

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

Balaton Workshop 2017 – Tihany

## Máté Csanad for the PHENIX Collaboration

Eötvös University, Budapest, Hungary

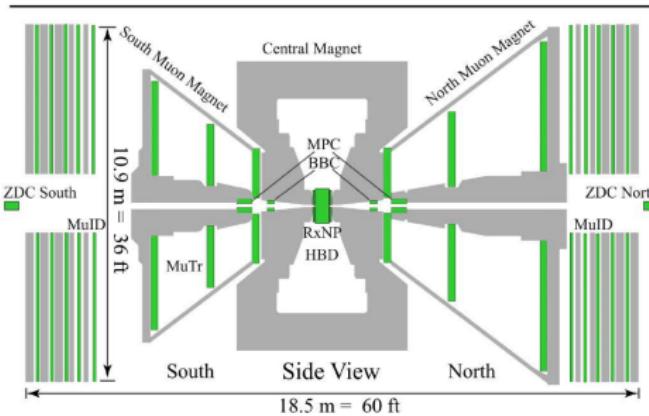
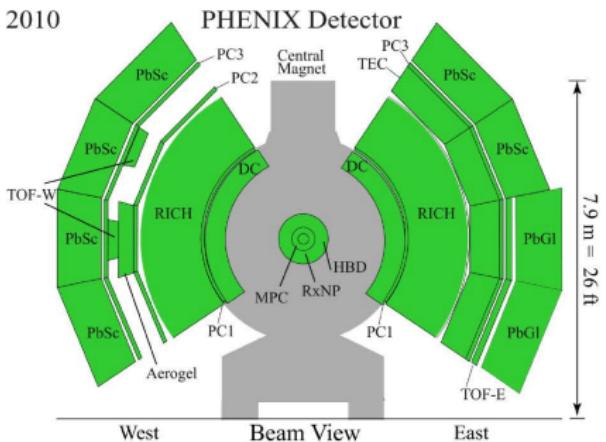


# Outline

- 1 The PHENIX experiment
- 2 Bose-Einstein correlations
- 3 Lévy-type HBT and the critical point
- 4 PHENIX Lévy HBT results:  $\sqrt{s_{NN}} = 200$  GeV, MinBias
- 5 PHENIX Lévy HBT results:  $\sqrt{s_{NN}}$  & centrality dependence
- 6 Summary

# The PHENIX Experiment

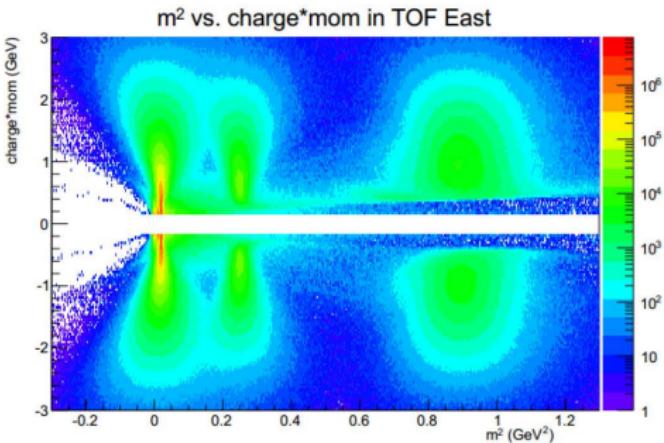
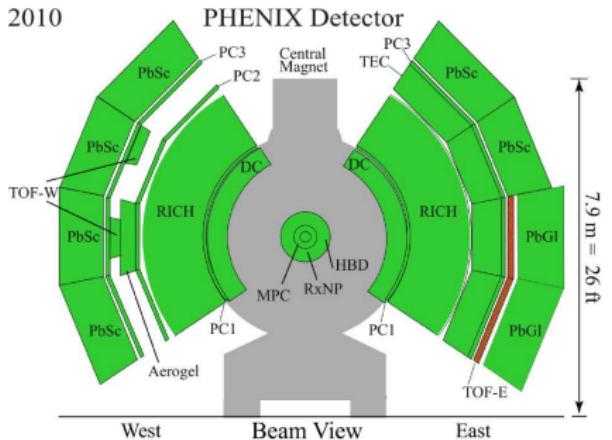
2010



- ▶ 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

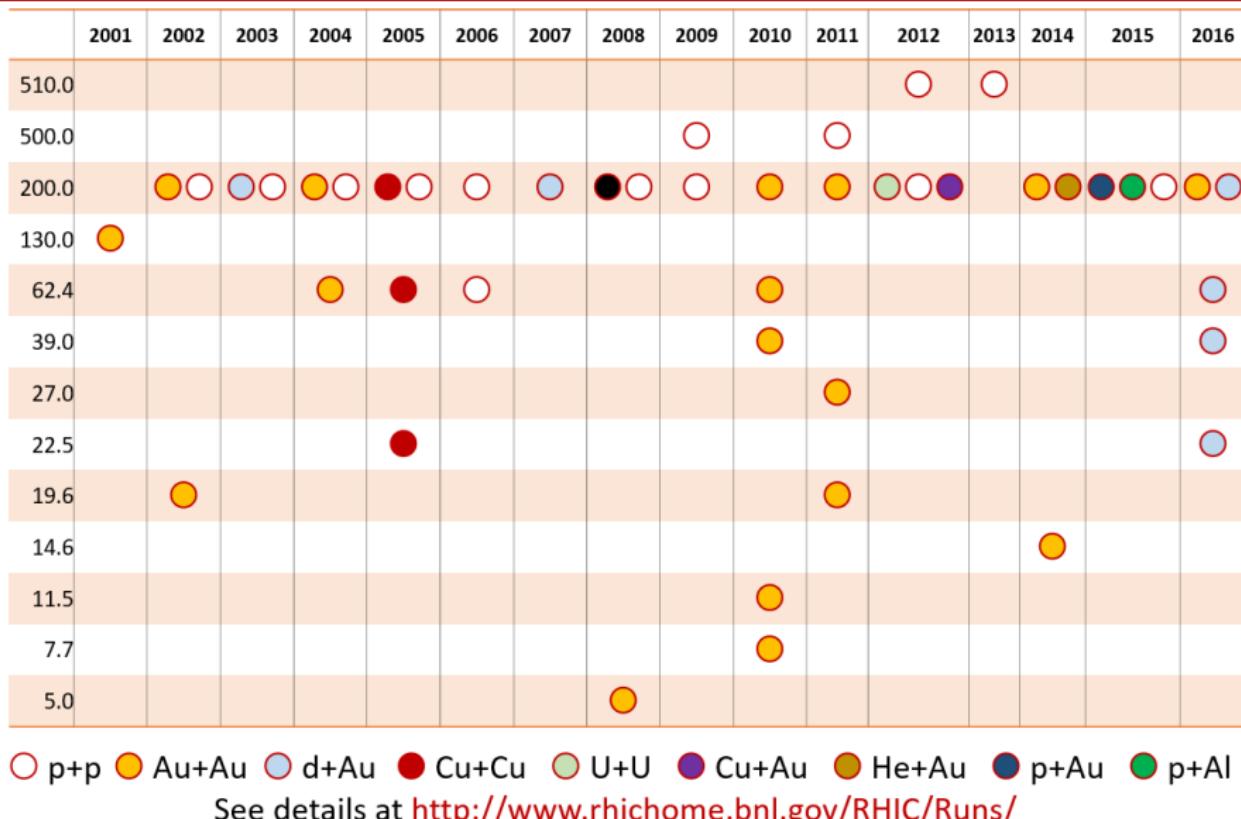
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# PHENIX runs at a glance



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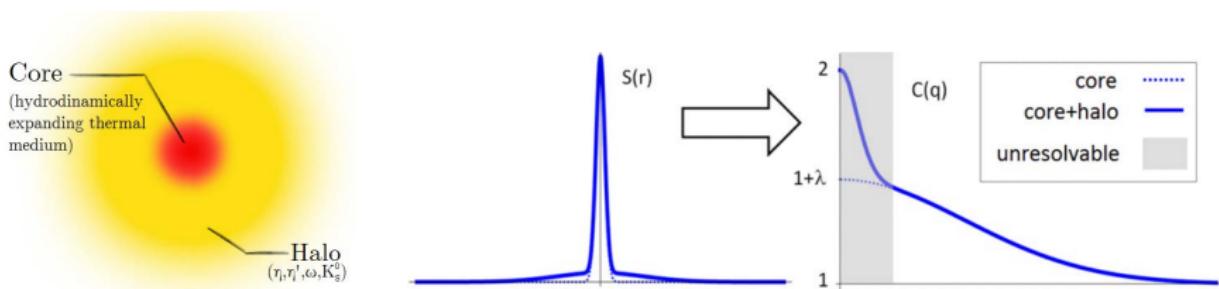
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# Bose-Einstein correlations in heavy ion physics

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

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

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



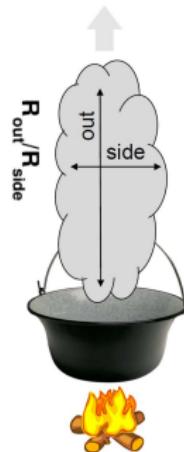
Bolz et al, Phys.Rev. D47 (1993) 3860-3870; Csörgő, Lörstad, Zimányi, Z.Phys. C71 (1996) 491-497

# 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 1<sup>st</sup> order phase transition
- ▶ Plus lots of other details (pre-eq flow, initial state, EoS, ...)

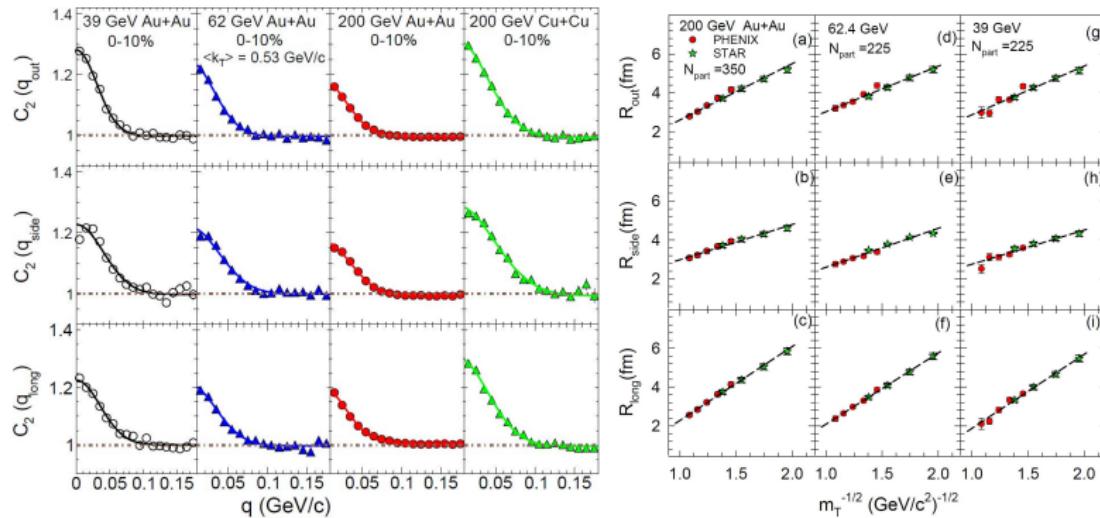
S. Chapman, P. Scotto, U. Heinz, Phys.Rev.Lett. 74 (1995) 4400

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

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

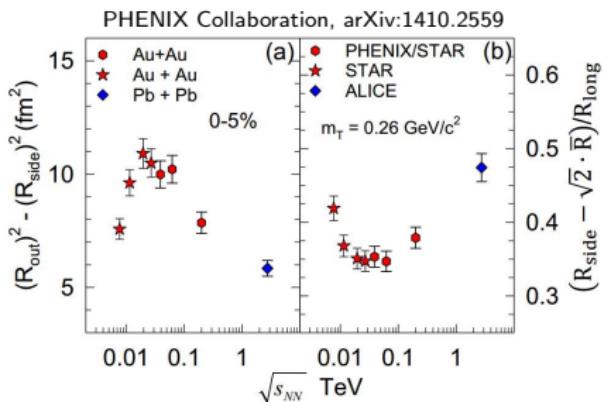
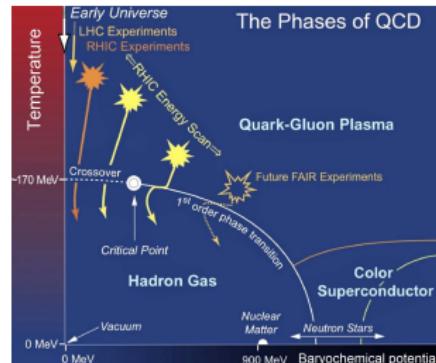
# Example: recent PHENIX HBT measurements

- ▶ 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
- ▶  $R_o^2 - R_s^2$ : 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  $\alpha$   
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, Csanad, Csorgo, Nagy, Braz.J.Phys. 37 (2007) 1002

- ▶ Lvy-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:

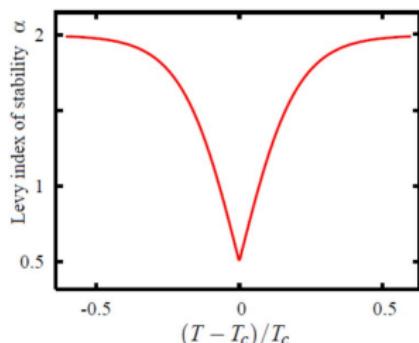
$$C_2(q) = 1 + \lambda \cdot e^{-(Rq)^\alpha} \quad \begin{aligned} \alpha = 2 &: \text{Gaussian} \\ \alpha = 1 &: \text{Exponential} \end{aligned}$$

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

Csorgo, 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  $\alpha_{\text{Levy}}$   $\leftrightarrow$  proximity of CEP?
- ▶ Non-static system, finite size effects...



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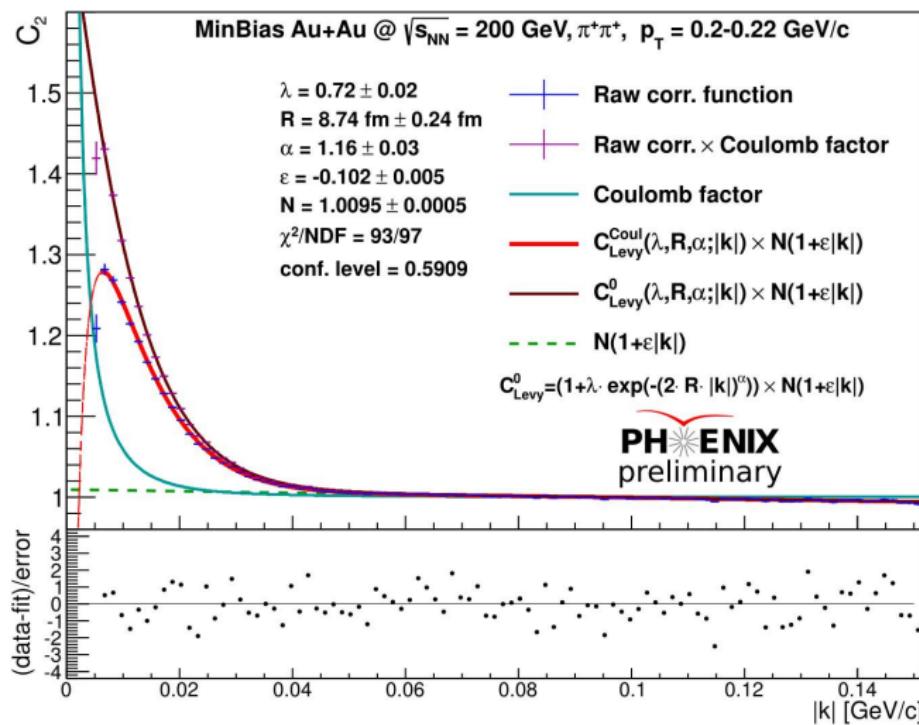
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# PHENIX Lévy HBT analysis

- ▶ 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  $\pm 30$  cm
  - ▶ Particle identification:
    - ▶ time-of-flight data from PbSc e/w, TOF e/w, momentum, flight length
    - ▶  $2\sigma$  cuts on  $m^2$  distribution
  - ▶ Single track cuts:
    - ▶  $2\sigma$  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  $|k|_{LCMS}$  in various  $m_T$  bins
  - ▶ Levy fits for 31  $m_T$  bins with Coulomb effect incorporated

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

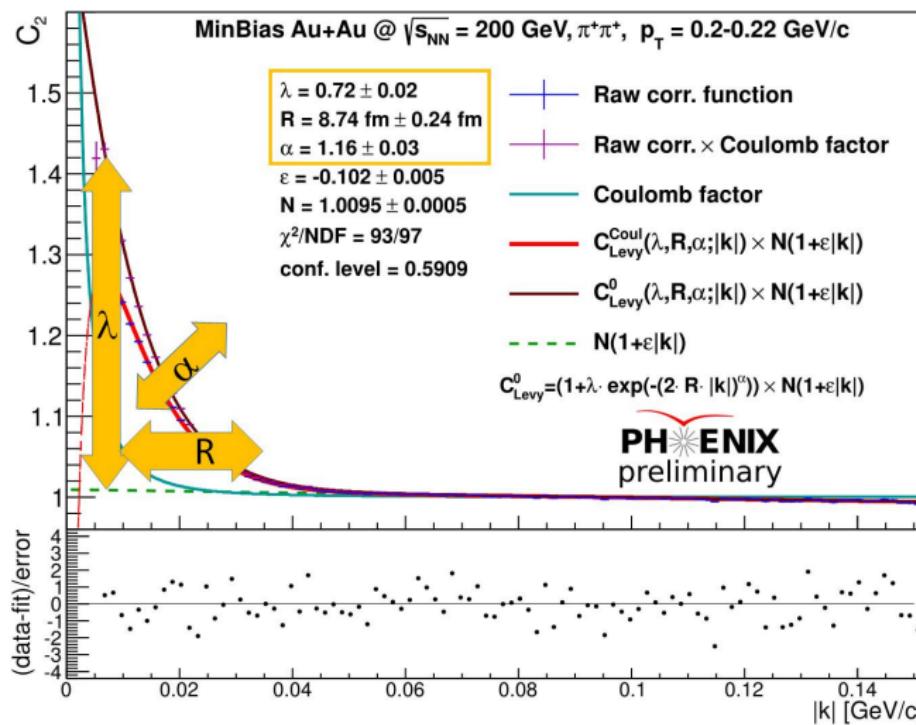
Measured in 31  $m_T^2 = m^2 + p_T^2$  bins for  $\pi^+\pi^+$  and  $\pi^-\pi^-$  pairs



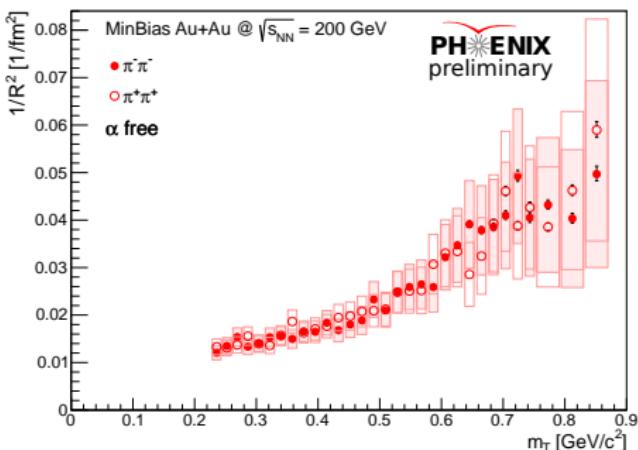
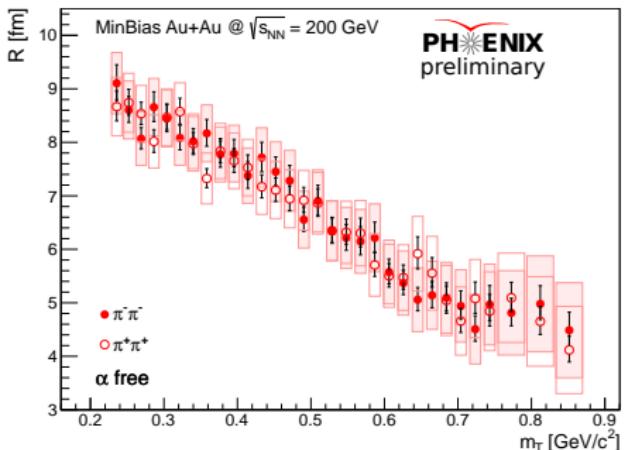
Physical parameters:  $R, \lambda, \alpha$ ; measured versus pair  $m_T$

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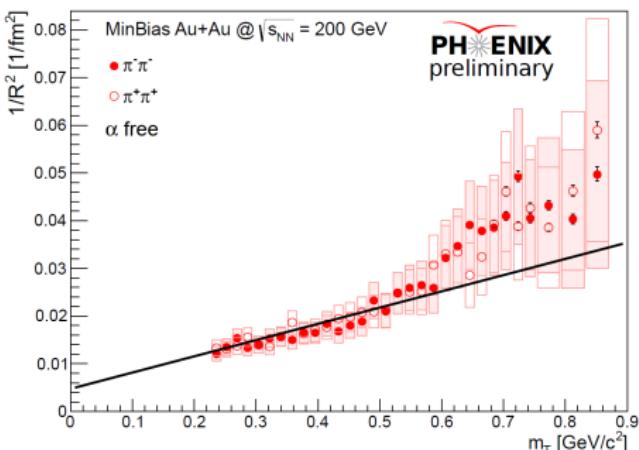
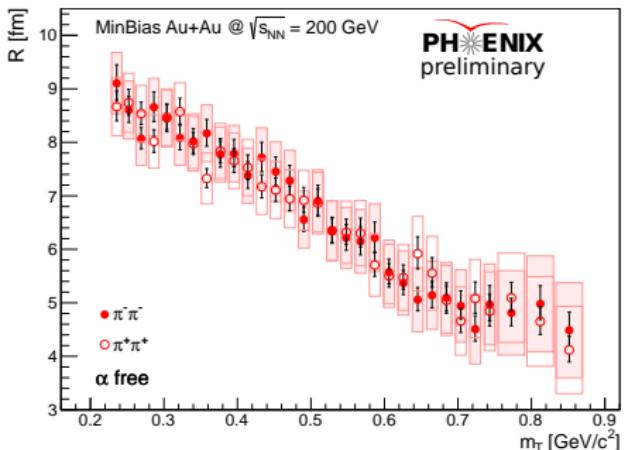


# Levy scale parameter $R$



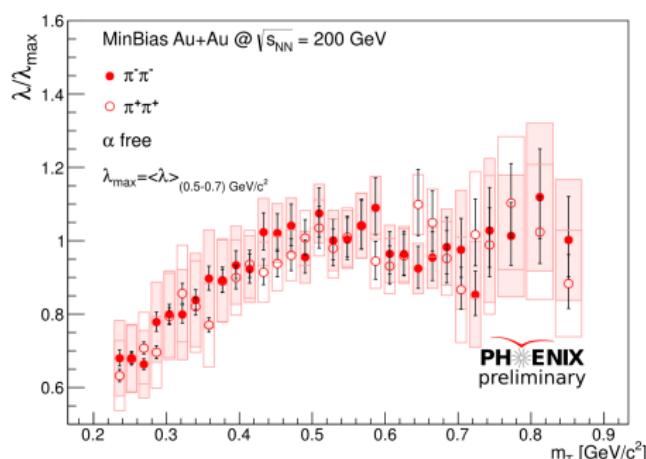
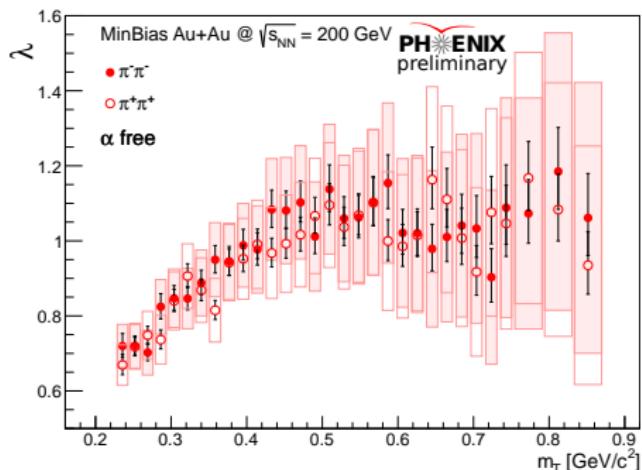
- ▶ Similar decreasing trend as Gaussian HBT radii
- ▶ Hydro behaviour not invalid
- ▶ The linear scaling of  $1/R^2$ , breaks for high  $m_T$

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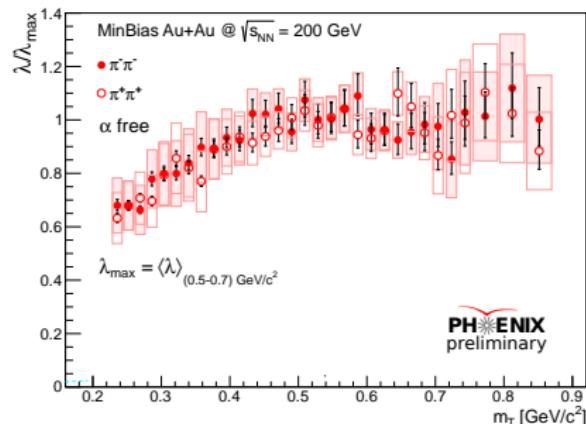
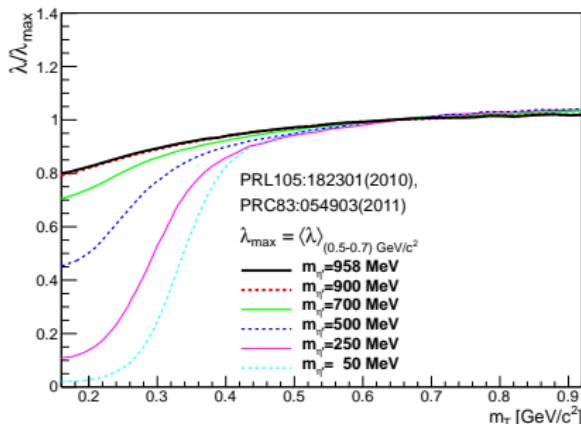
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# Correlation strength $\lambda$



- ▶ 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  $\lambda$ 
  - ▶ Resonance effects, partially coherent pion production
- ▶  $\lambda/\lambda_{\max}$  with smaller systematic uncertainties
- ▶ Precise measurement may help extract physics info

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



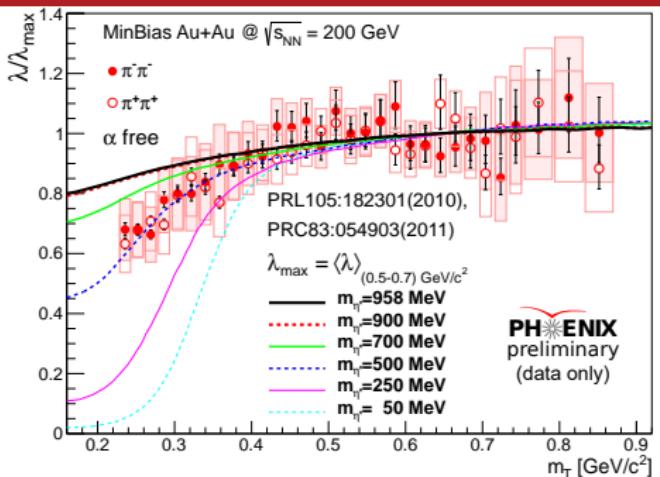
- ▶  $\lambda(m_T)$  measures core/(core+halo) fraction
- ▶ May be connected to mass modifications (c.f. chiral restoration)
  - ▶ Decreased  $\eta'$  mass  $\rightarrow \eta'$  enhancement  $\rightarrow$  halo enhancement
  - ▶ Kinematics:  $\eta'$  decay pions will have low  $m_T$   $\rightarrow$ 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

Kapusta, Kharzeev, McLerran, Phys.Rev. D53 (1996) 5028, hep-ph/9507343

Vance, Csörgő, Kharzeev, Phys.Rev.Lett. 81 (1998) 2205, nucl-th/9802074

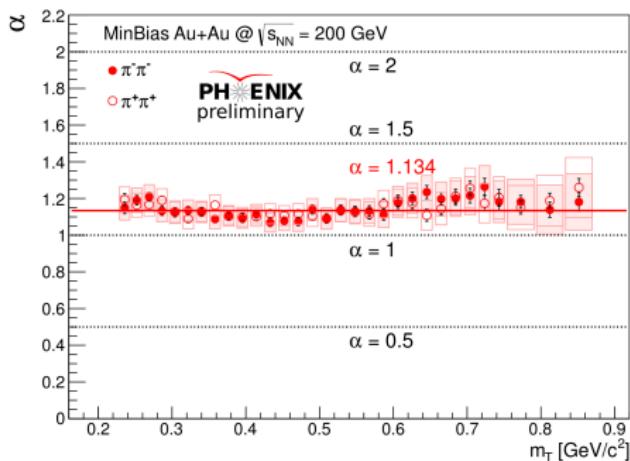
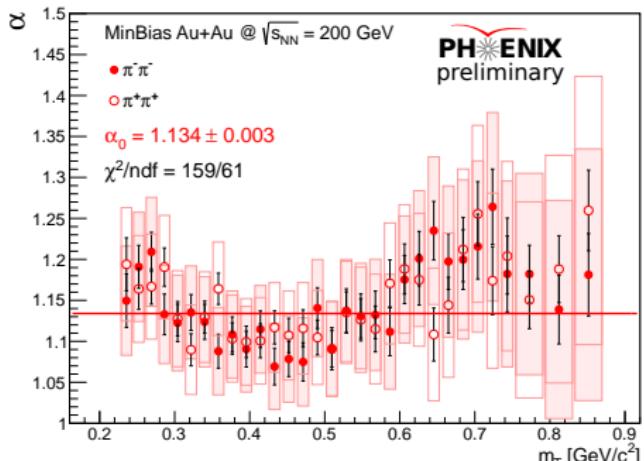
Csörgő, Vértesi, Sziklai, Phys.Rev.Lett. 105 (2010) 182301, arXiv:0912.5526

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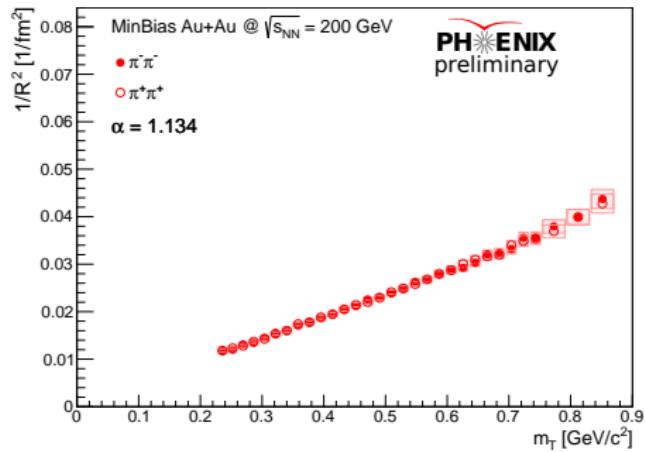
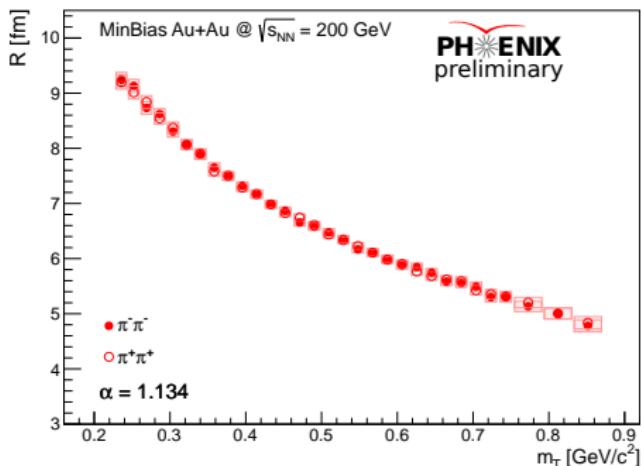
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# Levy exponent $\alpha$



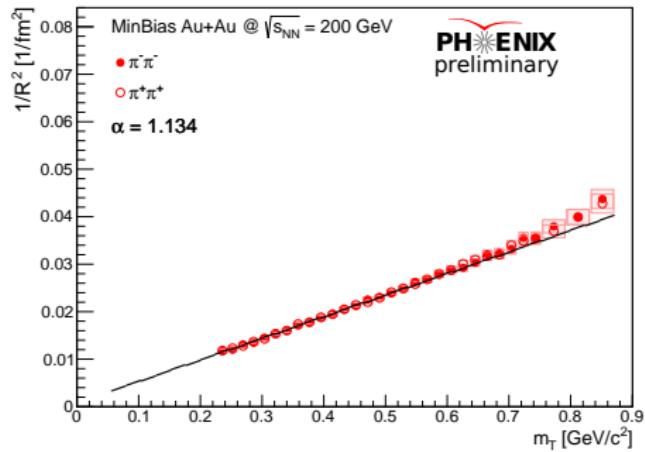
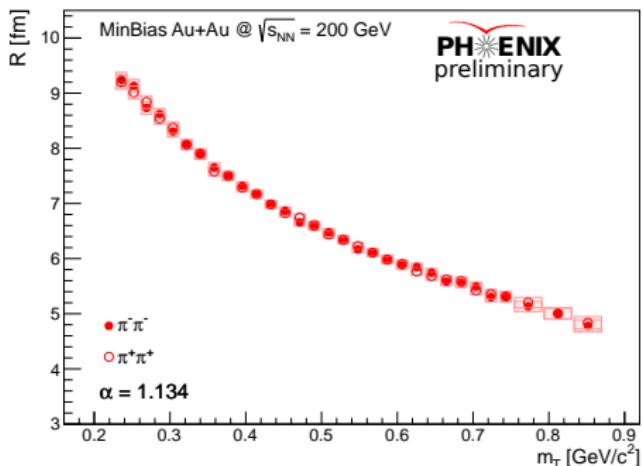
- ▶ The measured value is far from Gaussian ( $\alpha = 2$ ) and expo. ( $\alpha = 1$ )
- ▶ Also far from the rfd.3D Ising value at CEP ( $\alpha = 0.5$ )
- ▶ More or less constant (at least within systematic errors)
- ▶ Motivation to do fits with fixed  $\alpha = 1.134$
- ▶ Note:  $\alpha(m_T) = \text{constant}$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

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



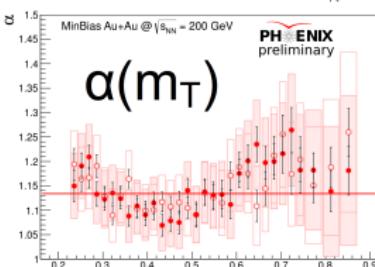
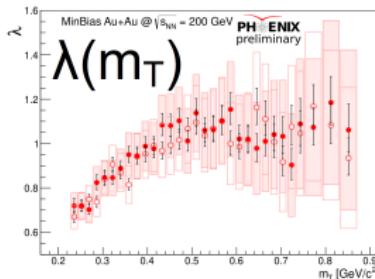
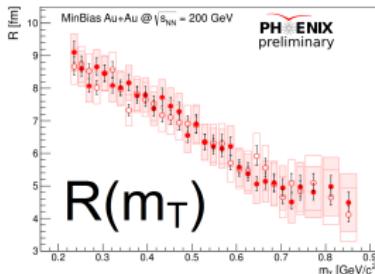
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- ▶ Remarkable linearity of  $1/R^2$
- ▶ Hydro behavior valid, despite  $\alpha < 2$

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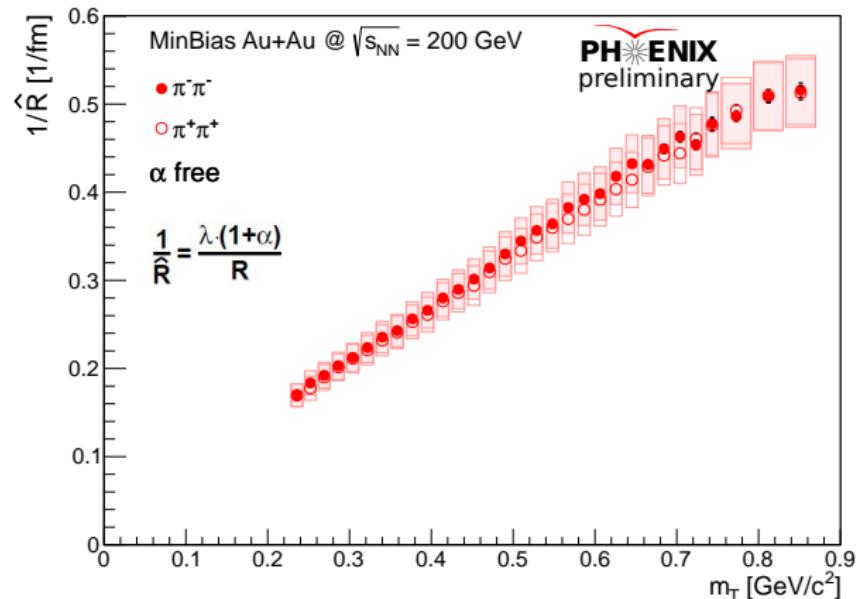
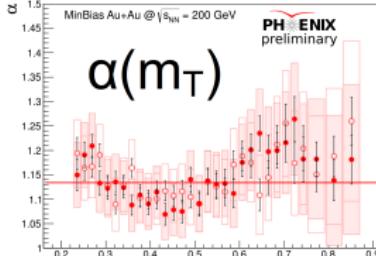
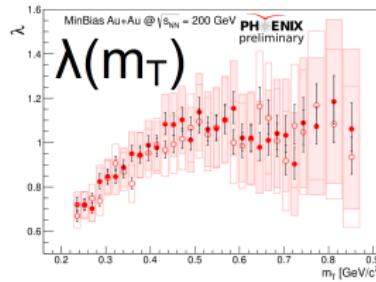
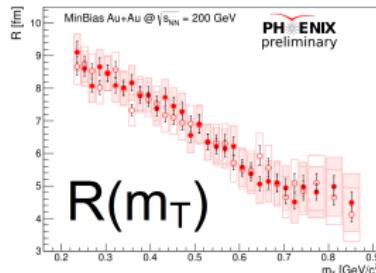


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# Newly discovered scaling parameter $\hat{R}$

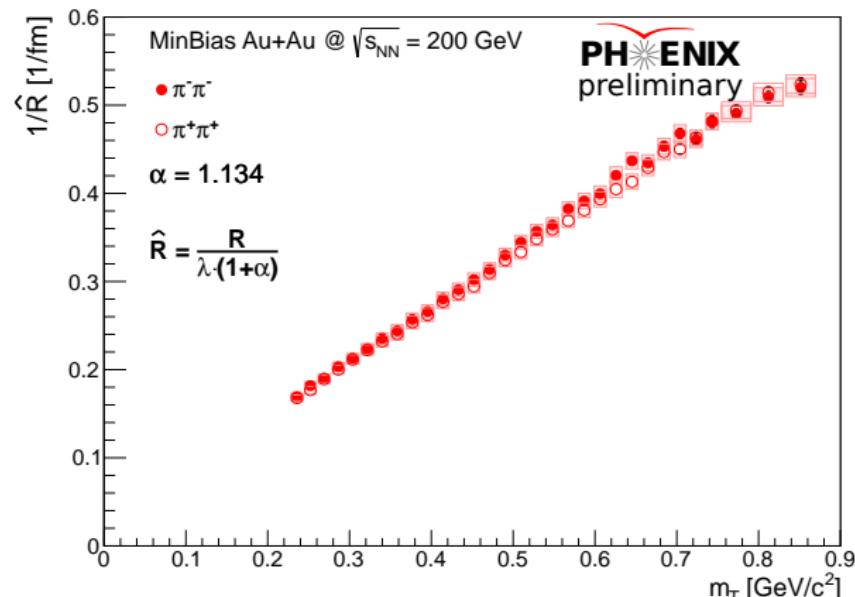
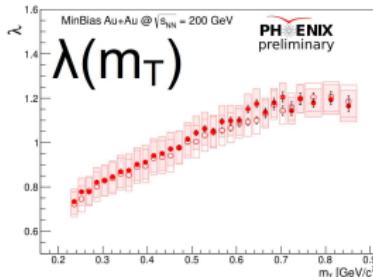
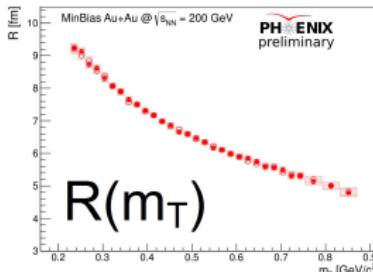


# Newly discovered scaling parameter $\hat{R}$



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

# Newly discovered scaling parameter $\hat{R}$



►  $\alpha = 1.134$  fixed

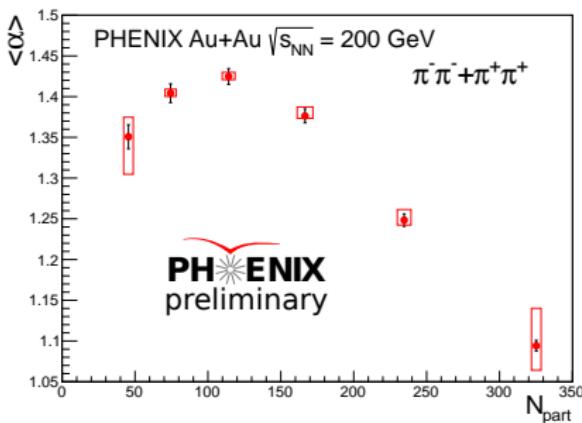
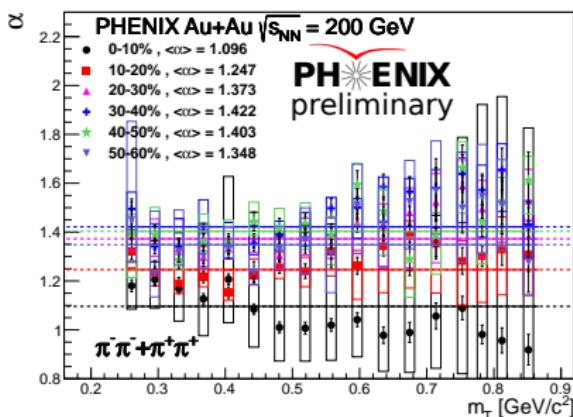
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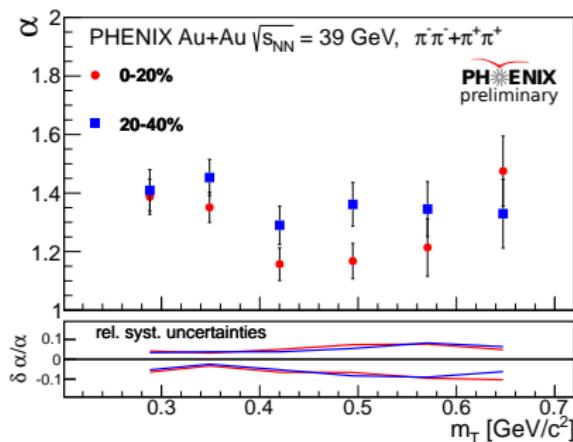
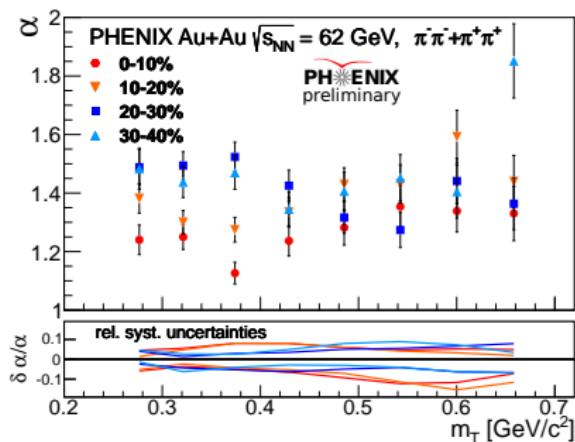
# Lévy exponent $\alpha$ at 200 GeV

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

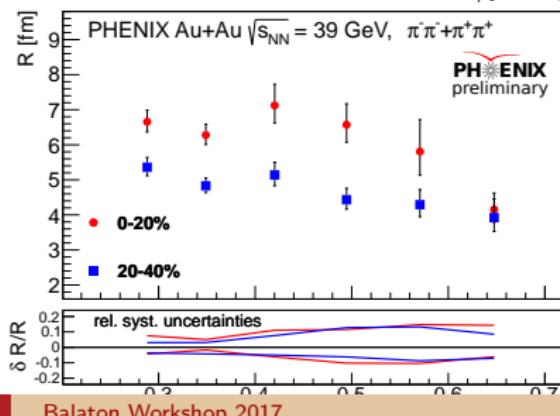
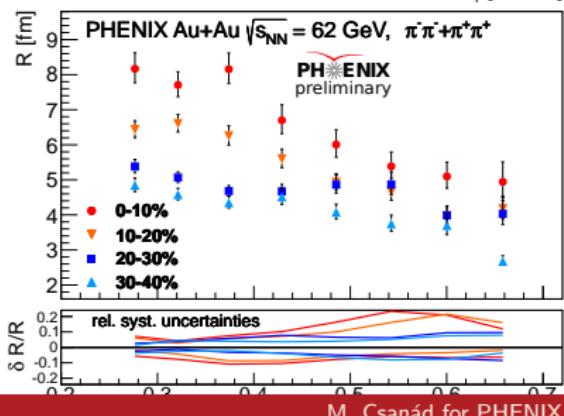
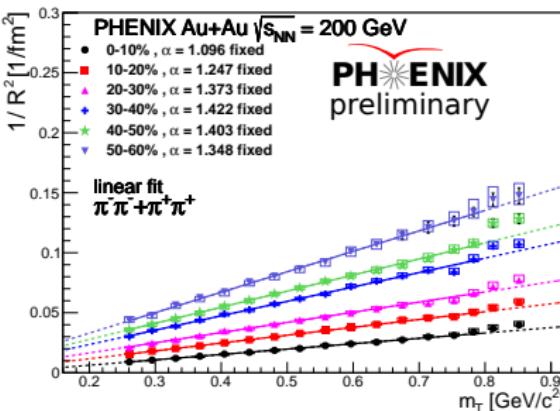
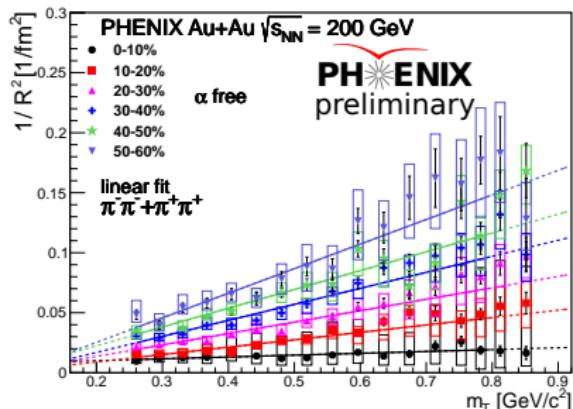


# Lévy exponent $\alpha$ at 62 and 39 GeV

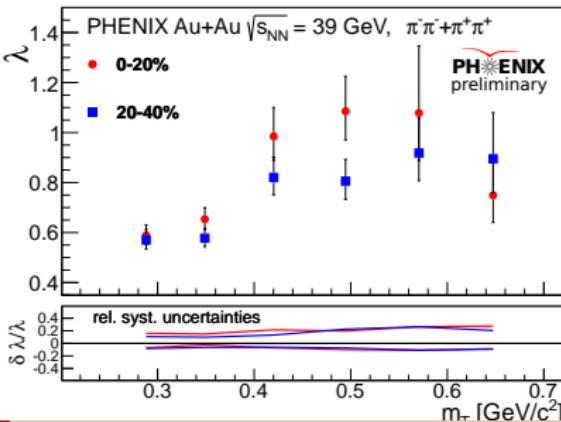
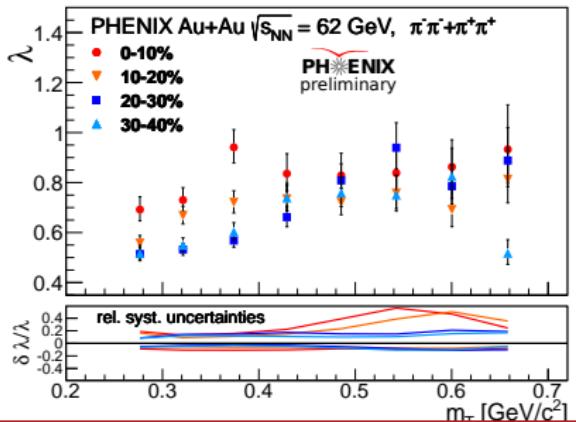
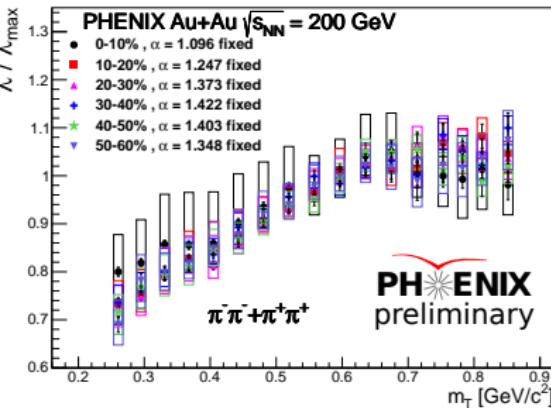
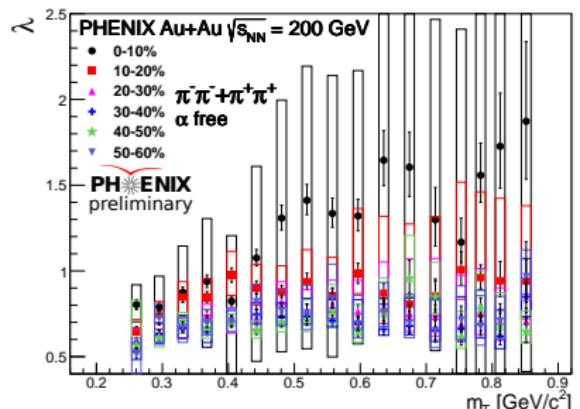
- ▶ Lévy exponent  $\alpha$ : no significant change vs  $\sqrt{s_{NN}}$  at 39-62-200 GeV
- ▶ Usual values between 1 and 1.5
- ▶ Non-monotonicity in  $m_T$



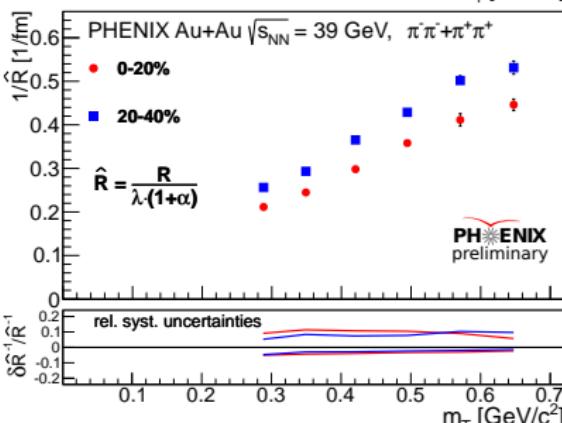
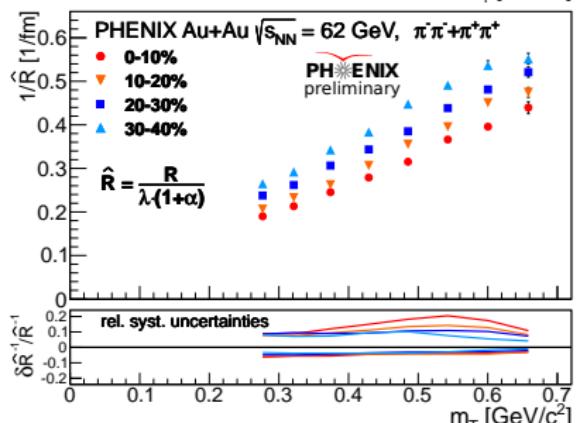
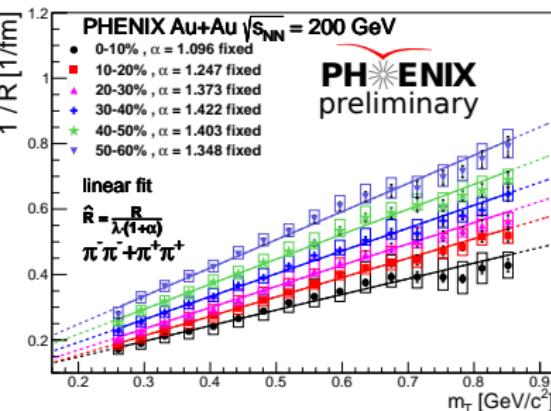
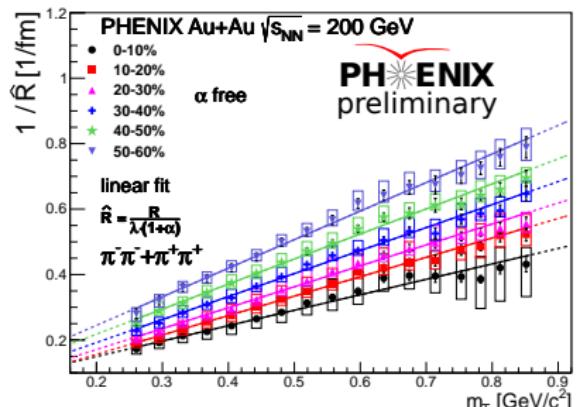
# Lévy scale $R$ : similar trends for all $\sqrt{s_{NN}}$ and cent.



# "Hole" in $\lambda$ : all energies and centralities



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



# Outline

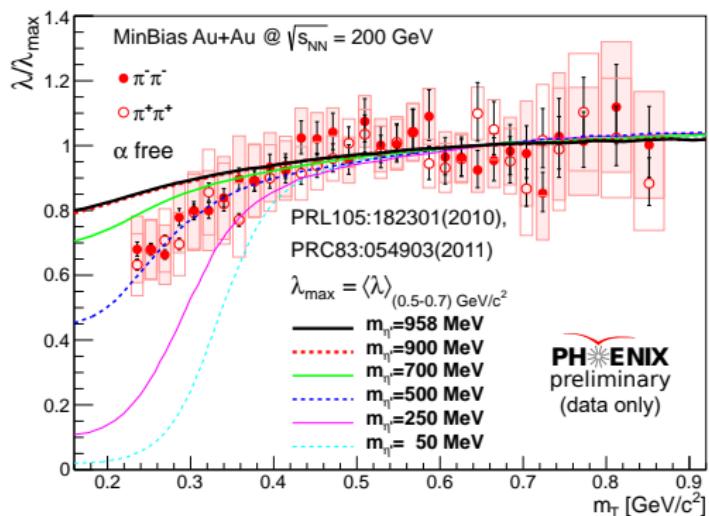
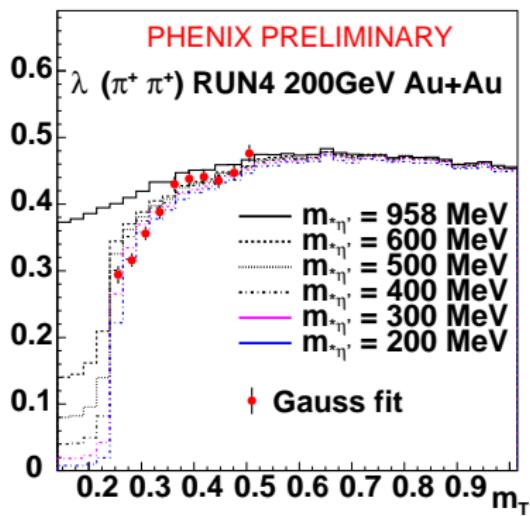
- 1 The PHENIX experiment
- 2 Bose-Einstein correlations
- 3 Lévy-type HBT and the critical point
- 4 PHENIX Lévy HBT results:  $\sqrt{s_{NN}} = 200$  GeV, MinBias
- 5 PHENIX Lévy HBT results:  $\sqrt{s_{NN}}$  & centrality dependence
- 6 Summary

# Summary

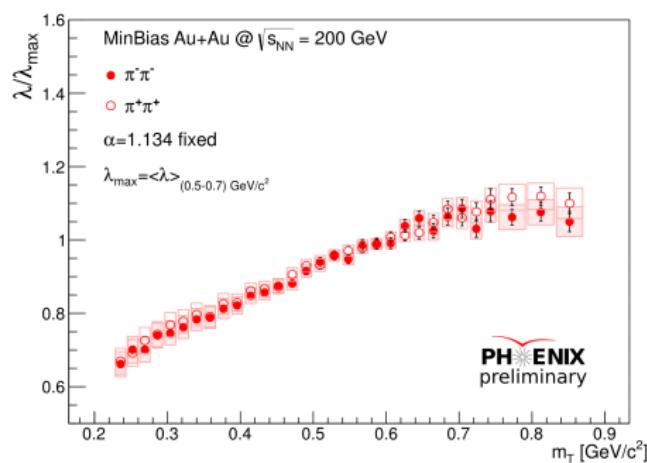
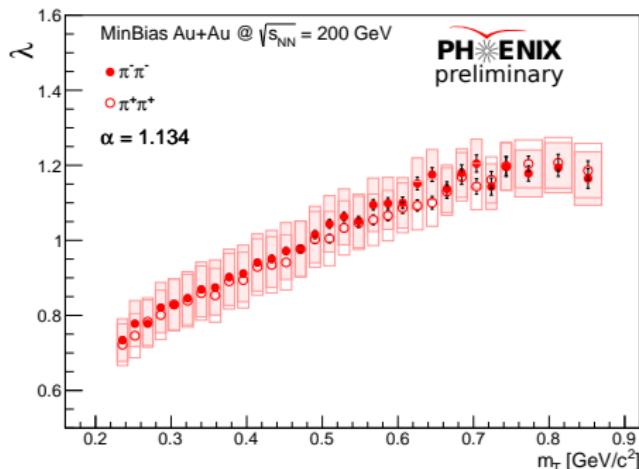
- ▶ B-E correlation functions, run-10 200 GeV Au+Au,  $\sim 7$  billion evts.
- ▶ Levy fits yield statistically acceptable description
- ▶ Fine  $m_T$  binned Levy source parameters ( $R$ ,  $\lambda$ ,  $\alpha$ )
  - ▶ Nearly constant  $\alpha$ , away from 2, 1 and 0.5  $\leftrightarrow$  distance to CEP?
  - ▶ Linear scaling of  $1/R^2(m_T)$   $\leftrightarrow$  hydro?
  - ▶ Low- $m_T$  decrease in  $\lambda(m_T)$   $\leftrightarrow$  resonances,  $\eta'$  in-medium mass?
- ▶ New empirically found scaling parameter  $\hat{R} = R / (\lambda \cdot (1 + \alpha))$
- ▶ Centrality and  $\sqrt{s_{NN}}$  dependence also explored
  - ▶ No  $\alpha$  decrease down to  $\sqrt{s_{NN}} = 39$  GeV
  - ▶ Non-monotonic  $\alpha$  vs  $N_{\text{part}}$  dependence
  - ▶ “Hole” in  $\lambda(m_T)$  present down to  $\sqrt{s_{NN}} = 39$  GeV (c.f. SPS result!)
  - ▶ No change in  $1/R^2$  and  $\hat{R}$  scaling

# Outline

# Run4 preliminary&Gauss → Run10 preliminary&Lévy

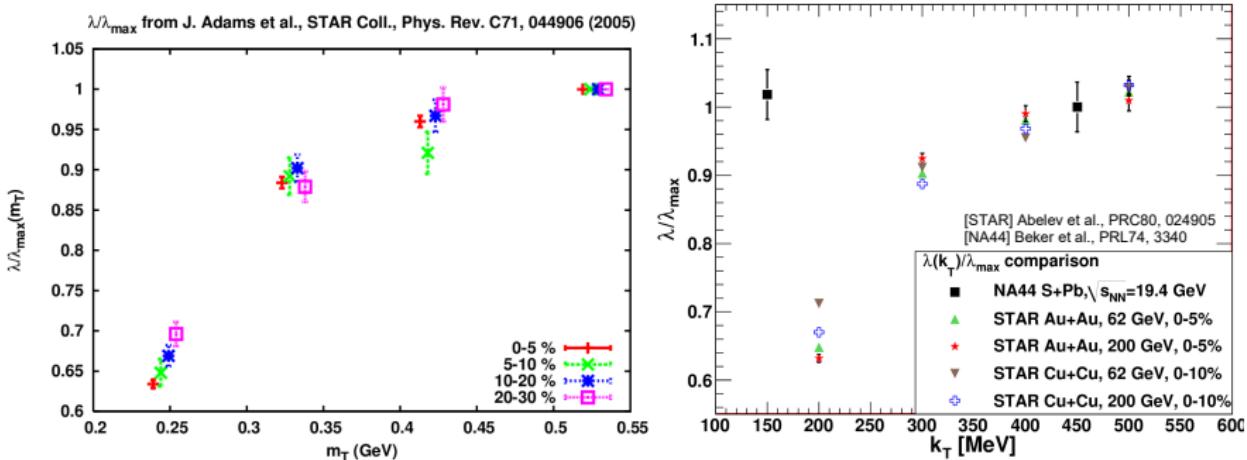


# Correlation strength $\lambda$ with fixed $\alpha = 1.134$



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

# Backup slides



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