PHENIX results on the Lévy stable Bose-Einstein correlation functions

Sándor Lökös for the PHENIX Collaboration

Eötvös University & Eszterházy University, Hungary
Outline

1. The PHENIX experiment
2. Bose-Einstein correlations
3. PHENIX Lévy HBT results: $\sqrt{s_{NN}} = 200$ GeV, 0-30%
4. Summary & outlook
The PHENIX Experiment

- Versatile detector, operating until 2016
- Tracking via Drift Chambers and Pad Chambers
- Charged pion ID with TOF, from ~ 0.2 to 2 GeV/c
- This analysis: PID also with EMCal

Sándor Lökös for PHENIX
Eötvös University & Eszterházy University
The PHENIX Experiment

- Versatile detector, operating until 2016
- Tracking via Drift Chambers and Pad Chambers
- Charged pion ID with TOF, from \( \sim 0.2 \) to 2 GeV/c
- This analysis: PID also with EMCal
# PHENIX runs at a glance

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>510.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>130.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>62.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- p+p
- Au+Au
- d+Au
- Cu+Cu
- U+U
- Cu+Au
- He+Au
- p+Au
- p+Al

Outline

1. The PHENIX experiment
2. Bose-Einstein correlations
3. PHENIX Lévy HBT results: $\sqrt{s_{NN}} = 200$ GeV, 0-30%
4. Summary & outlook
Bose-Einstein correlations

- Correlation function from one- and two-particle momentum distributions:

\[
C_2(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_2(p_2)} \rightarrow C_2(q, K) = 1 + \frac{|\tilde{S}(q, K)|^2}{|\tilde{S}(q = 0, K)|^2}
\]

where \( q = p_1 - p_2 \) and \( K = (p_1 + p_2)/2 \)

- Several effects could modify the correlation functions:
  - Like-charged pions \( \rightarrow \) Coulomb correction needed: \( C_{B-E} = K(q) \cdot C_m(q) \)
  - Strong final state interaction
  - Effect of the resonance pions \( \rightarrow \) core-halo model:
    - \( S = S_{\text{core}} + S_{\text{halo}} \)
    - Long-lived resonances contribute to the halo
    - In-medium \( \eta' \) mass modification \( \rightarrow \) specific, \( m_T \) dependent suppression
  - Partial coherence
  - Squeezed states
Lévy-type of distribution and anomalous diffusion

- Expanding medium, increasing mean free path: anomalous diffusion
- Lévy-distribution from generalized central limit theorem could be valid

\[ S(x, p) = \frac{1}{(2\pi)^3} \int d^3 q e^{i q x} e^{-\frac{1}{2}|xR|^\alpha} \]

- \( C_2 \) with Lévy source:

\[ C_2(Q) = 1 + \lambda \cdot e^{-(RQ)^\alpha} \]

Lévy index \( \Rightarrow \begin{cases} 
\alpha = 2 & \text{Gaussian} \Rightarrow \text{normal diffusion} \\
0 < \alpha \leq 2 & \text{Lévy} \Rightarrow \text{anomalous diffusion}
\end{cases} \)

- For details see e.g.:

Sándor Lökös for PHENIX

Eötvös University & Eszterházy University
Outline

1. The PHENIX experiment
2. Bose-Einstein correlations
3. PHENIX Lévy HBT results: $\sqrt{s_{NN}} = 200$ GeV, 0-30%
4. Summary & outlook

Sándor Lökös for PHENIX
Eötvös University & Eszterházy University
PHENIX Lévy HBT analysis

- Dataset used for the analysis:
  - Run-10, Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $7.3 \cdot 10^9$ events
  - 0-30% centrality was used
  - Additional offline requirements: collision vertex position less than ±30 cm
  - Particle identification:
    - time-of-flight data from PbSc e/w, TOF e/w, momentum, flight length
    - $2\sigma$ cuts on $m^2$ distribution
  - Correlation variable $Q = \sqrt{(p_{1x} - p_{2x})^2 + (p_{1y} - p_{2y})^2 + q_{\text{long,LCMS}}^2}$, where $q_{\text{long,LCMS}}^2 = \frac{4(p_{1z}E_2 - p_{2z}E_1)}{(E_1 + E_2)^2 - (p_{1z} + p_{2z})^2}$
  - Single track cuts: $2\sigma$ matching cuts in TOF & PbSc for pions
  - Pair-cuts:
    - A random member of pairs assoc. with hits on same tower were removed
    - customary shaped cuts on $\Delta \varphi - \Delta z$ plane for PbSc e/w, TOF e/w
  - 1D corr. func. as a function of $Q$ in various $m_T$ bins
    - Lévy fits for 31 $m_T$ bins ($m_T$ from $\sim 0.280$ GeV/c$^2$ to $\sim 0.870$ GeV/c$^2$)
    - Coulomb effect incorporated in fit function

Sándor Lökös for PHENIX
Eötvös University & Eszterházy University
Example $C(Q)$ measurement result

Measured in 31 $m_T^2 = m^2 + p_T^2$ bins for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs

$\lambda = 0.81 \pm 0.04$
$R = 7.71 \text{ fm} \pm 0.27 \text{ fm}$
$\alpha = 1.24 \pm 0.03$
$\varepsilon = -0.0294 \pm 0.0017$
$N = 1.0072 \pm 0.0004$
$\chi^2/\text{NDF} = 78/83$
$\text{conf. level} = 63.8\%$

$C(\lambda, R, \alpha; Q) \times N \times (1 + \varepsilon Q)$

$C(0) = 1 + \lambda \cdot \exp(-R^\alpha \cdot Q^\alpha)$

arxiv:1709.05649 (accepted for publication in Phys.Rev.C)

Physical parameters: $R, \lambda, \alpha$; measured versus pair $m_T$
Example $C(Q)$ measurement result

Measured in 31 $m_T^2 = m^2 + p_T^2$ bins for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs

![Graph showing $C(Q)$ measurement](image)

*Physical parameters: $R, \lambda, \alpha$; measured versus pair $m_T$*

arxiv:1709.05649 (accepted for publication in Phys.Rev.C)
Lévy scale parameter $R$

- Similar decreasing trend as Gaussian HBT radii
- Hydro predicts $1/R_{\text{Gauss}}^2 = a + bm_T$
- Hydro behavior not invalid for $R_{\text{Lévy}}$!
- The linear scaling of $1/R^2$ breaks for high $m_T$

[Graph showing data points and fit]

```
PHENIX 0-30% Au+Au $\sqrt{s_{NN}} = 200$ GeV

$p^+p^-$
$p^+p^+$

$A = (0.034 \pm 0.002\text{(stat)}^{+0.019}_{-0.021}\text{(syst)}) \frac{c^2}{\text{fm GeV}}$
$B = (0.006 \pm 0.001\text{(stat)}^{+0.009}_{-0.007}\text{(syst)}) \frac{c^2}{\text{fm GeV}}$

$\chi^2 / NDF = 34 / 27, CL = 17\%$
```

arxiv:1709.05649 (accepted for publication in Phys.Rev.C)
Lévy exponent $\alpha$

arxiv:1709.05649 (accepted for publication in Phys.Rev.C)

- Measured value is far from Gaussian ($\alpha = 2$), also not expo. ($\alpha = 1$)
- More or less constant (at least within systematic errors)
- Note: $\alpha(m_T) = \text{const.}$ fit statistically not acceptable (only with syst.)
Correlation strength $\lambda$

From the Core-Halo model, measure the core-halo fraction: $\lambda = \left( \frac{N_C}{N_C + N_H} \right)^2$

- Observed suppression at small $m_T \rightarrow$ increase of halo fraction
- Different effects can cause change in $\lambda$
- Resonance effects, partially coherent pion production
- $\lambda/\lambda_{\text{max}}$ with smaller systematic uncertainties
- Precise measurement may help extract physics info

arxiv:1709.05649 (accepted for publication in Phys.Rev.C)
A possible interpretation of $\lambda(m_T)$

![Graph showing data points and fits for $\lambda(m_T)$]

arxiv:1709.05649 (accepted for publication in Phys.Rev.C)

- May be connected to mass modifications (c.f. $U_A(1)$ chiral restoration)
  - Decreased $\eta'$ mass $\rightarrow$ $\eta'$ enhancement $\rightarrow$ halo enhancement
  - Kinematics: $\eta'$s low $m_T$ decay pions $\rightarrow$ decreased $\lambda$ at small $m_T$

The results are not inconsistent with modified $m_\eta$

Interesting scaling parameter $\hat{R}$

![Graph 1]

![Graph 2]

![Graph 3]
Interesting scaling parameter $\hat{R}$

$$\hat{R} = \frac{1}{m_T} \left(1 + \alpha \right)$$

Charge averaged fit:

$$\chi^2 / \text{NDF} = 54 / 26 \text{, CL} = 0.12\%$$

$$\hat{A} = (0.591 \pm 0.003 \text{(stat)} + 0.142 \text{(syst)}) \frac{c^2}{\text{fm GeV}}$$

$$\hat{B} = (0.031 \pm 0.001 \text{(stat)} + 0.015 \text{(syst)}) \frac{c^2}{\text{fm GeV}}$$

Empirically found scaling parameter

Remarkably linear in $m_T$

Physical interpretation $\rightarrow$ open question

arxiv:1709.05649 (accepted for publication in Phys.Rev.C)
Outline

1. The PHENIX experiment
2. Bose-Einstein correlations
3. PHENIX Lévy HBT results: $\sqrt{s_{NN}} = 200$ GeV, 0-30%
4. Summary & outlook
Summary & outlook

▶ Lévy fits gives acceptable description ↔ anomalous diffusion?

▶ Nearly constant $\alpha$, away from 2, 1 and 0.5 ↔ distance to CEP?

▶ Linear scaling of $1/R^2(m_T)$ ↔ hydro?

▶ Low-$m_T$ decrease in $\lambda(m_T)$ ↔ resonances, $\eta'$ in-medium mass?

▶ Empirically found scaling parameter $\hat{R} = R/(\lambda \cdot (1 + \alpha))$

▶ Current projects and plans:
  ▶ Centr. and coll. en. dependence: Dániel Kincses’s talk on Saturday
  ▶ 3D HBT analysis: Máté Csanád’s talk on Wednesday
  ▶ 3-particle analysis: Máté Csanád’s talk on Wednesday
  ▶ kaon-kaon correlation, Lévy HBT in p+p collision, ...
Thank you for your attention!
Run4 preliminary & Gauss → Run10 preliminary & Lévy

\[ \lambda (\pi^+ \pi^+) \text{ RUN4 200GeV Au+Au} \]

\[ m^{*}\eta' = 958 \text{ MeV} \]
\[ m^{*}\eta' = 600 \text{ MeV} \]
\[ m^{*}\eta' = 500 \text{ MeV} \]
\[ m^{*}\eta' = 400 \text{ MeV} \]
\[ m^{*}\eta' = 300 \text{ MeV} \]
\[ m^{*}\eta' = 200 \text{ MeV} \]

Gauss fit

PHENIX PRELIMINARY

Sándor Lökös for PHENIX

Eötvös University & Eszterházy University
STAR centrality dependent results (left) and the comparison of STAR results in different energy with NA44 data (right)
Lévy source function and kinematic variables

Basic two-particle variables

\[ K^\mu = \frac{p_1^\mu + p_2^\mu}{2}, \quad q^\mu = p_1^\mu - p_2^\mu, \quad q_{inv} = \sqrt{-q^\mu q^\mu} \]

- \( C_2(q_{inv}) \) - Lorentz invariant 1 dimensional function
- \( |k| = \frac{1}{2} \sqrt{q_{out}^2 + q_{side}^2 + q_{long}^2} \) instead of \( q_{inv} \) - better
- \( C_2(|k|) \) - 1 dim. function
- Generalized Gaussian - Lévy-distribution
  - Anomalous diffusion
  - Generalized limit theorem
    \[ \mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3q e^{iqr} e^{-\frac{1}{2}\frac{1}{|k|} |qR|^{\alpha}} \]
    \[ S(r) = (1 - \sqrt{\lambda}) \mathcal{L}(\alpha, R_H, r) + \sqrt{\lambda} \cdot \mathcal{L}(\alpha, R_C, r) \]
    \[ C_2(|k|) = 1 + \lambda \cdot e^{-(2R|k|)^{\alpha}} \] (1)

- Shape of the correlation functions with Lévy source \( (R_H \to \infty) \):
  \[ C_2(|k|) = 1 + \lambda \cdot e^{-(2R|k|)^{\alpha}} \] (2)