PHENIX results on Levy analysis of Bose-Einstein correlation functions

Zimányi Winter School on Heavy Ion Physics

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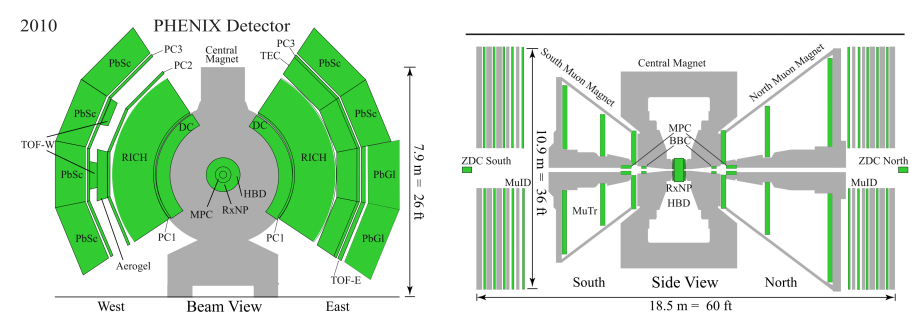
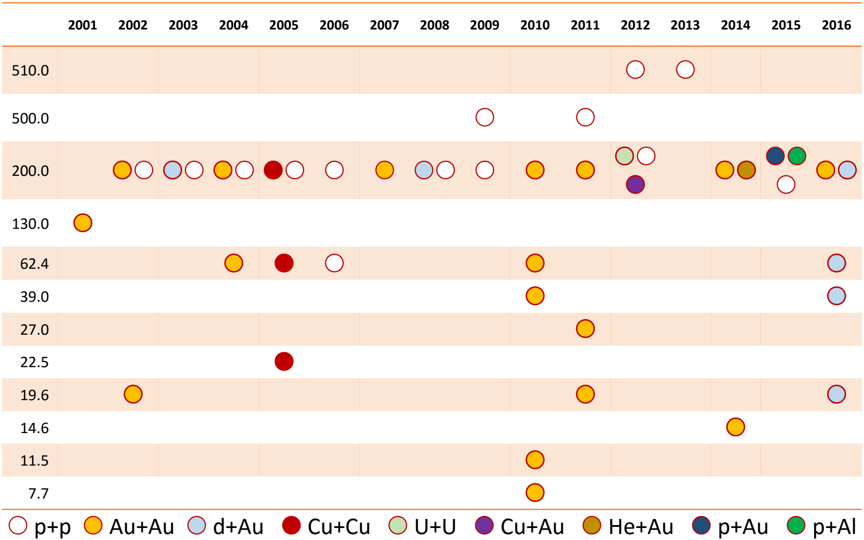
The PHENIX Experiment



The PHENIX detector system

- Observing collisions of p, d, Cu, Au, Al, He, U
- Charged pion ID from $\sim$ 0.2 to 2 GeV/c
- Beam energy scan is important

The RHIC Beam Energy Scan



See details at http://www.rhichome.bnl.gov/RHIC/Runs/

Introduction to Bose-Einstein correlations

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

$$C_2(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)} \quad (1)$$

The invariant momentum distributions

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

- $S(x, p)$ source func. (usually assumed to be Gaussian - Lévy is more general)
- Ψ_2 - interaction free case - $|\Psi_2|^2 = 1 + \cos(qx)$

$$x = x_1 - x_2$$
$$q = k_1 - k_2$$
$$K = (k_1 + k_2)/2$$

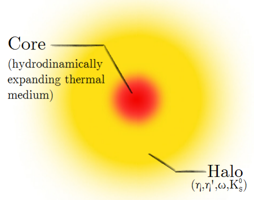
If $k_1 \simeq k_2$: $C_2 \to$ inverse Fourier-trf. $\to S$

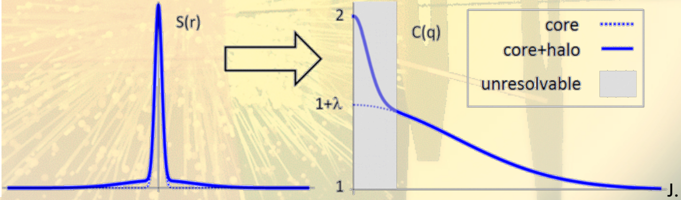
$$C_2(q, K) \simeq 1 + \left|\frac{\tilde{S}(q, K)}{\tilde{S}(0, K)}\right|^2, \quad \tilde{S}(q, k) = \int S(x, k)e^{iqx}d^4x$$

- Sometimes this simple formula fails (cf. experimentally observed oscillations at L3, CMS)

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
    - $C_{B\text{-}E}(q) = K(q) \cdot C_{measured}(q)$
    - 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 $\lesssim$ 10 fm
- Resonance pions - from very far regions - Halo





Bolz et al, Phys.Rev. D47 (1993) 3860-3870
T. Csörgő. B. Lörstad and J. Zimányi, Z.Phys. C71 (1996) 491-497

The out-side-long system, HBT radii

- Corr. func. (with Gaussian source): $C_2(q) = 1 + \lambda \cdot e^{-R^2_{\mu\nu} q^\mu q^\nu}$
- 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 $R^2_{\mu\nu}$ matrix, $R_{out}, R_{side}, R_{long}$ nonzero - HBT radii
- Out-side difference - $\Delta\tau$ emission duration
- From a simple hydro calculation:

$$R^2_{out} = \frac{R^2}{1 + \frac{m_T}{T_0} u_T^2} + \beta_T^2 \Delta\tau^2 \qquad R^2_{side} = \frac{R^2}{1 + \frac{m_T}{T_0} u_T^2}$$

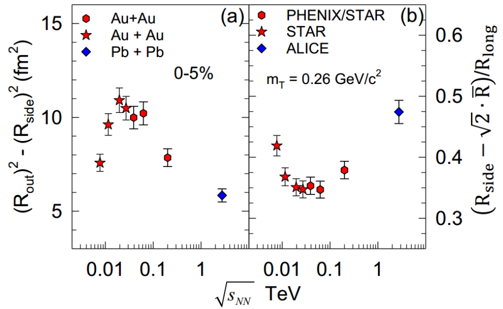
- RHIC: ratio is near one $\rightarrow$ no strong 1[st] order phase trans.

S. Chapman, P. Scotto, U. Heinz, Phys.Rev.Lett. 74 (1995) 4400-4403
T. Csörgő and B. Lörstad, Phys.Rev. C54 (1996) 1390-1403

Beam energy & system size dependence of HBT radii

PHENIX Collaboration, arXiv:1410.2559

- 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 α!

A possible way of finding the critical point

- Generalized Gaussian - Levy-distribution
  - Anomalous diffusion
  - Generalized central limit th.
  - $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy
  - Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042
  - Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828 (2006) 525, nucl-th/0512060
  - Csörgő, PoS HIGH-pTLHC08:027 (2008), nucl-th/0903.0669

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

- Shape of the correlation functions with Levy source:

$$C_2(|k|) = 1 + \lambda \cdot e^{-(2R|k|)^\alpha}$$

$\alpha = 2$: Gaussian

$\alpha = 1$: Exponential

- Critical behaviour $\rightarrow$ described by critical exponents
- Spatial corr. $\propto r^{-(d-2+\eta)}$ $\rightarrow$ defines η exponent
- Symmetric stable distributions (Levy) $\rightarrow$ spatial corr. $\propto r^{-1-\alpha}$
- α identical to critical exponent η

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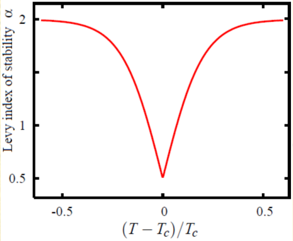
A possible way of finding the critical point

- QCD universality class $\leftrightarrow$ 3D Ising
  - Halasz et al., Phys.Rev.D58 (1998) 096007, hep-ph/9804290
  - Stephanov et al., Phys.Rev.Lett.81 (1998) 4816, hep-ph/9806219
- At the critical point:
  - random field 3D Ising: $\eta = 0.50 \pm 0.05$
    - Rieger, Phys.Rev.B52 (1995) 6659, cond-mat/9503041
  - 3D Ising: $\eta = 0.03631(3)$
    - El-Showk et al., J.Stat.Phys.157 (4-5): 869, hep-th/1403.4545
- Change in $\alpha_{\text{Levy}} \leftrightarrow$ proximity of CEP
- Motivation for precise Levy HBT!

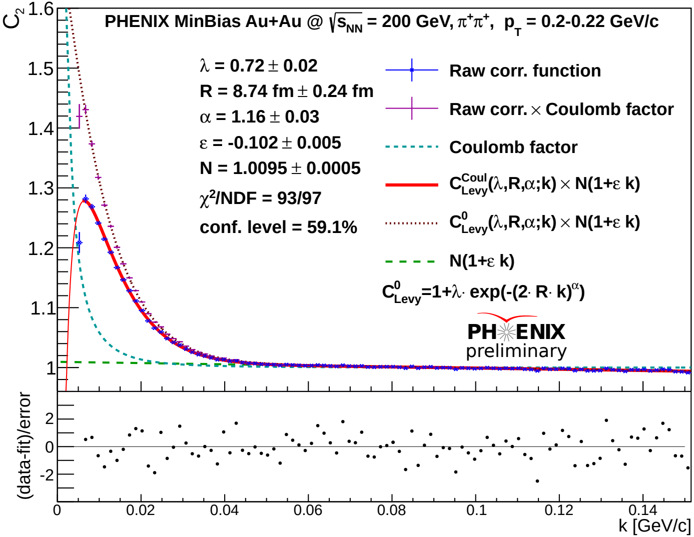


PHENIX Levy HBT analysis

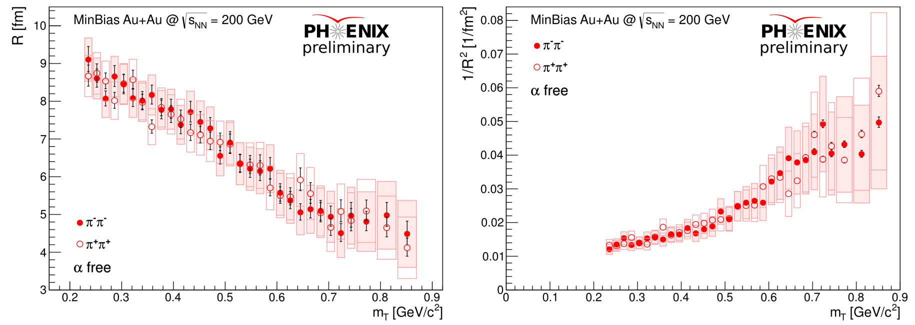
A brief overview

- Dataset:
  - $\sqrt{s_{NN}}$=200 GeV Au+Au, min. bias, $\sim$7 billion events$\rightarrow$fine p_T binning
- Goal:
  - Detailed shape analysis of 1D two-pion corr. func.
    - Levy source instead of Gaussian $\rightarrow$ better agreement with data
  - Extraction and analysis of the source parameters
    - Precision measurement of $\lambda(m_T), \alpha_{Levy}(m_T), R_{Levy}(m_T)$
    - Lot of new physics in these results
    - Search for CEP $\rightarrow$ lower energies

An example correlation function

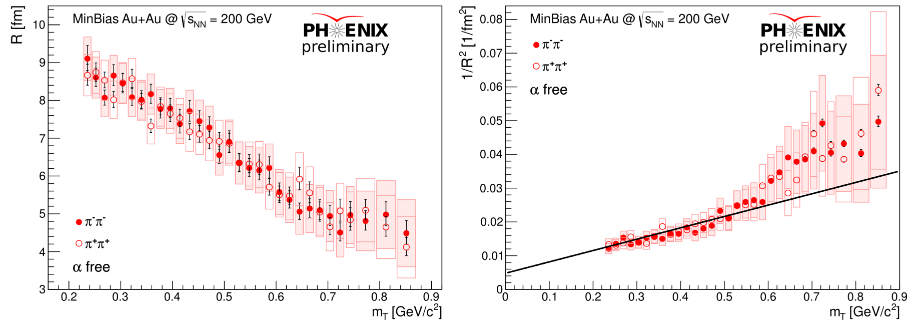


Levy scale parameter R



- Similar decreasing trend as HBT radii
- Hydro behaviour not invalid
- Hard to say whether the $1/R^2$ scaling is linear or not

Levy scale parameter R



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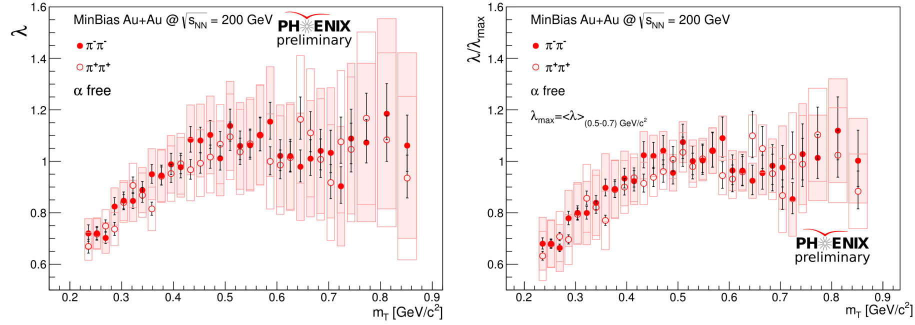
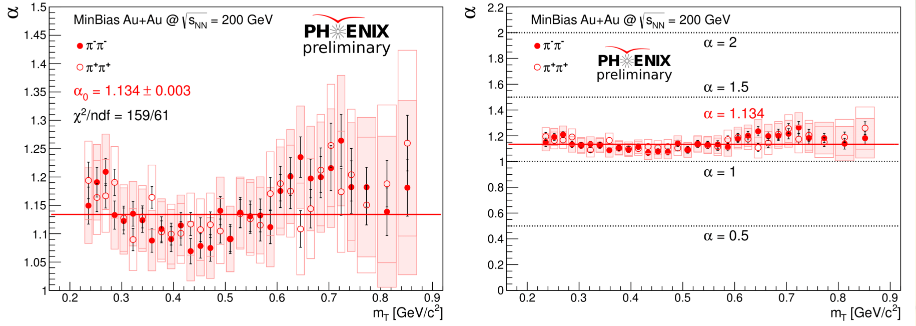
Correlation strength λ



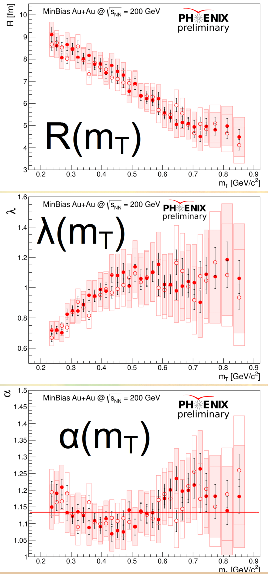
- From the Core-Halo model: $\lambda = \left(\frac{N_C}{N_C+N_H}\right)^2$
- Observed decrease at small $m_T \to$ increase of halo fraction
- Different effects can cause change in λ
  - Resonance effects
  - Partial coherence of the fireball
- Precise measurement is important

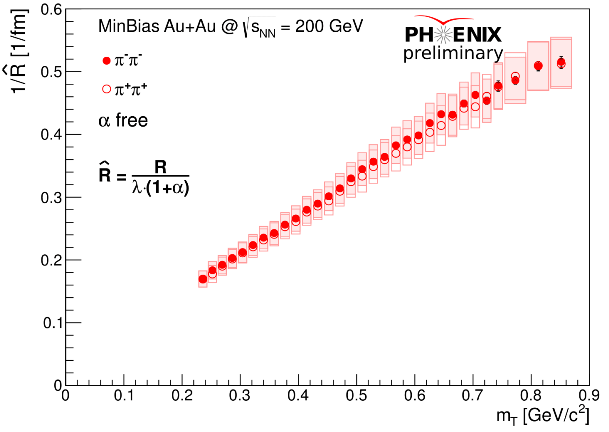
Levy exponent α



- The measured value is far from Gaussian ($\alpha = 2$) and expo. ($\alpha = 1$)
- Also far from the rfd.3D Ising value at CEP ($\alpha = 0.5$)
- More or less constant (at least within systematic errors)
- Although the constant fit is statistically not acceptable
- Motivation to do fits with fixed $\alpha = 1.134$

Newly discovered scaling parameter $\widehat{R}$





- Empirically found scaling parameter
- Linear in m_T
- Physical interpretation → open question

Summary

- PHENIX Levy HBT analysis preliminary results:
  - Dataset: Run-10 200 GeV Au+Au, $\sim$7 billion evts.
  - Precise measurement of Levy source parameters (R, λ, α)
  - New empirically found scaling parameter $\left(\widehat{R}\right)$
  - Future plans: lower energies, 3 pion corr., pion-kaon comparison
  - Expected physics info: CEP, partial coherence, resonance effects

Thank you for your attention!