

PHENIX results on Levy analysis of Bose-Einstein correlation functions

Critical Point and Onset of Deconfinement, Wroclaw 2016

Dániel Kincses for the PHENIX Collaboration

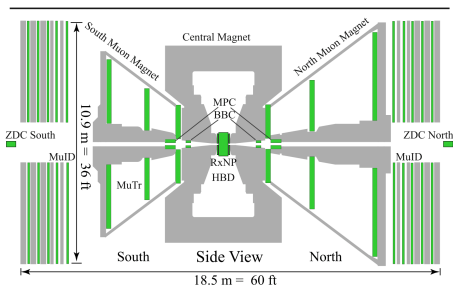
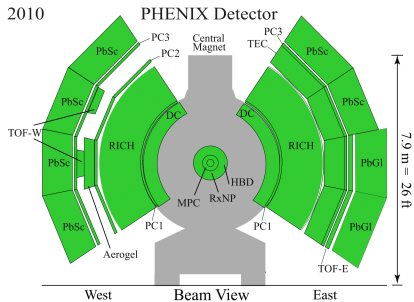
Eötvös Loránd University, Hungary



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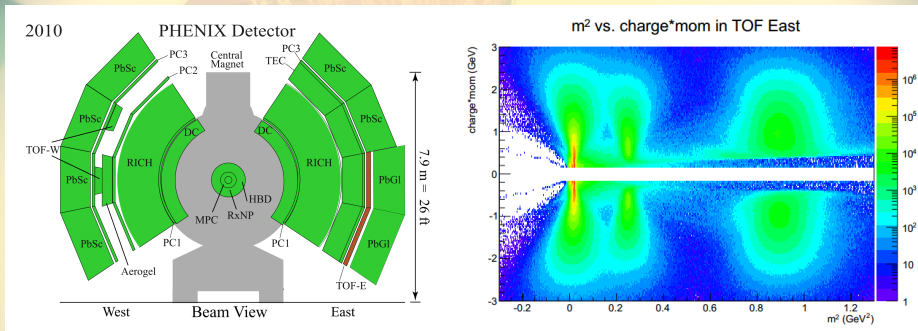
The PHENIX Experiment



The PHENIX detector system

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

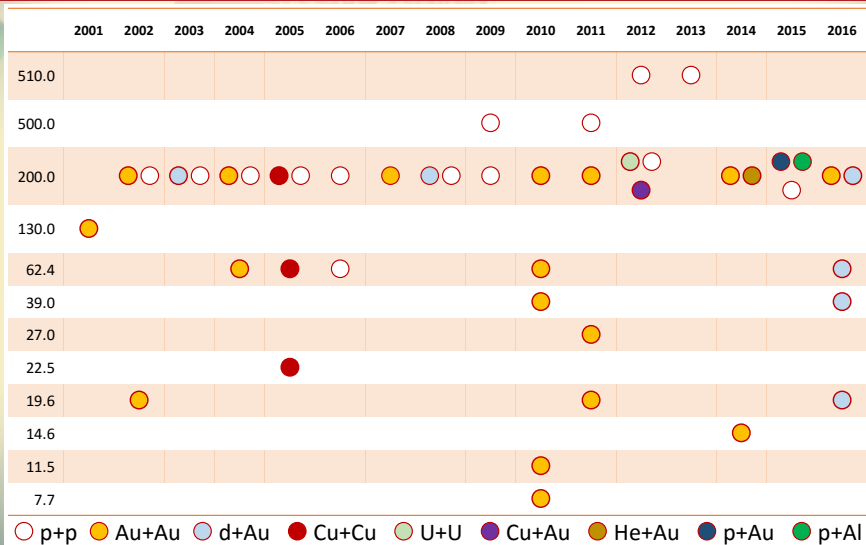
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The RHIC Beam Energy Scan



○ p+p ● Au+Au ○ d+Au ● Cu+Cu ○ U+U ● Cu+Au ● He+Au ● p+Au ● p+Al

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 - $|\Psi_2|^2 = 1 + \cos(qx)$

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

$$x = x_1 - x_2$$

$$q = k_1 - k_2$$

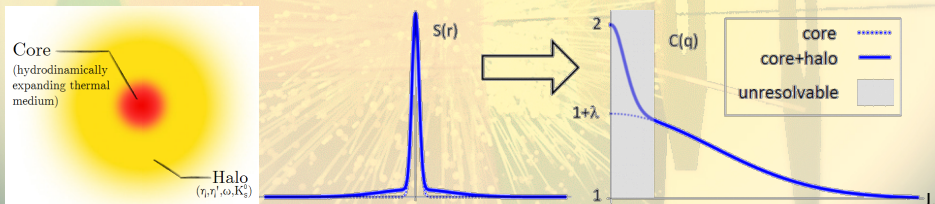
$$K = (k_1 + k_2)/2$$

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

- ▶ 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
 - ▶ $C_{B-E}(q) = K(q) \cdot C_{measured}(q)$
 - ▶ 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): $C_2(\mathbf{q}) = 1 + \lambda \cdot e^{-R_{\mu\nu}^2 q^\mu q^\nu}$
- ▶ 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 - $\Delta\tau$ emission duration
- ▶ From a simple hydro calculation:

$$R_{out}^2 = \frac{R^2}{1 + \frac{m_T}{T_0} \beta_T^2} + \beta_T^2 \Delta\tau^2 \quad R_{side}^2 = \frac{R^2}{1 + \frac{m_T}{T_0} \beta_T^2}$$

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

S. Chapman, P. Scotto, U. Heinz, Phys.Rev.Lett. 74 (1995) 4400-4403

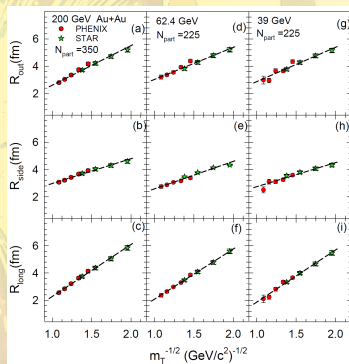
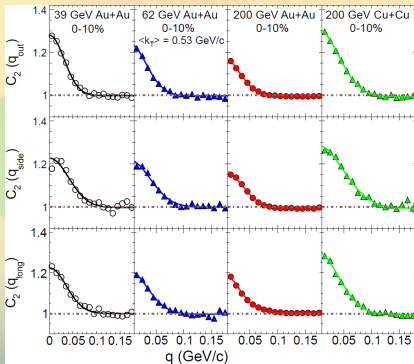
T. Csörgő and B. Lörstad, Phys.Rev. C54 (1996) 1390-1403



Beam energy & system size dependence of HBT radii

PHENIX Collaboration, arXiv:1410.2559

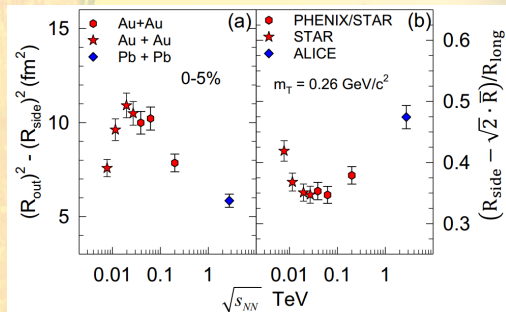
- ▶ Corr. func. in 3D, Gaussian fit (details: arXiv:1410.2559)
- ▶ $\pi^+\pi^+$, $\pi^-\pi^-$ data combined
- ▶ Linear $1/\sqrt{m_T}$ scaling of HBT radii
- ▶ Interpolation to common m_T , PHENIX and STAR consistent



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-pTLC08:027 (2008), nucl-th/0903.0669

$$\left. \begin{array}{l} \text{▶ Anomalous diffusion} \\ \text{▶ Generalized central limit th.} \end{array} \right\} \mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$$

▶ Shape of the correlation functions with Levy source:

$$C_2(|k|) = 1 + \lambda \cdot e^{-(2R|k|)^\alpha} \quad \begin{array}{l} \alpha = 2 : \text{Gaussian} \\ \alpha = 1 : \text{Exponential} \end{array}$$

▶ 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

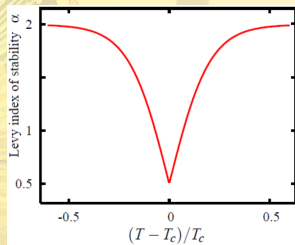
- ▶ Halasz et al., Phys.Rev.D58 (1998) 096007, hep-ph/9804290
- ▶ Stephanov et al., Phys.Rev.Lett.81 (1998) 4816, hep-ph/9806219

▶ 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 α_{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, ~ 7 billion events \rightarrow fine p_T binning

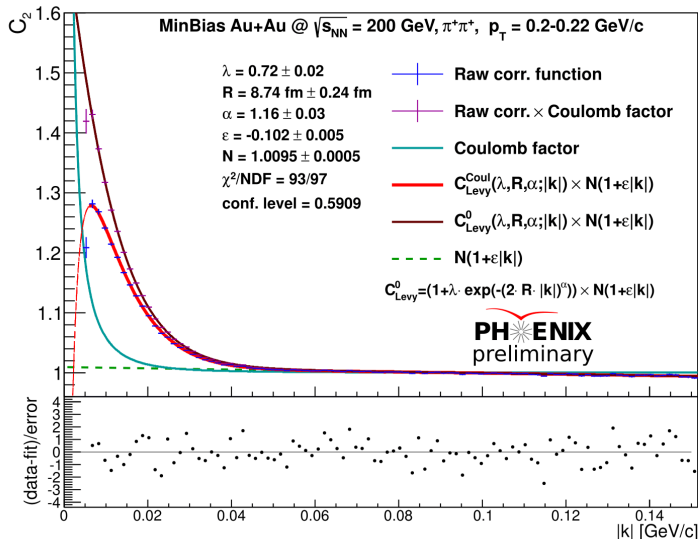
▶ Goal:

- ▶ 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

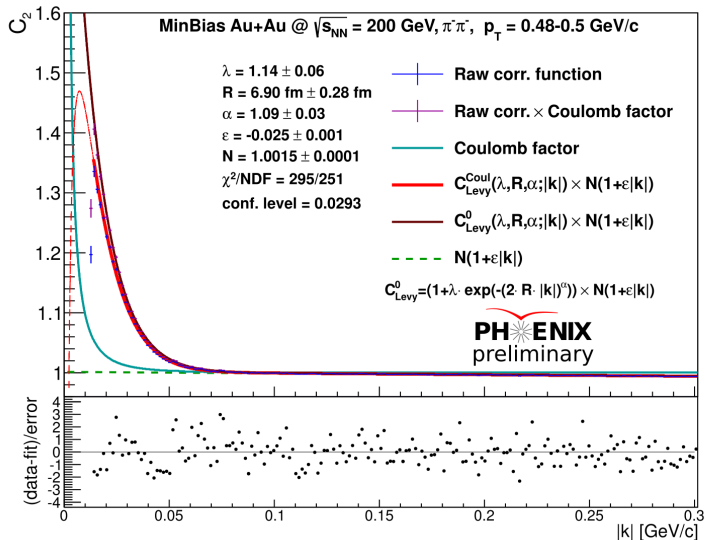
The basics of the analysis

- ▶ Dataset used for the analysis:
 - ▶ Run-10, Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $7.3 \cdot 10^9$ events
 - ▶ Min. bias trigger
 - ▶ Additional offline requirements:
 - ▶ Collision vertex position less than ± 30 cm
 - ▶ Single track cuts:
 - ▶ 2σ matching cuts in TOF & PbSc for pions
 - ▶ Particle identification:
 - ▶ time-of-flight data from PbSc e/w, TOF e/w, momentum, flight length
 - ▶ 2σ cuts on m^2 distribution
 - ▶ 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
- ▶ Fit method
 - ▶ Levy fits for 31 p_T bins with Coulomb effect incorporated

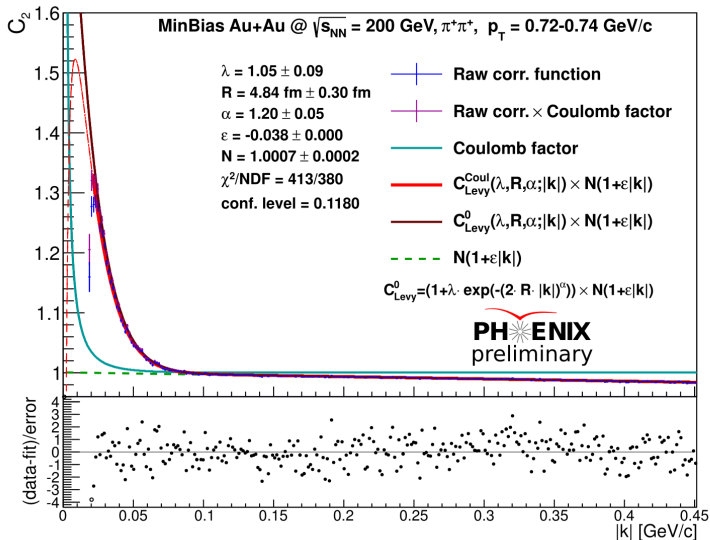
Example correlation functions



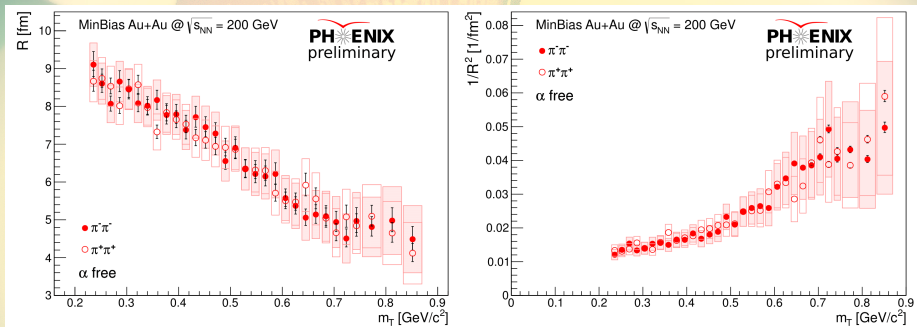
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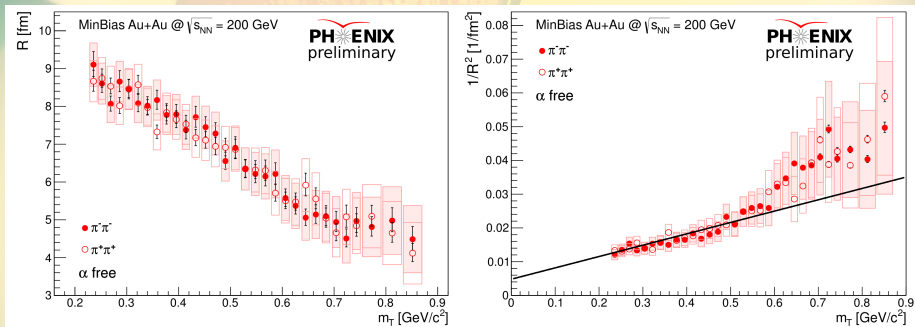


Levy scale parameter R



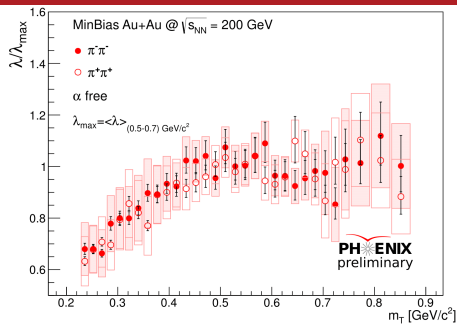
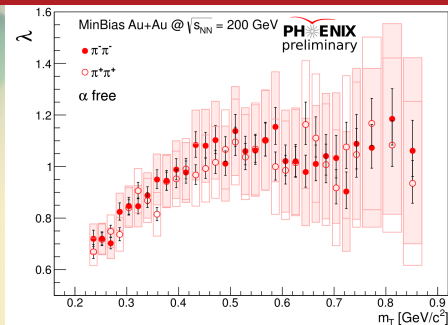
- ▶ Similar decreasing trend as HBT radii
- ▶ Hydro behaviour not invalid
- ▶ Hard to say whether the $1/R^2$ scaling is linear or not

Levy scale parameter R



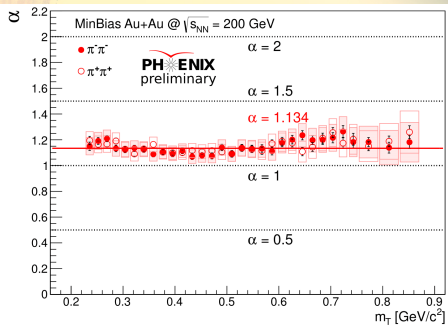
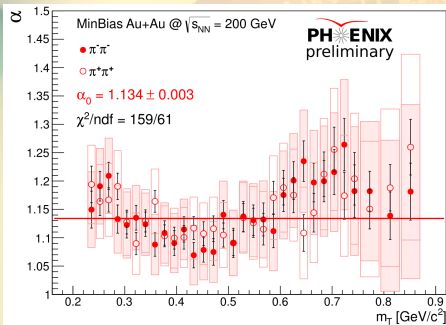
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Correlation strength λ



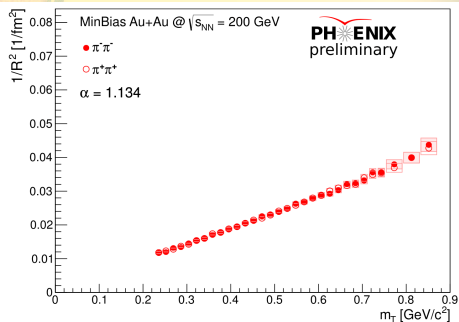
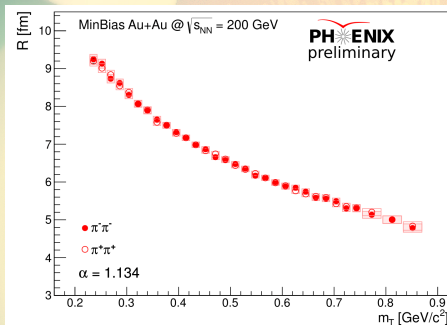
- ▶ From the Core-Halo model: $\lambda = \left(\frac{N_C}{N_C + N_H} \right)^2$
- ▶ Observed decrease at small $m_T \rightarrow$ increase of halo fraction
- ▶ Different effects can cause change in λ
 - ▶ Resonance effects
 - ▶ Partial coherence of the fireball
- ▶ Precise measurement is important

Levy exponent α



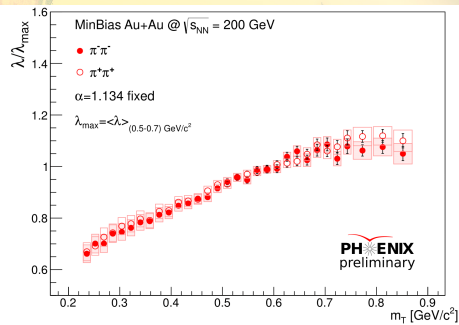
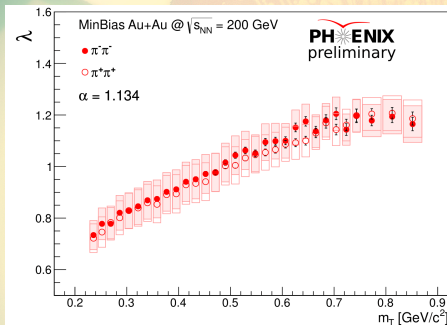
- ▶ The measured value is far from Gaussian ($\alpha = 2$) and expo. ($\alpha = 1$)
- ▶ Also far from the rfd.3D Ising value at CEP ($\alpha = 0.5$)
- ▶ More or less constant (at least within systematic errors)
- ▶ Although the constant fit is statistically not acceptable
- ▶ Motivation to do fits with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

Levy scale parameter R with fixed $\alpha = 1.134$



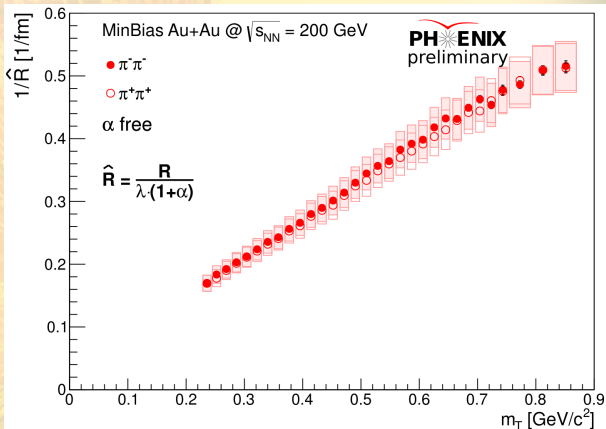
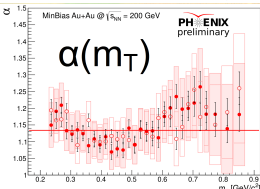
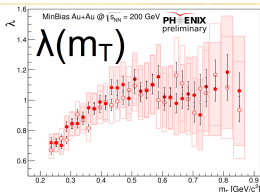
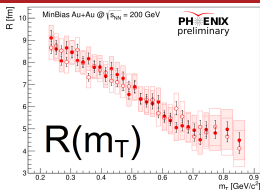
- ▶ More smooth trend
- ▶ Hydro behaviour seems to be more valid
- ▶ The linearity of $1/R^2$ holds

Correlation strength λ with fixed $\alpha = 1.134$



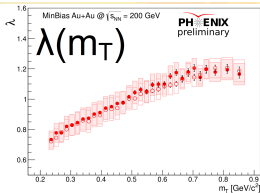
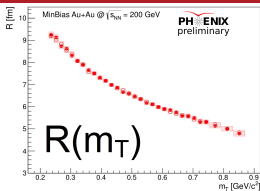
- ▶ More smooth trend
- ▶ Smaller systematic errors

Newly discovered scaling parameter \hat{R}

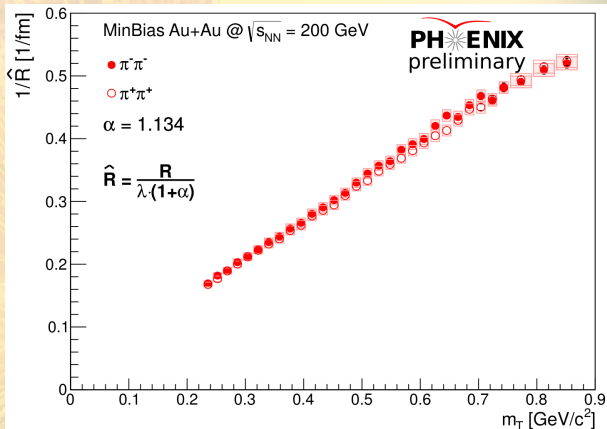


- ▶ Empirically found scaling parameter
- ▶ Linear in m_T
- ▶ Physical interpretation → open question

Newly discovered scaling parameter \hat{R}



- ▶ $\alpha = 1.134$ fixed



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

Summary I

- ▶ Earlier PHENIX HBT result:
 - ▶ 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

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

Thank you for your attention!

I would like to invite You to the 16th Zimanyi Winter School on Heavy Ion Physics
Budapest, Hungary, Dec. 5. - Dec. 9. 2016

<http://zimanyischool.kfki.hu/16/>