PHENIX results on the Lévy analysis of Bose-Einstein correlation functions

BGL 17 – 10th Bolyai-Gauss-Lobachevsky Conference

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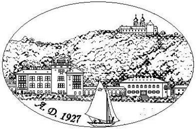
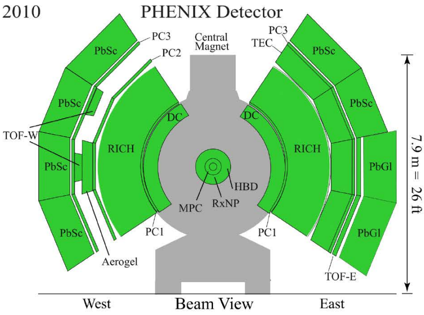
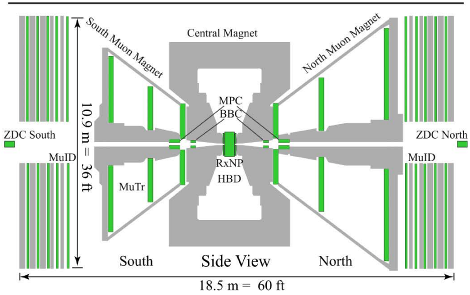


Outline

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

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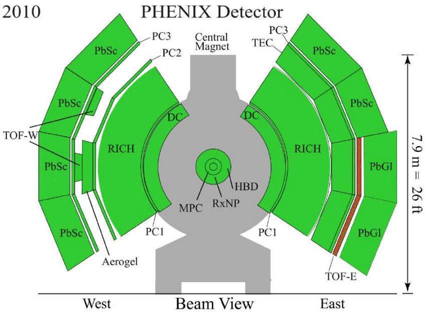

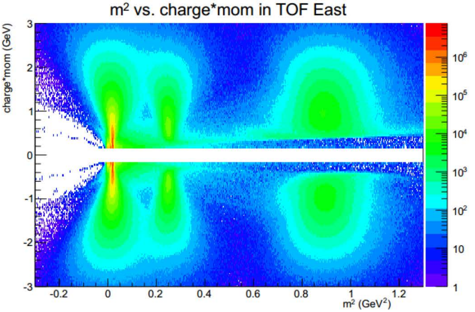

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PHENIX runs at a glance

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
510.0												p+p	p+p			
500.0									p+p		p+p					
200.0		Au+Au, p+p	d+Au, p+p	Au+Au, p+p	Cu+Cu, p+p	p+p	d+Au	(black circle), p+p	p+p	Au+Au	Au+Au	U+U, p+p, Cu+Au		Au+Au, He+Au	p+Au, p+Al, p+p	Au+Au, d+Au
130.0	Au+Au															
62.4				Au+Au	Cu+Cu	p+p				Au+Au						d+Au
39.0										Au+Au						d+Au
27.0											Au+Au					
22.5					Cu+Cu											d+Au
19.6		Au+Au									Au+Au					
14.6														Au+Au		
11.5										Au+Au						
7.7										Au+Au						
5.0								Au+Au								

○ 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/

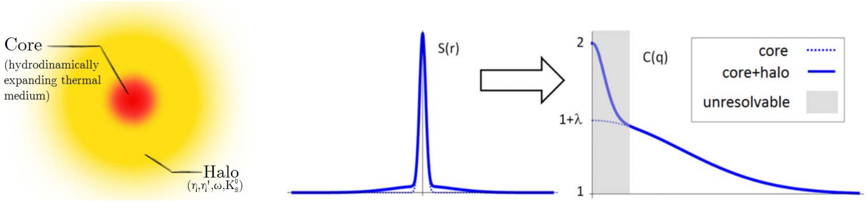
Outline

Bose-Einstein correlations in heavy ion physics

- Quantum statistics connects spatial and momentum space distributions
- Spatial source $S(x)$ versus momentum correlation function $C_2(q)$:

$$C_2(q) \simeq 1 + \left|\widetilde{S}(q)/\widetilde{S}(0)\right|^2, \ \widetilde{S}(q) = \int S(x) e^{iqx} d^4x, \ q = p_1 - p_2$$

- Final state interactions distort the simple Bose-Einstein picture
- Coulomb interaction important, handled via two-particle wave function
- Resonance pions: Halo around primordial Core



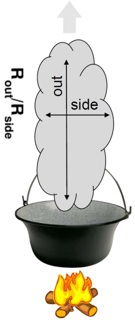
Bolz et al, Phys.Rev. D47 (1993) 3860-3870; Csörgő, Lörstad, Zimányi, Z.Phys. C71 (1996) 491-497

The out-side-long system, HBT radii

- $C(q)$ usually measured in the Bertsch-Pratt pair coordinate-system
  - out: direction of the average transverse momentum (K_t)
  - long: beam direction
  - side: orthogonal to the latter two
- $R_{out}, R_{side}, R_{long}$: HBT radii
- Out-side difference $\rightarrow$ $\Delta\tau$ emission duration
- From a simple hydro calculation:

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

$$R^2_{side} = \frac{R^2}{1+u_T^2 m_T/T_0}$$

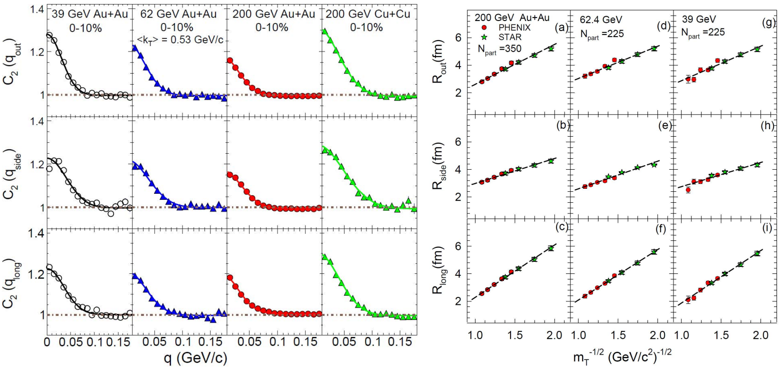


- RHIC: ratio is near one $\rightarrow$ no strong 1st order phase transition
- Plus lots of other details (pre-eq flow, initial state, EoS, ...)

S. Chapman, P. Scotto, U. Heinz, Phys.Rev.Lett. 74 (1995) 4400
T. Csörgő and B. Lörstad, Phys.Rev. C54 (1996) 1390
S. Pratt, Nucl.Phys. A830 (2009) 51C

Example: recent PHENIX HBT measurements

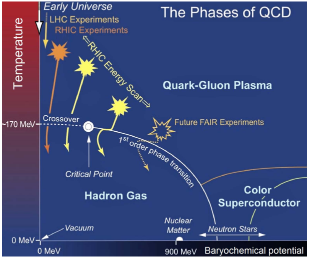
- Corr. func. in Bertsch-Pratt system, radii from Gaussian fit
- Linear $1/\sqrt{m_T}$ scaling of HBT radii for all systems and energies
- Interpolation to common m_T, PHENIX and STAR consistent



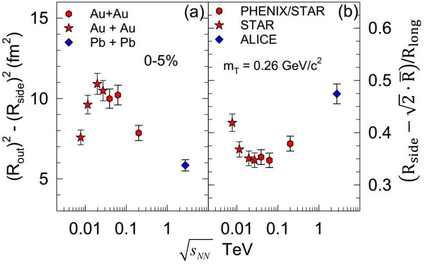
PHENIX Collaboration, arXiv:1410.2559; STAR Collaboration, arXiv:1403.4972

HBT radii and the search for the critical endpoint

- Signals of QCD CEP: softest point, long emission
- $R_o^2 - R_s^2$: related to emission duration
- $(R_s - \sqrt{2} \cdot \overline{R})/R_l$: related to expansion velocity
- Non-monotonic patterns
- Indication of the CEP?
- Further detailed studies done
  Roy Lacey, arXiv:1606.08071 & arXiv:1411.7931 (PRL114)
- Maybe Levy exponent α gives further insight?



PHENIX Collaboration, arXiv:1410.2559



Outline

Lévy distributions in heavy ion physics

- Expanding medium, increasing mean free path: anomalous diffusion

Metzler, Klafter, Physics Reports 339 (2000) 1-77, Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002

- Lévy-stable distribution: $\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$
  - Generalized Gaussian from generalized central limit theorem
  - $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy

- Shape of the correlation functions with Levy source:

$$C_2(q) = 1 + \lambda \cdot e^{-(Rq)^\alpha} \qquad \begin{array}{l} \alpha = 2 : \text{Gaussian} \\ \alpha = 1 : \text{Exponential} \end{array}$$

- 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 associated to critical exponent η

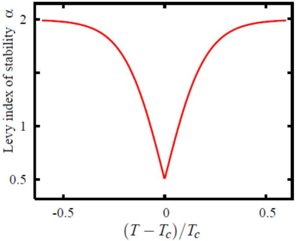
Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042

A possible way of finding the critical point

- QCD universality class $\leftrightarrow$ 3D Ising
  - Halasz et al., Phys.Rev.D58 (1998) 096007
  - Stephanov et al., Phys.Rev.Lett.81 (1998) 4816
- At the critical point:
  - random field 3D Ising: $\eta = 0.50 \pm 0.05$

    Rieger, Phys.Rev.B52 (1995) 6659
  - 3D Ising: $\eta = 0.03631(3)$

    El-Showk et al., J.Stat.Phys.157 (4-5): 869
- Modulo finite size effects
- Distance from the critical point?
- Motivation for precise Levy HBT!
- Change in $\alpha_{\rm Levy} \leftrightarrow$ proximity of CEP?
- Non-static system, finite size effects...



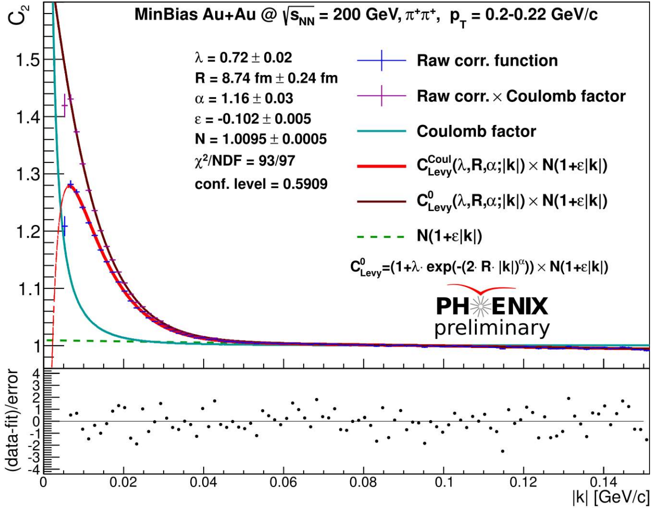
Outline

PHENIX Lévy HBT analysis

- Dataset used for the analysis:
  - Run-10, Au+Au, $\sqrt{s_{NN}} = 200$ GeV, 7.3·10^9 events
  - 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 σ cuts on m^2 distribution
  - Correlation variable $|k|_{\text{LCMS}}$: $|\mathbf{p}_1 - \mathbf{p}_2|$ in longitudinally comoving frame
  - Single track cuts:
    - 2σ 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 $|k|_{\text{LCMS}}$ in various m_T bins
  - Levy fits for 31 m_T bins (m_T in $[0.228, 0.871]$ GeV/c^2)
  - Coulomb effect incorporated in fit function

Example $C(|k|_{LCMS})$ measurement result

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



Physical parameters: R, λ, α; measured versus pair m_T

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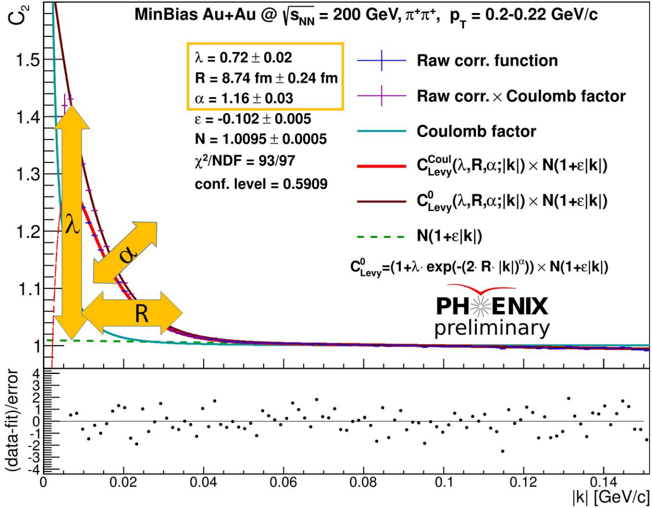

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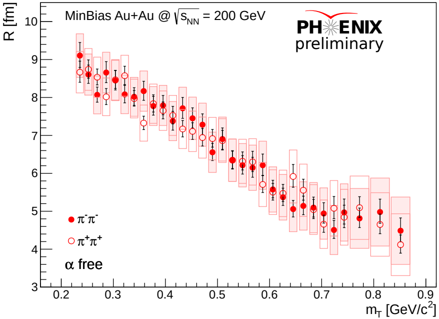
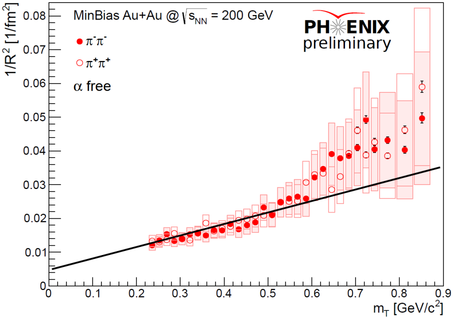
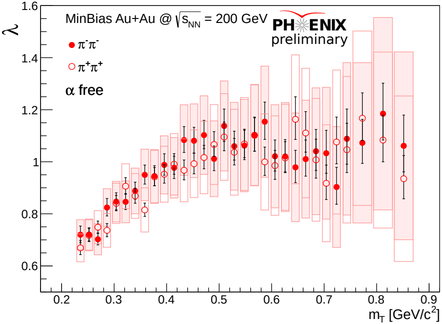
Levy scale parameter R

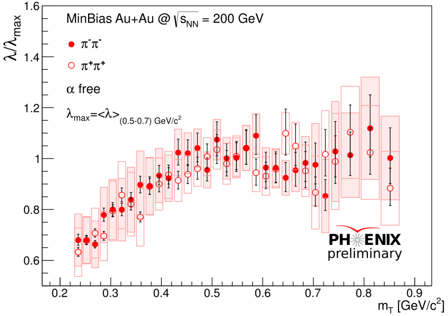




- Similar decreasing trend as Gaussian HBT radii
- Hydro predicts $1/R^2_{Gauss} = a + bm_T$
- Hydro behaviour not invalid for R_{Levy}!
- The linear scaling of $1/R^2$, breaks for high m_T

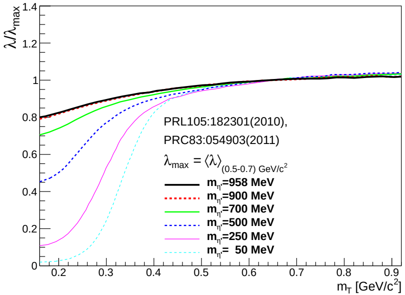
Correlation strength λ

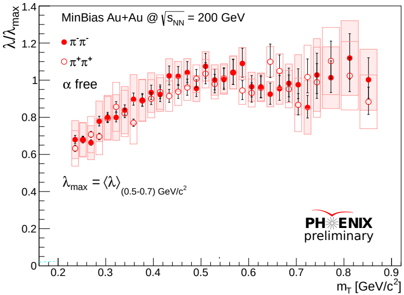




- From the Core-Halo model: $\lambda = \left(\frac{N_C}{N_C+N_H}\right)^2$
- Observed decrease ("hole") at small m_T $\rightarrow$ increase of halo fraction
- Different effects can cause change in λ
  - Resonance effects, partially coherent pion production
- $\lambda/\lambda_{\mathrm{max}}$ with smaller systematic uncertainties
- Precise measurement may help extract physics info

A possible (?) interpretation of $\lambda(m_T)$





- $\lambda(m_T)$ measures core/(core+halo) fraction
- May be connected to mass modifications (c.f. chiral restoration)
  - Decreased η' mass $\rightarrow$ η' enhancement $\rightarrow$ halo enhancement
  - Kinematics: η' decay pions will have low m_T $\rightarrow$ decreased λ at small m_T
- Incompatibility with unmodified in-medium η' mass?

Kapusta, Kharzeev, McLerran, Phys.Rev. D53 (1996) 5028, hep-ph/9507343
Vance, Csörgő, Kharzeev, Phys.Rev.Lett. 81 (1998) 2205, nucl-th/9802074
Csörgő, Vértesi, Sziklai, Phys.Rev.Lett. 105 (2010) 182301, arXiv:0912.5526

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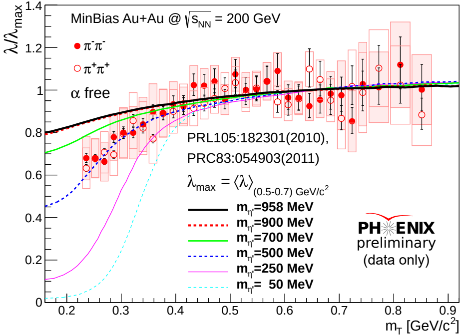

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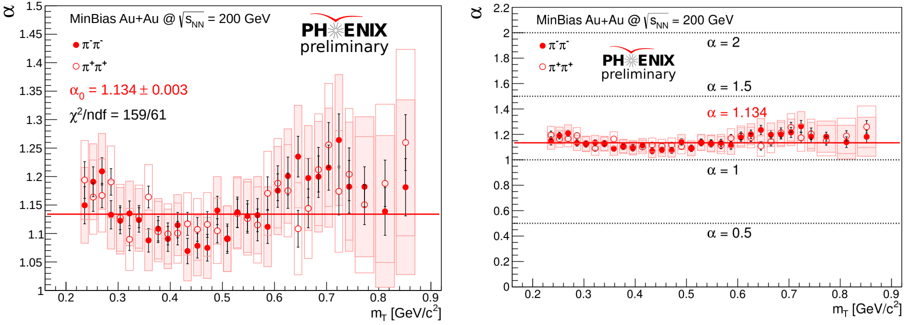
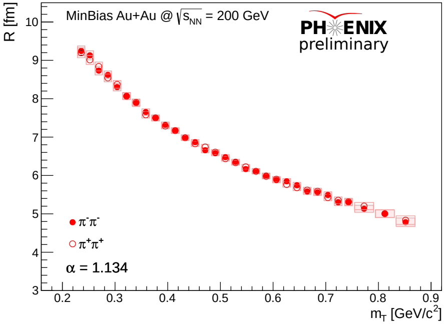
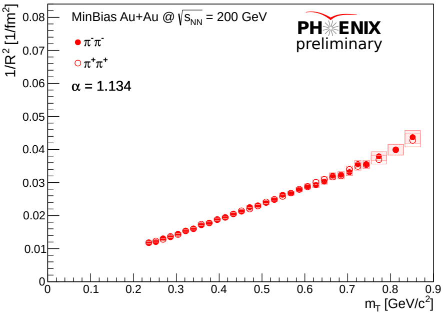
Levy exponent α



- Measured values far from Gaussian ($\alpha = 2$), also not expo. ($\alpha = 1$)
- Also far from the random field 3D Ising value at CEP ($\alpha = 0.5$)
- More or less constant (at least within systematic errors)
- Motivation to do fits with fixed $\alpha = 1.134$
- Note: $\alpha(m_T) =$ const. fit statistically not acceptable (only with syst.)

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





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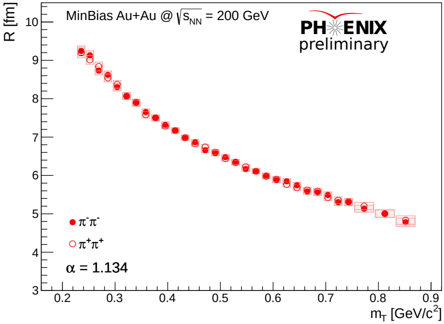
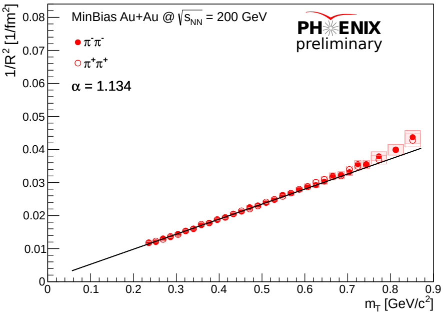
- Remarkable linearity of $1/R^2$
- Hydro behavior valid, despite $\alpha < 2$

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





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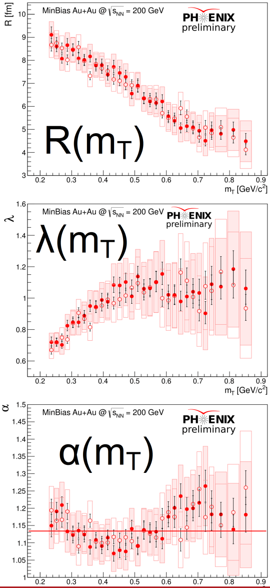
Newly discovered scaling parameter $\widehat{R}$



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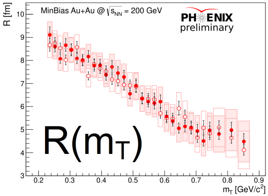

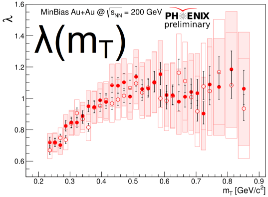

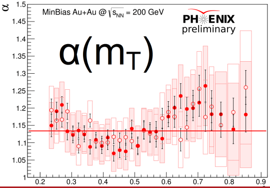

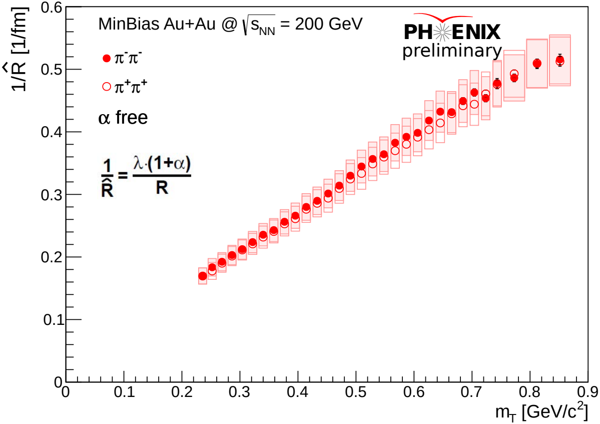

- Empirically found scaling parameter
- Linear in m_T
- Physical interpretation → open question

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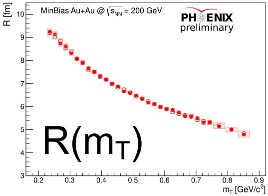
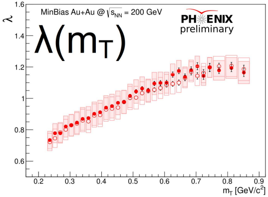
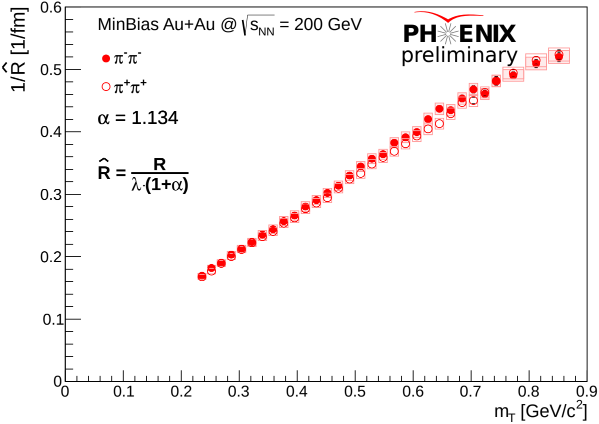




- $\alpha = 1.134$ fixed



- Empirically found scaling parameter
- Linear in m_T
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Outline

Summary

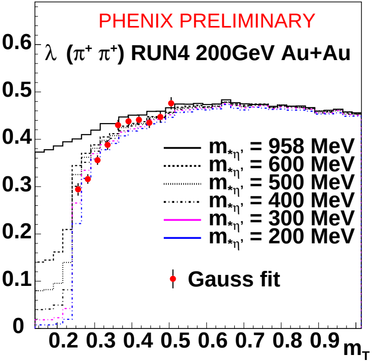
- B-E correlation functions, run-10 200 GeV Au+Au, $\sim$7 billion evts.
- Levy fits yield statistically acceptable description
- Fine m_T binned Levy source parameters (R, λ, α)
  - Nearly constant α, away from 2, 1 and 0.5 $\leftrightarrow$ distance to CEP?
  - Linear scaling of $1/R^2(m_T)$ $\leftrightarrow$ hydro?
  - Low-m_T decrease in $\lambda(m_T)$ $\leftrightarrow$ resonances, η' in-medium mass?
- New empirically found scaling parameter $\widehat{R} = R/(\lambda \cdot (1+\alpha))$

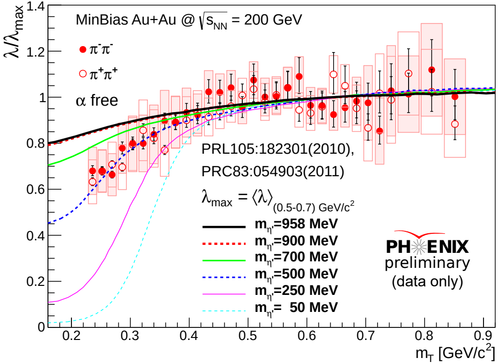
Thank you for your attention!

If you are interested in these subjects: come to the 17th Zimanyi-COST Winter School
Budapest, Hungary, Dec. 4. - Dec. 8. 2017
`http://zimanyischool.kfki.hu/17/`

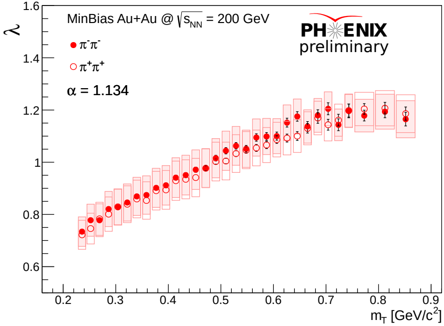
Outline

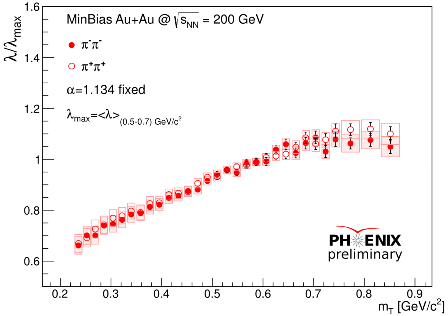
Run4 preliminary&Gauss → Run10 preliminary&Lévy





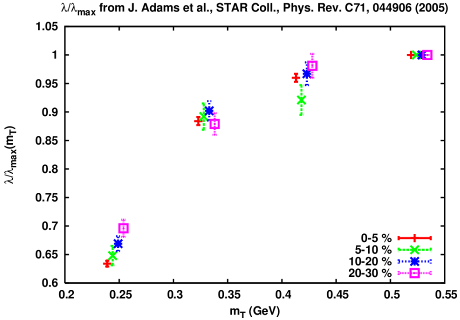
Correlation strength λ with fixed $\alpha = 1.134$

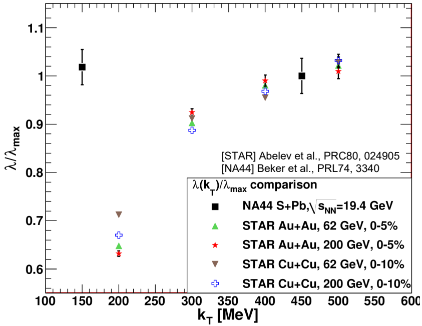




- More smooth trend
- Smaller systematic errors
- Saturation at large m_T
- Decrease ("hole") for smaller m_T values

Low energy comparison





STAR centrality dependent results (left) and the comparison of STAR results in different energye with NA44 data (right)

Lévy source function and kinematic variables

- Basic two-particle variables

$$K^\mu = \frac{p_1^\mu + p_2^\mu}{2}, \qquad q^\mu = p_1^\mu - p_2^\mu, \qquad q_{inv} = \sqrt{-q^\mu q_\mu} \tag{1}$$

- $C_2(q_{inv})$ - 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
- Anomalous diffusion, generalized central limit theorem: Levy

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

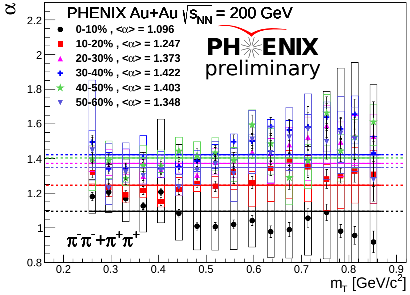
$$S(r) = (1-\sqrt{\lambda})\mathcal{L}(\alpha, R_H, r) + \sqrt{\lambda} \cdot \mathcal{L}(\alpha, R_C, r) \tag{3}$$

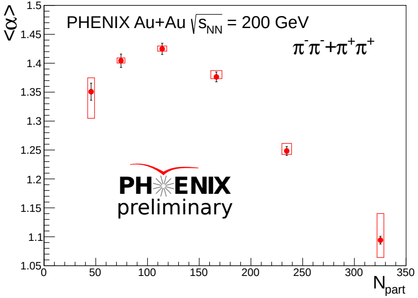
- Shape of the correlation functions with Levy source ($R_H \to \infty$):

$$C_2(|k|) = 1 + \lambda \cdot e^{-(2R|k|)^\alpha} \tag{4}$$

Lévy exponent α at 200 GeV

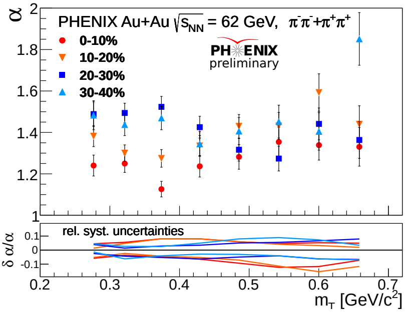
- Slightly non-monotonic behavior as a function of m_T
- Average $\langle\alpha\rangle$ non-monotonic behavior versus N_{part}
- $\alpha = \langle\alpha\rangle$ constant fits were performed

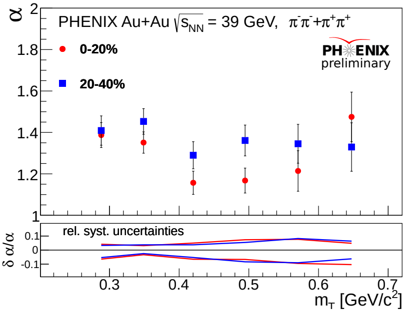




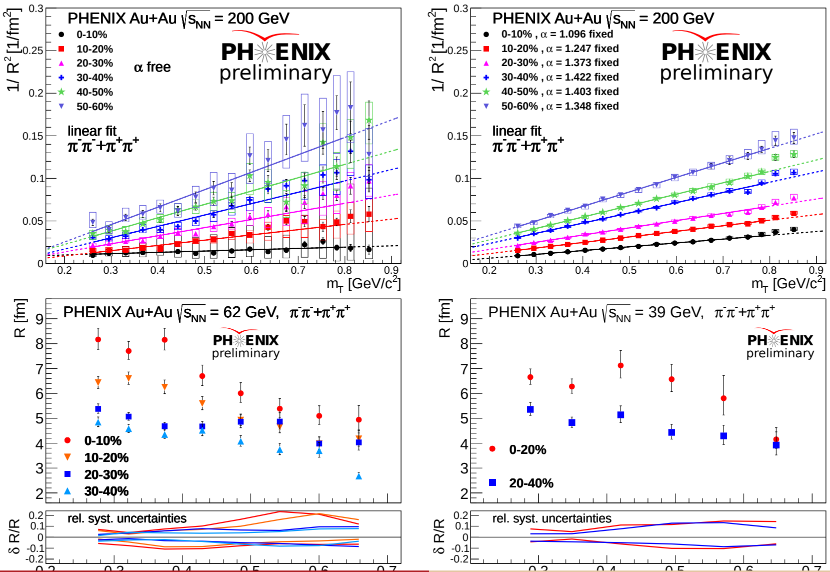
Lévy exponent α at 62 and 39 GeV

- Lévy exponent α: no significant change vs $\sqrt{s_{NN}}$ at 39-62-200 GeV
- Usual values between 1 and 1.5
- Non-monotonicity in m_T

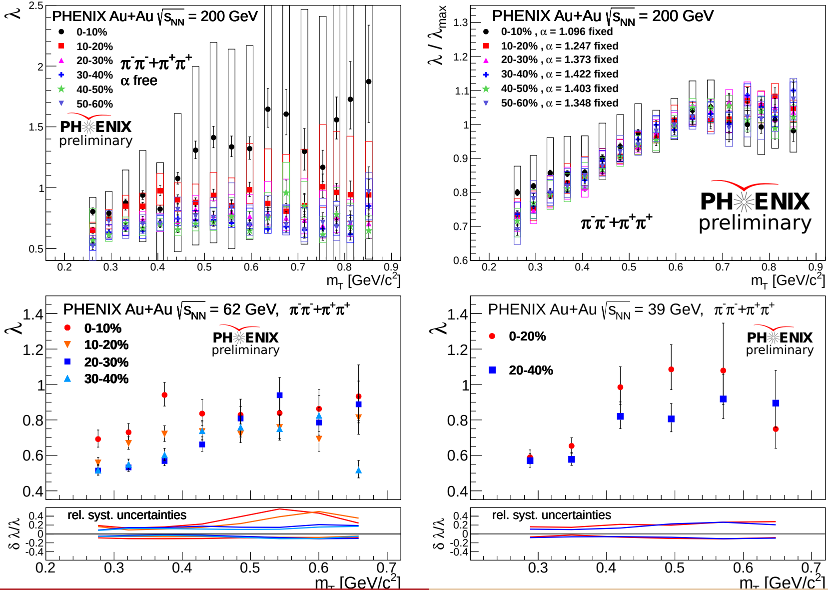




Lévy scale R: similar trends for all $\sqrt{s_{NN}}$ and cent.



“Hole” in λ: all energies and centralities



$\hat{R}$ scaling for all energies & centralities