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Lévy femtoscopy with PHENIX at RHIC

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Summary. — In this paper we present the measurement of charged pion two-particle correlation functions and their Lévy parameters in 0–30% centrality $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. The measured correlation functions can be statistically well described by Bose-Einstein correlation functions from Lévy-shaped source distributions. Using a fine transverse momentum binning, we extract 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, a strongly coupled Quark Gluon Plasma (sQGP) is formed [1-4] for a very short period 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 Hanbury Brown and Twiss (HBT) [7]. In an interaction-free case, the two-particle Bose-Einstein correlation functions are related to the Fourier transformation of the source function ($S(x,k)$, describing the probability density of particle creation at the space-time point x and with four-momentum x):

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

where $\widetilde{S}(q,k) = \int S(x,k) e^{iqx} \mathrm{d}^4 x$ is the Fourier-transform 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, the $1+e^{-(QR)^2}$ correlations are 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): $S = S_{\rm core} + S_{\rm halo}$. These two components have characteristically different sizes ($\lesssim 10$ 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 $\lambda = N_{\rm core}/(N_{\rm core}+N_{\rm halo})$ was introduced, being 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 [13] to the η' meson yield, expected [14] to increase in case of chiral $U_A(1)$ symmetry restoration in heavy-ion collisions (due to the expected in-medium mass decrease of the η'). Note that a study [15] reported the compatibility of existing $\lambda(m_T)$ data and predictions based on a decreased in-medium η' mass.

Experimental results show [16, 17] 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 [18-20] This leads to a correlation function of

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

where α is the (K-dependent) Lévy-exponent, which is conjectured [21] to be identical to the critical exponent η, conjectured to take a value of 0.5 or even lower, identically to the universality class of the 3D Ising model (possibly with random external fields) [21-25]. Since 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 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 particular 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. [26]).

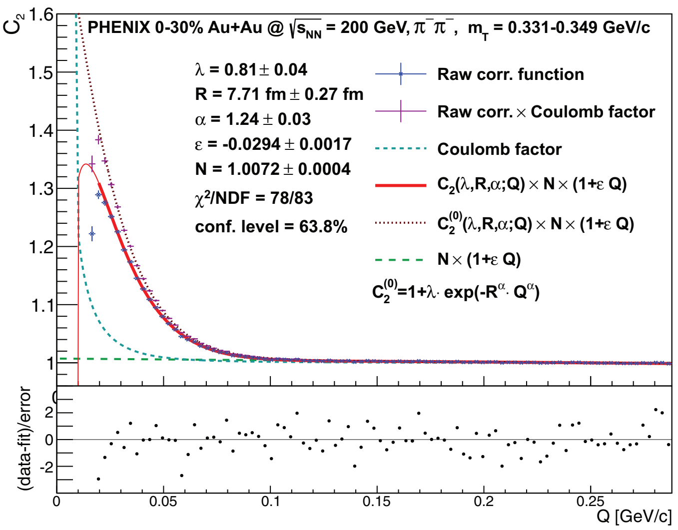

Fig. 1. – Example fit of to a $\pi^-\pi^-$ correlation function, for $m_T = 0.331$–0.349 GeV/c^2. The fit shows the measured correlation function and the complete fit function, while a "Coulomb-corrected" fit function $C^{(0)}(Q)$ is also shown, with the data multiplied by $C^{(0)}/C^{\mathrm{Coul}}$.

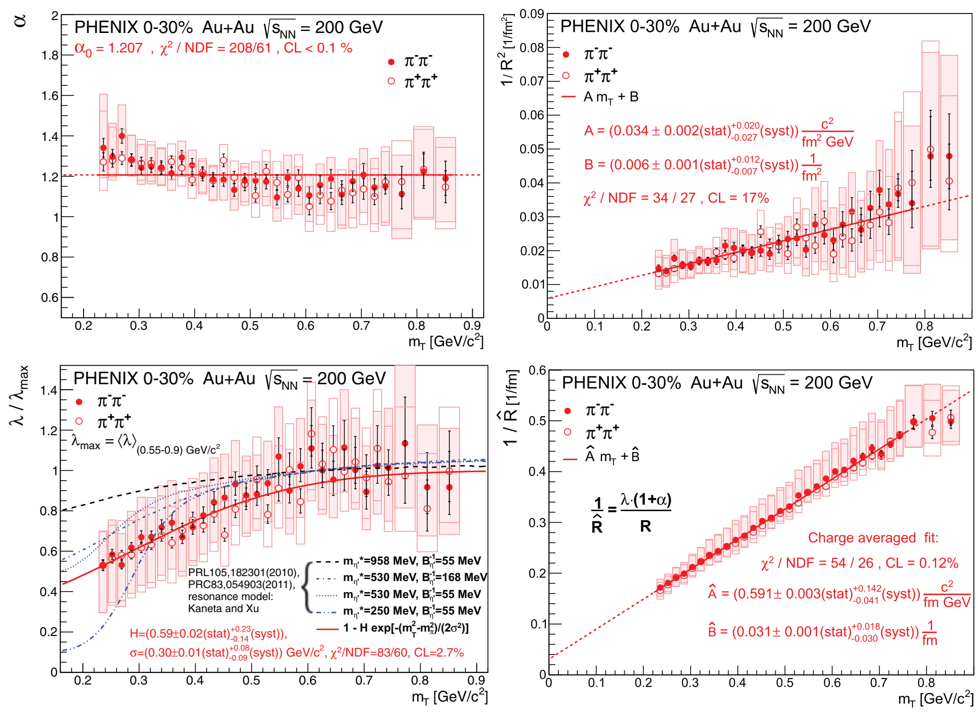

Fig. 2. – Fit parameters *versus* average m_T of the pair with statistical and symmetric systematic uncertainties shown as bars and boxes, respectively.

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

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