

# THREE-DIMENSIONAL LÉVY HBT RESULTS FROM PHENIX\*

BÁLINT KURGYIS

for the PHENIX Collaboration

Eötvös Loránd University, Pázmány Péter sétány 1/A, 1117 Budapest, Hungary

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In heavy-ion collisions, we measure the Bose–Einstein correlation functions to map out the femtoscopic homogeneity region of the particle emitting source. Previously, a one-dimensional measurement with a Lévy-shaped source was done at the PHENIX experiment. In this paper, we present the three-dimensional Lévy HBT results of PHENIX and their comparison with the one-dimensional results.

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## 1. Introduction

The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) has collected a large amount of data with different collision systems ( $p+p$ ,  $p+A$ ,  $A+A$ ) at different collision energies [1]. This gives the chance to thoroughly investigate the created quark–gluon plasma (QGP) and its properties. The QGP cools down and from it hadrons are created. We can map out the femtoscopic homogeneity region of this particle emitting source by measuring the Bose–Einstein correlation functions of identical bosons. The shape of the source was often assumed to be a Gaussian [2, 3]. However, there were indications of non-Gaussian behavior [4–6]. More recently, PHENIX measured the Bose–Einstein correlation functions in one dimension [7] and found that the data can be best described by a more general, Lévy-shaped source. The Lévy parameters were only measured in one dimension so far, but it is important to investigate the appropriacy of the Lévy-type source assumption in three-dimensional HBT measurements. Here, we present the preliminary results of a three-dimensional Lévy analysis of same charged pions from  $\sqrt{s_{NN}} = 200$  GeV Au+Au data.

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## 2. The Lévy-type source

One possible explanation for the appearance of Lévy distributions in heavy-ion collisions is the rapidly expanding medium, where the mean free path increases, thus anomalous diffusion emerges [8]. The Lévy distribution is characterized by the Lévy exponent  $\alpha$ . At two special values of  $\alpha$ , the Lévy distribution can be formulated analytically:  $\alpha = 2$  leads to a Gaussian distribution and  $\alpha = 1$  leads to a Cauchy distribution. In general, the Lévy stable distribution can be expressed with an integral formula

$$\mathcal{L}(\alpha, \mathbf{R}, \mathbf{r}) = \frac{1}{(2\pi)^3} \int d^3q e^{i\mathbf{q}\mathbf{r}} e^{-\frac{1}{2}|\mathbf{q}\mathbf{R}|^\alpha}. \quad (1)$$

We can measure the three-dimensional Lévy HBT scale parameters ( $R_{\text{out}}$ ,  $R_{\text{side}}$ ,  $R_{\text{long}}$ ) by comparing data to the Bose–Einstein correlation functions of Lévy sources. These scale parameters differ from the usually measured Gaussian radii but still they describe the homogeneity region of the particle emitting source.

Furthermore, it is important to consider the role of pions coming from resonance decays in the system. We can take these into account via the core–halo model [9, 10], where we assume a two-component source. One is a hot, dense and hydrodynamically expanding core with a characteristic size  $\sim 10$  fm/ $c$ . The core emits the primordial pions and yields the correlation function that we can measure. The other component is a rather wide spatial distribution of the decay products of long-lived resonances with a characteristic scale much larger than 10 fm/ $c$ , which transforms into a very narrow peak in the relative momentum space, thus it is experimentally unresolvable. It turns out that  $\lambda$  correlation strength parameter (intercept of the correlation function at  $\mathbf{q} = 0$ ) can be expressed as:  $\lambda = N_{\text{core}}^2 / (N_{\text{core}} + N_{\text{halo}})^2$ , where  $N_{\text{core}}$  and  $N_{\text{halo}}$  are the numbers of pions coming from the core and the halo, respectively. Hence, this way, we can describe the ratio of primordial pions in the system by measuring lambda.

With the above assumptions, we end up with the following form for the interaction free two-particle correlation function [11]:

$$C_2^{(0)}(\mathbf{q}; \mathbf{R}, \lambda, \alpha) = 1 + \lambda \exp(-|\mathbf{q}\mathbf{R}|^\alpha). \quad (2)$$

Additionally, one needs to consider the Coulomb interaction between the charged pions. We can take this into account in the following way:

$$C_2^{(C)}(\mathbf{q}; \mathbf{R}, \lambda, \alpha) = K(\mathbf{q}; \mathbf{R}, \lambda, \alpha) C_2^{(0)}(\mathbf{q}; \mathbf{R}, \lambda, \alpha), \quad (3)$$

where the  $K(\mathbf{q})$  is the Coulomb correction factor. In this analysis, we used a very detailed numerical table for  $K(\mathbf{q})$  and fitted the data with an iterative method as described in Ref. [7]. Here, the assumption of a spherically symmetric source is used.

### 3. Three-dimensional Lévy HBT at PHENIX

We analyzed  $\sqrt{s_{NN}} = 200$  GeV Au+Au data from the 2010 data taking period at the PHENIX experiment. The two-particle relative momentum correlation functions were measured for  $\pi^+\pi^+$  and  $\pi^-\pi^-$  pairs from the 0–30% centrality events in 31 different transverse momentum ( $m_T$ ) bins. For the measurements, we used the Bertsch–Pratt coordinates (out, side, long), in the longitudinally comoving system. Then, we fitted the data with correlation functions from a Lévy-shaped source. This way, we could extract the transverse momentum dependence of the model parameters. For the fitting, we used a modified Poisson likelihood term ( $\chi_\lambda^2$ ) as in Ref. [12] that considers the Poisson error for the bin counts. Figure 1 shows an example of the projections of the measured three-dimensional correlation function along the out, side and long directions and also the projected fit.

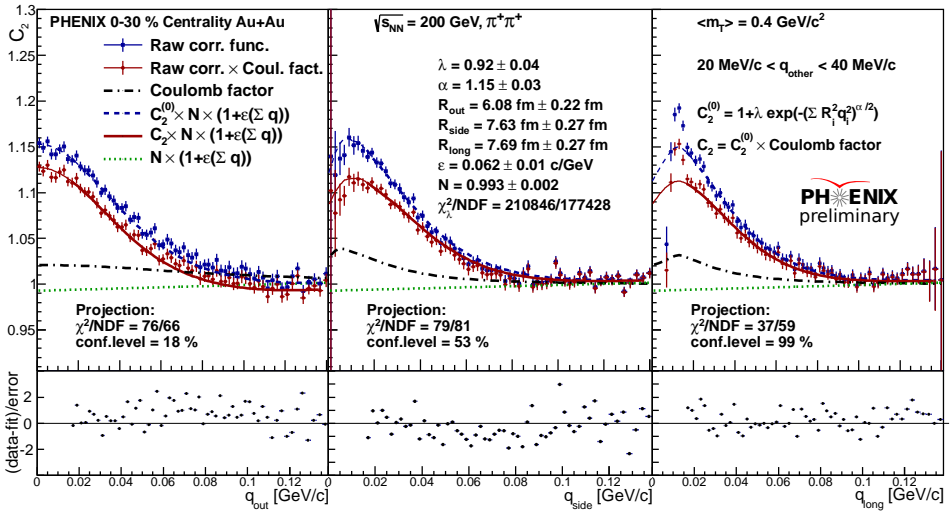


Fig. 1. An example plot of the correlation functions measured in three dimensions by showing the projections along the out, side and long directions. We can see the raw data points and the fitted theoretical curve. The first few points are not fitted because of two track resolution. The Coulomb corrected correlation functions are also shown.

In addition to the investigation of the transverse momentum dependence of the Lévy parameters, we also did a comparison with previous one-dimensional results from Lévy HBT at PHENIX [7]. Figure 2 shows the transverse momentum dependence of the Lévy model parameters. In the top panel, we can see the Lévy scale parameters ( $R_{\text{out}}$ ,  $R_{\text{side}}$ ,  $R_{\text{long}}$ ) as a function of  $m_T$ . At the first few  $m_T$  bins, the source is rather asymmetric, which might affect the accuracy of the way we handled the Coulomb

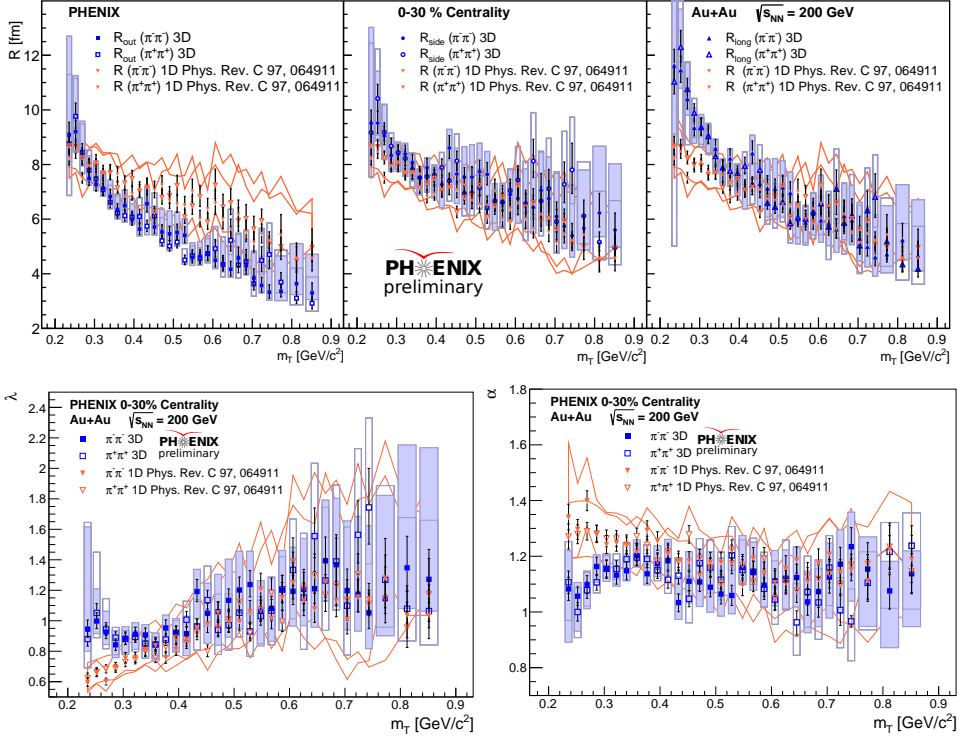


Fig. 2. Top: The transverse momentum dependence of the  $R_{out}$ ,  $R_{side}$ ,  $R_{long}$  Lévy scale parameters from this measurement and the previous one-dimensional results are also shown. Bottom: We can see the results of this measurement compared with the previous one-dimensional results as the function of transverse mass: the Lévy exponent ( $\alpha$ ) on the right and the strength of the correlation ( $\lambda$ ) on the left.

interaction. Except the first few points, the radii are consistent with the one-dimensional radius. The often measured Gaussian radii usually show a hydrodynamical scaling ( $R \propto 1/\sqrt{m_T}$ ) across various collision centralities and particle types [2, 13]. Here, we are not measuring the Gaussian radii, but the Lévy scale parameters and these still follow the hydrodynamical scaling. The bottom left plot of Fig. 2 shows the transverse momentum dependence of the correlation strength ( $\lambda$ ). Apart from a small deviation at the lower  $m_T$  bins, the new results are consistent with the published one-dimensional PHENIX results [7]. In the bottom right plot of Fig. 2, we can see the Lévy exponent ( $\alpha$ ) as a function of the transverse momentum measured in this analysis and also previously in Ref. [7]. The results are consistent with each other, the only deviation is at the low- $m_T$  region. This might occur because the source is the most asymmetric in that region, therefore, a non-spherically symmetric Coulomb correction may have to be used. These plots indicate

that the best description of the data is given by the general Lévy-shaped source (with  $\alpha \sim 1.2$ ) and not by a Gaussian ( $\alpha = 2$ ) or Cauchy ( $\alpha = 1$ ) source.

#### 4. Summary

We measured the three-dimensional Bose–Einstein correlation functions and investigated the transverse mass dependence of Lévy parameters. We found that the Lévy exponent and the strength of the correlation are compatible with the one-dimensional measurement. This means that the best description of the data is given by the general Lévy-shaped source with an exponent  $\alpha \sim 1.2$ , which is far from the Gaussian case ( $\alpha = 2$ ) and also differs from the Cauchy distribution ( $\alpha = 1$ ). The transverse mass dependence of the Lévy scale parameters ( $R_{\text{out}}$ ,  $R_{\text{side}}$ ,  $R_{\text{long}}$ ) shows us that we have an asymmetric source, especially at the low- $m_T$  region. Additionally, we observed the hydrodynamical scaling ( $R \propto 1/\sqrt{m_T}$ ) of the homogeneity length. For the approximative Coulomb correction, a more advanced calculation is needed, to treat the asymmetric source appropriately. With this, we hope to understand the low- $m_T$  behavior of the parameters better, where the preliminary results indicate the most asymmetric source.

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