

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

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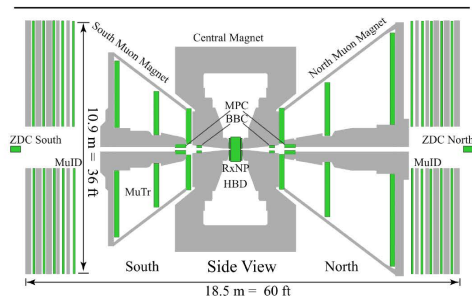
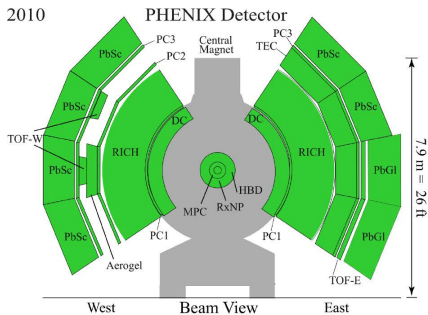


Outline

- 1 The PHENIX experiment
- 2 Bose-Einstein correlations
- 3 PHENIX Lévy HBT results
- 4 Summary

The PHENIX Experiment

2010

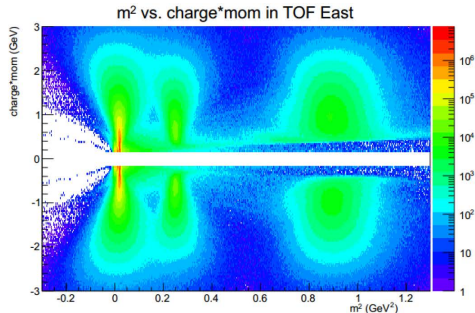
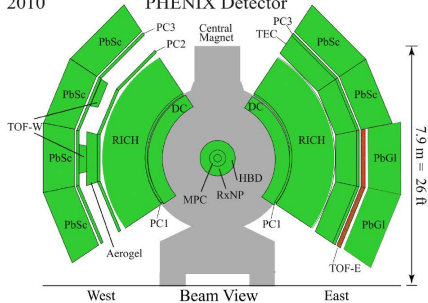


- ▶ Versatile detector, operating until 2016
- ▶ Tracking via Drift Chambers and Pad Chambers
- ▶ Charged pion ID with TOF, from ~ 0.2 to 2 GeV/c
- ▶ This analysis: PID also with EMCal

The PHENIX Experiment

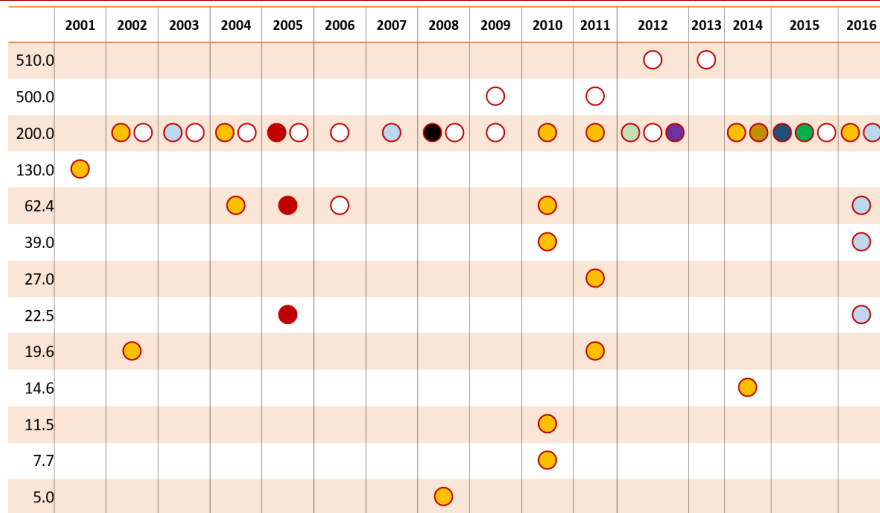
2010

PHENIX Detector



- ▶ Versatile detector, operating until 2016
- ▶ Tracking via Drift Chambers and Pad Chambers
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PHENIX runs at a glance



○ 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

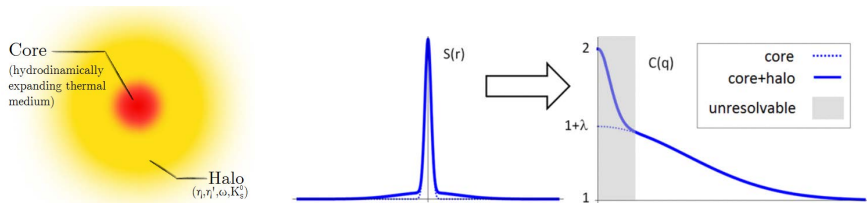
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Bose-Einstein correlations in heavy ion physics

- ▶ Everyone here knows this part, but ...
- ▶ Quantum statistics connects spatial and momentum space distributions
- ▶ Spatial source $S(x)$ versus momentum correlation function $C_2(q)$:

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

- ▶ 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

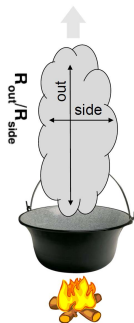
The out-side-long system, HBT radii

- ▶ $C(q)$ 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:

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

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

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



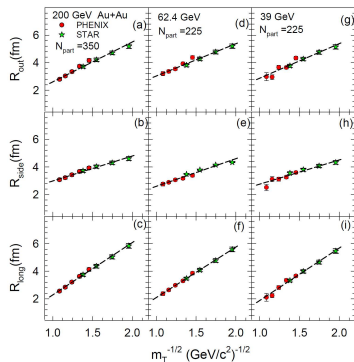
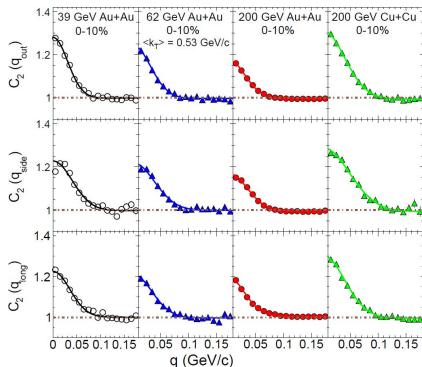
S. Chapman, P. Scotto, U. Heinz, Phys.Rev.Lett. 74 (1995) 4400

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

S. Pratt, Nucl.Phys. A830 (2009) 51C

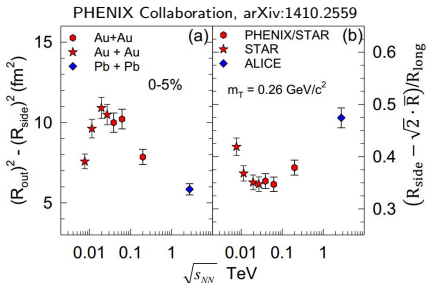
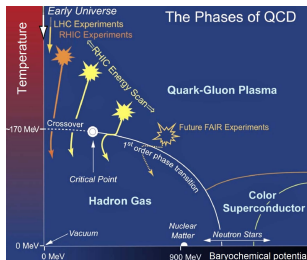
Example: recent PHENIX HBT measurements

- ▶ Corr. func. in BP 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



HBT radii and the search for the critical endpoint

- ▶ Signals of QCD CEP: softest point, long emission
- ▶ $R_0^2 - R_s^2$: related to emission duration
- ▶ $(R_s - \sqrt{2} \cdot \bar{R})/R_l$: 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?



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

- ▶ Shape of the correlation functions with Levy source:

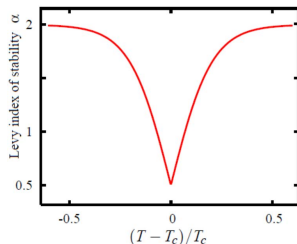
$$C_2(q) = 1 + \lambda \cdot e^{-(Rq)^\alpha} \quad \begin{array}{l} \alpha = 2 : \text{Gaussian} \\ \alpha = 1 : \text{Exponential} \end{array}$$

- ▶ 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

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 Lévy HBT!
- ▶ Change in $\alpha_{\text{Lévy}} \leftrightarrow$ proximity of CEP?

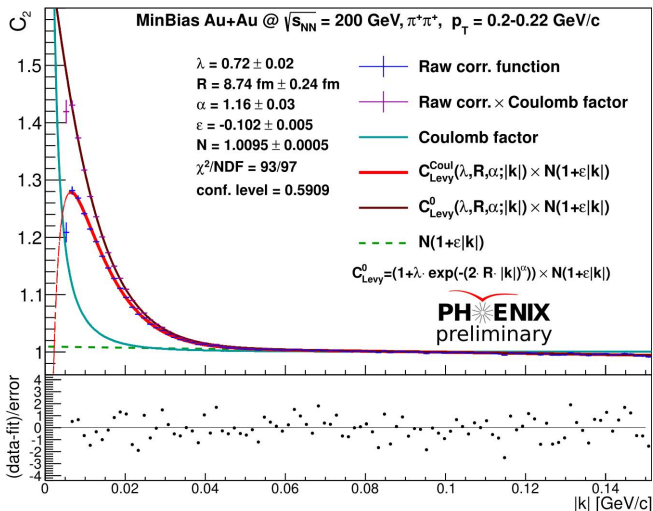


PHENIX Lévy HBT analysis

- ▶ Dataset used for the analysis:
 - ▶ Run-10, Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $7.3 \cdot 10^9$ events
 - ▶ Minimum bias results so far
 - ▶ 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
 - ▶ 2σ cuts on m^2 distribution
 - ▶ 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 with Coulomb effect incorporated

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

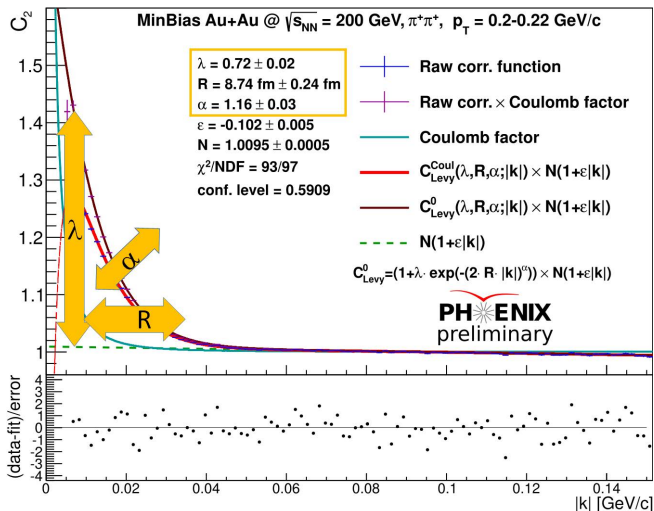
Measured in 31 $m_T^2 = m^2 + p_T^2$ bins for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs



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

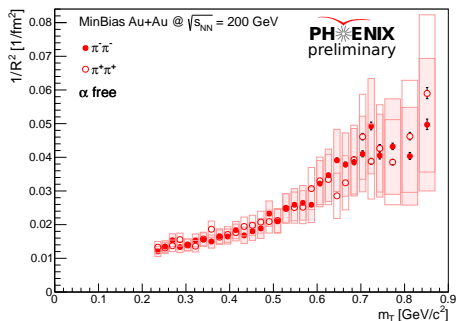
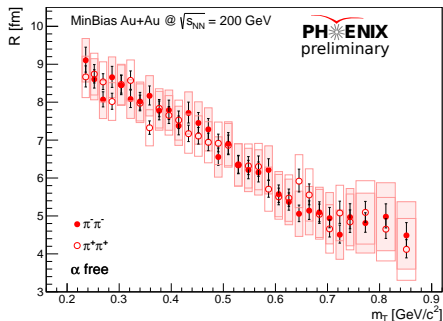
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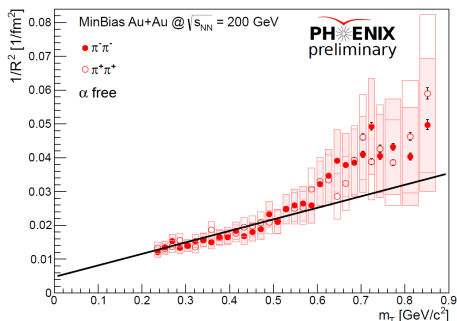
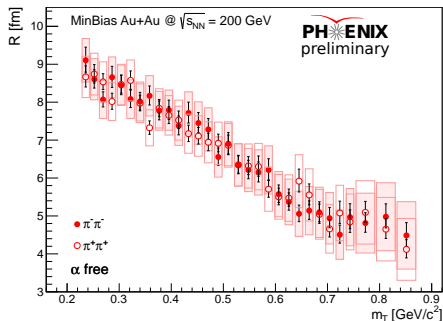
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Levy scale parameter R



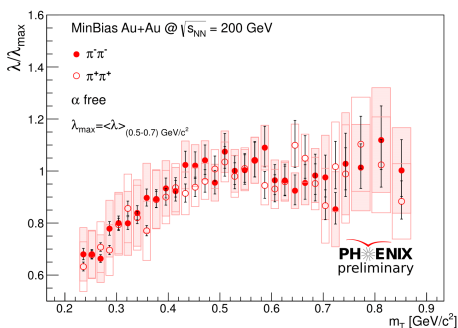
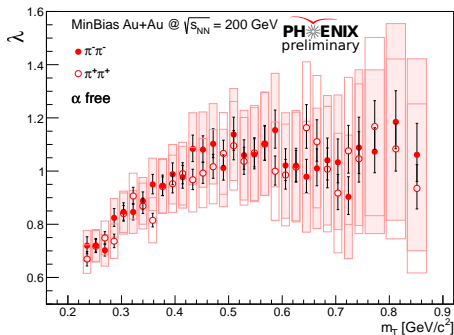
- ▶ Similar decreasing trend as Gaussian HBT radii
- ▶ Hydro behaviour not invalid
- ▶ The linear scaling of $1/R^2$, breaks for high m_T

Levy scale parameter R



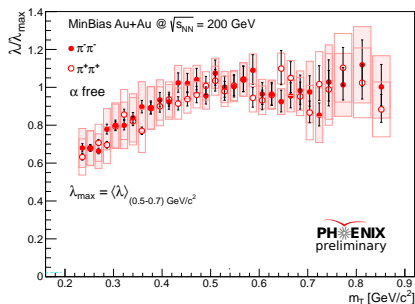
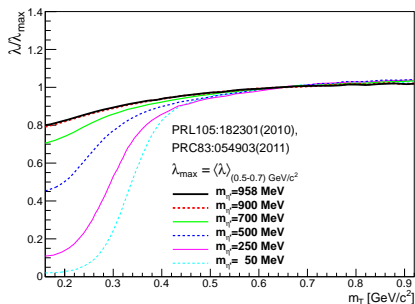
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Correlation strength λ



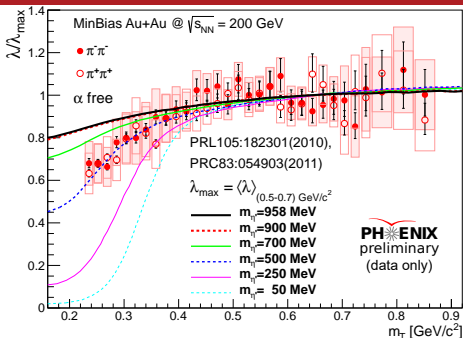
- ▶ From the Core-Halo model: $\lambda = \left(\frac{N_C}{N_C + N_H} \right)^2$
- ▶ Observed decrease (“hole”) at small $m_T \rightarrow$ increase of halo fraction
- ▶ Different effects can cause change in λ
 - ▶ Resonance effects, partially coherent pion production
- ▶ λ/λ_{\max} with smaller systematic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

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



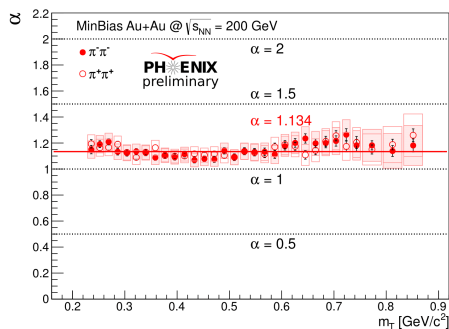
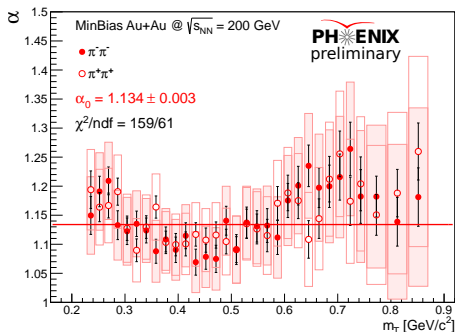
- ▶ $\lambda(m_T)$ measures core/(core+halo) fraction
- ▶ May be connected to mass modifications (c.f. chiral restoration)
 - ▶ Decreased η' mass $\rightarrow \eta'$ enhancement \rightarrow halo enhancement
 - ▶ Kinematics: η' decay pions will have low $m_T \rightarrow$ decreased λ at small m_T
- ▶ Incompatibility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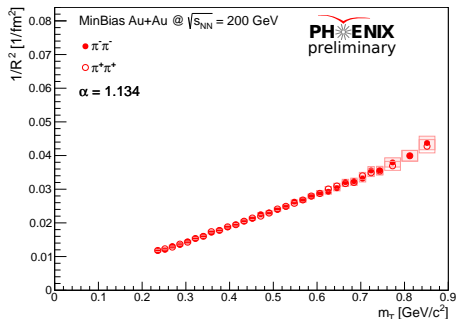
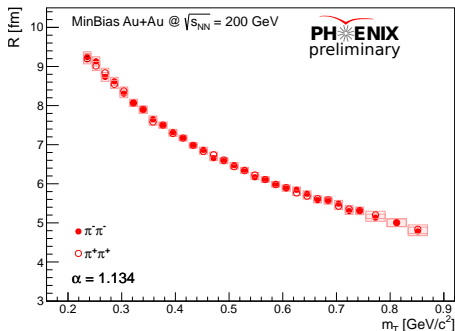
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Levy exponent α



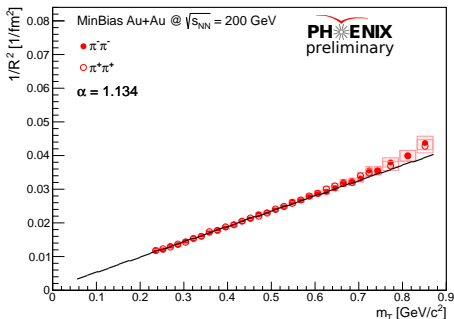
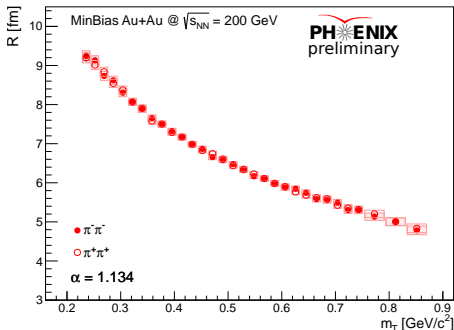
- ▶ The measured value is far from Gaussian ($\alpha = 2$) and expo. ($\alpha = 1$)
- ▶ Also far from the rfd.3D Ising value at CEP ($\alpha = 0.5$)
- ▶ More or less constant (at least within systematic errors)
- ▶ Motivation to do fits with fixed $\alpha = 1.134$
- ▶ Note: $\alpha(m_T) = \text{constant}$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

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



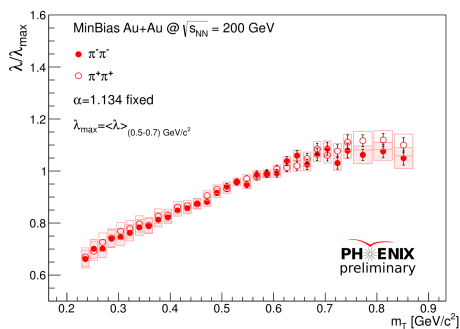
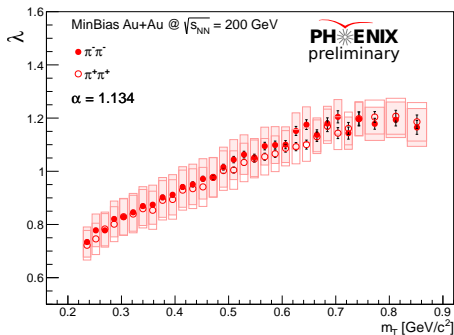
- ▶ More smooth trend
- ▶ Remarkable linearity of $1/R^2$
- ▶ Hydro behavior valid, despite $\alpha < 2$

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



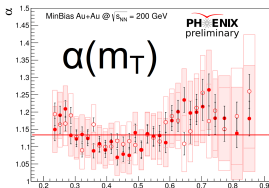
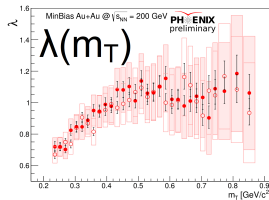
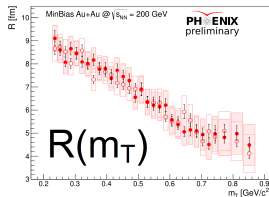
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Correlation strength λ with fixed $\alpha = 1.134$

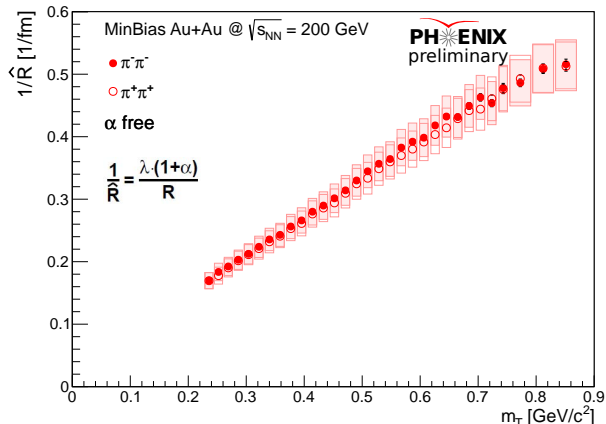
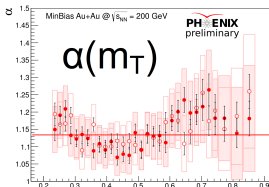
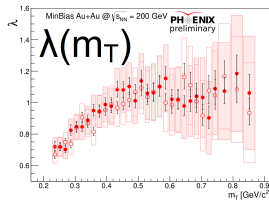
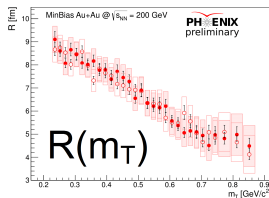


- ▶ More smooth trend
- ▶ Smaller systematic errors
- ▶ Saturation at large m_T
- ▶ Decrease (“hole”) for smaller m_T values

Newly discovered scaling parameter \hat{R}

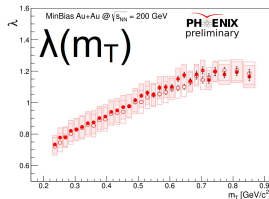
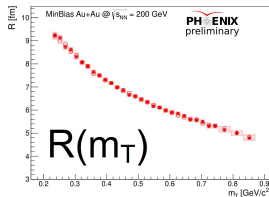


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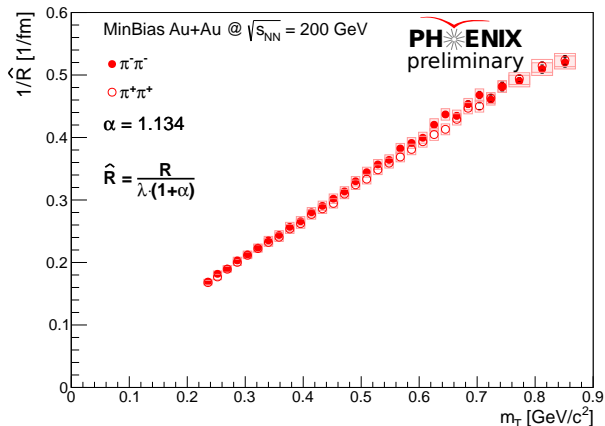


- ▶ Empirically found scaling parameter
- ▶ Linear in m_T
- ▶ Physical interpretation → open question

Newly discovered scaling parameter \hat{R}



► $\alpha = 1.134$ fixed



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Summary

- ▶ B-E correlation functions, run-10 200 GeV Au+Au, ~ 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 $\hat{R} = R/(\lambda \cdot (1 + \alpha))$
- ▶ Further work: centrality & $\sqrt{s_{NN}}$ dependence, 3π correlations, kaons
- ▶ See talks by S. Lökös and T. Novák

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/>

Run4 preliminary&Gauss → Run10 preliminary&Lévy

