PHENIX results on Bose–Einstein correlation functions

XV. Zimányi Winter School on Heavy Ion Physics

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- Summary
The PHENIX Experiment

- Observing collisions of p, d, Cu, Au, U
- Charged pion ID from \( \sim 0.2 \) to 2 GeV/c
- Beam energy scan is important
Observing collisions of p, d, Cu, Au, U
Charged pion ID from $\sim 0.2$ to 2 GeV/c$^2$
Beam energy scan is important
### The RHIC Beam Energy Scan

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

Bose-Einstein correlations - a short summary

\(N_1(p), N_2(p)\) - invariant momentum distributions, the definition of the correlation function:

\[
C_2(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)}
\]

The invariant momentum distributions

\[
N_1(p) \text{ - norm., } N_2(p_1, p_2) = \int S(x_1, p_1)S(x_2, p_2)|\Psi_2(x_1, x_2)|^2 d^4x_2 d^4x_1
\]

- \(S(x, p)\) source function (usually Gauss shaped - Lévy is more general)
- \(\Psi_2\) - interaction free case - \(|\Psi_2|^2 = 1 + \cos(qx)\)

If \(k_1 \simeq k_2\): \(C_2 \rightarrow \text{inverse Fourier-trf. } \rightarrow S\)

\[
C_2(q, K) \simeq 1 + \left|\frac{\tilde{S}(q, K)}{\tilde{S}(0, K)}\right|^2, \quad \tilde{S}(q, k) = \int S(x, k)e^{iqx}d^4x
\]

- Sometimes this simple formula fails (cf. experimentally observed oscillations at L3, CMS)
- see also the talks of A. Bialas at WPCF 2015, WPCF 2014

D. Kincses for PHENIX (Zimányi 2015)

PHENIX HBT results
Final state interactions, resonances

- Final state interactions distort the simple Bose-Einstein picture
  - identical charged pions - Coulomb interaction
    - different methods of handling, an usual practice: Coulomb-correction
      \[ C_{B-E}(q) = K(q) \cdot C_{\text{measured}}(q) \]
    - An other possibility to fit with the effect incorporated in the fitted func.

- Resonance pions reduce the correlation function
  \[ S = S_C + S_H \]

- Primordial pions - Core < 10 fm
- Resonance pions - from very far regions - Halo

The out-side-long system, HBT radii

- Corr. func. (with Gaussian source): \( C_2(q) = 1 + \lambda \cdot e^{-R_{\mu\nu}^2 q^\mu q^\nu} \)

- Bertsch-Pratt pair coordinate-system
  - out direction: direction of the average transverse momentum \((K_t)\)
  - long direction: beam direction (z axis)
  - side direction: orthogonal to the latter two

- LCMS system (Lorentz boost in the long direction)

- From the \( R_{\mu\nu}^2 \) matrix, \( R_{out}, R_{side}, R_{long} \) nonzero - HBT radii

- Out-side difference - \( \Delta T \) emission duration

- From a simple hydro calculation:

  \[
  R_{out}^2 = \frac{R^2}{1 + \frac{m_T}{T_0} \beta_T^2} + \beta_T^2 \Delta T^2 \\
  R_{side}^2 = \frac{R^2}{1 + \frac{m_T}{T_0} \beta_T^2}
  \]

- RHIC: ratio is near one → no strong 1st order phase trans.

Comparison of charged pion and kaon femtoscopy
PHENIX Collaboration, PhysRevC.92.034914

Dataset used for the analysis:
- Run-7, Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $4.2 \cdot 10^9$ events
- Min. bias trigger, at least two hits in each BBC required
- Additional offline requirements:
  - One ZDC hit on each side
  - Collision vertex position less than $\pm 30$ cm
- Single track cuts:
  - $2\sigma$ matching cuts in PC3 & PbSc for pions
  - $2.5\sigma$ matching cuts in PC3 & PbSc for kaons
- Particle identification:
  - time-of-flight data from PbSc west, momentum, flight length
  - $2\sigma$ cuts on $m^2$ distribution
  - $\pi/K$ separation up to $\sim 1$ GeV/c
- Pair-cuts:
  - Pairs associated with hits on the same tower were removed
  - $(\Delta \phi^\pi > 0.07)$ or $(\Delta z^\pi > 5 \text{ cm} \& \Delta \phi^\pi > 0.02)$ or $(\Delta z^\pi > 70 \text{ cm})$
  - $(\Delta \phi^K > 0.04)$ or $(\Delta z^K > 4 \text{ cm} \& \Delta \phi^K > 0.01)$ or $(\Delta z^K > 65 \text{ cm})$
Both azimuthal-dependent and azimuthally integrated analysis (We only have time for the latter one)

Fitted function:

\[ C_2(q) = N[\lambda(1 + G(q))F_C + (1 - \lambda)] \]

\[ G(q) = e^{-R_s^2q_s^2 - R_o^2q_o^2 - R_l^2q_l^2} \left( e^{-2R_{os}q_sq_o} \right) \]
Comparison of charged pion and kaon femtoscopy

PHENIX Collaboration, PhysRevC.92.034914

- $R_s$ comparable
- $R_o, R_l$ different
- $\pi^+\pi^+, \pi^-\pi^-$ consistent
- Radii from PHENIX and STAR in agreement
- Greater difference in $\lambda$
- Comparison with HKM
Comparison of charged pion and kaon femtoscopy

PHENIX Collaboration, PhysRevC.92.034914

- Radii scale better for $k_T$
- Longer emission duration for kaons?
Beam energy & system size dependence of HBT radii


- $\pi^+\pi^+$, $\pi^-\pi^-$ data combined
- $1/\sqrt{m_T}$ transverse mass scaling of HBT radii
- Linear dependence for all systems and directions
- Interpolation to common $m_T$, PHENIX and STAR consistent

![Graphs showing HBT results](image-url)
quantities related to emission duration and expansion velocity

- non-monotonic patterns
- indication of CEP?

- More precise mapping and further detailed studies required
- Is there any other way to find the critical point?
- Maybe Levy exponent $\alpha$!
Ongoing work: PHENIX Levy HBT analysis & future plans

A brief overview

**Dataset:**
- \( \sqrt{S_{NN}} = 200 \text{ GeV Au+Au, min. bias, more than 7 billion events} \)
- Huge statistics, fine \( p_T \) binning possible

**Goal:**
- Detailed shape analysis of 1D two-pion corr. func.
  - Levy source instead of Gauss \( \rightarrow \) better agreement with data
  - Levy source instead of Gauss \( \rightarrow \) better agreement with data
- Extraction and analysis of the source parameters
  - Precision measurement of \( \lambda(m_T), \alpha_{Levy}(m_T), R_{Levy}(m_T) \)
Ongoing work: PHENIX Levy HBT analysis & future plans

The physics case behind the results

- Measurement of $\alpha_{\text{Levy}}(m_T)$
  - $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy
  - Results indicate strong deviation from Gaussian ($\alpha \simeq 1.15$)
  - $\alpha_{\text{Levy}}$ actually identical to critical exponent $\eta$
  - At the critical point: $\eta = 0.5$
  - Change in $\alpha_{\text{Levy}}$ related to the proximity of CEP
  - Plan: repeating the measurements at lower energies
  - A possible way of finding the Critical End Point?

Csörgő, arXiv:0903.0669 [nucl-th]
Recent PHENIX HBT results:

- Comparison of charged pion and kaon femtoscopy - PhysRevC.92.034914
  - 200 GeV Au+Au, Gaussian fits, azimuthally dep./int. analysis
  - $m_T$ scaling holds well for $R_s$
  - visible differences for $R_o$, $R_l$ between pions & kaons
  - differences larger in more central collisions
  - $k_T$ scaling works well for all radii
  - $R_o/R_s$ is larger for kaons → different $\Delta \tau$?

- Beam energy & system size dependence of HBT radii
  - $1/\sqrt{m_T}$ transverse mass scaling of HBT radii
  - Linear dependence for all systems and directions, PHENIX & STAR consistent
  - Specific combinations of radii vs. $\sqrt{s_{NN}}$ show non-monotonic behaviour
  - Indication of CEP? - further detailed studies required
Summary II

- Ongoing work: Levy HBT analysis
  - Dataset: Run-10 200 GeV Au+Au, ~7 billion evts.
  - Goal: precise measurement of Levy source parameters
  - Future plans: 3 pion correlations, lower energies
  - Expected physics info: mass modifications, partial coherence, CEP

Thank you for your attention!