not incompatible with predictions based on a reduced η' mass. We also show, that a new, empirically found scaling parameter $\hat{R} = R/(\lambda(1 + \alpha))$ may be defined with decreased statistical uncertainties, exhibiting a clear linear scaling with m_T .

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References

- [1] K. Adcox et al. (PHENIX Collaboration), Nucl. Phys. A757, 184 (2005).
- [2] J. Adams et al. (STAR Collaboration), Nucl. Phys. A757, 102 (2005).
- [3] I. Arsene et al. (BRAHMS Collaboration), Nucl. Phys. A757, 1 (2005).
- [4] B. B. Back et al. (PHOBOS Collaboration), Nucl. Phys. A757, 28 (2005).
- [5] G. Goldhaber et al., Phys. Rev. Lett. 3, 181 (1959).
- [6] G. Goldhaber *et al.*, Phys. Rev. **120**, 300 (1960).
- [7] R. Hanbury Brown and R. Q. Twiss, Nature 178, 1046 (1956).
- [8] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 93, 152302 (2004).
- [9] S. Afanasiev et al. (PHENIX Collaboration), Phys.Rev.Lett. 103, 142301 (2009).
- [10] A. N. Makhlin and Y. M. Sinyukov, Z. Phys. C39, 69 (1988).
- [11] T. Csörgő and B. Lörstad, Phys. Rev. C54, 1390 (1996).
- [12] A. Adare et al. (PHENIX Collaboration), [arXiv:1709.05649]
- [13] S. Afanasiev et al. (PHENIX Collaboration), Phys.Rev.Lett. 100, 232301 (2008).
- [14] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 98, 132301 (2007).
- [15] R. Metzler *et al.*, Phys. Rev. Lett. **82**, 3563 (1999).
- [16] T. Csörgő et al., Eur. Phys. J. C36, 67 (2004).
- [17] M. Csanád et al., Braz. J. Phys. 37, 1002 (2007).
- [18] T. Csörgő, PoS HIGH-PTLHC08, 027 (2008).
- [19] S. El-Showk et al., J. Stat. Phys. 157, 869 (2014).
- [20] H. Rieger, Phys. Rev. B 52, 6659 (1995).
- [21] M. A. Halasz et al., Phys. Rev. D58, 096007 (1998).
- [22] M. A. Stephanov et al., Phys. Rev. Lett. 81, 4816 (1998).
- [23] S. E. Vance *et al.*, Phys. Rev. Lett. **81**, 2205 (1998).
- [24] J. I. Kapusta *et al.*, Phys. Rev. **D53**, 5028 (1996).
- [25] T. Csörgő et al., Phys.Rev.Lett. 105, 182301 (2010).
- [26] T. Novák et al., Acta Phys. Polon. Supp. 9, 289 (2016).
- [27] D. Kincses for the PHENIX Collaboration, Acta Phys.Polon.Supp. 9, 243 (2016).