PHENIX results on Lévy analysis of HBT correlation functions

55th International School of Subnuclear Physics, Erice

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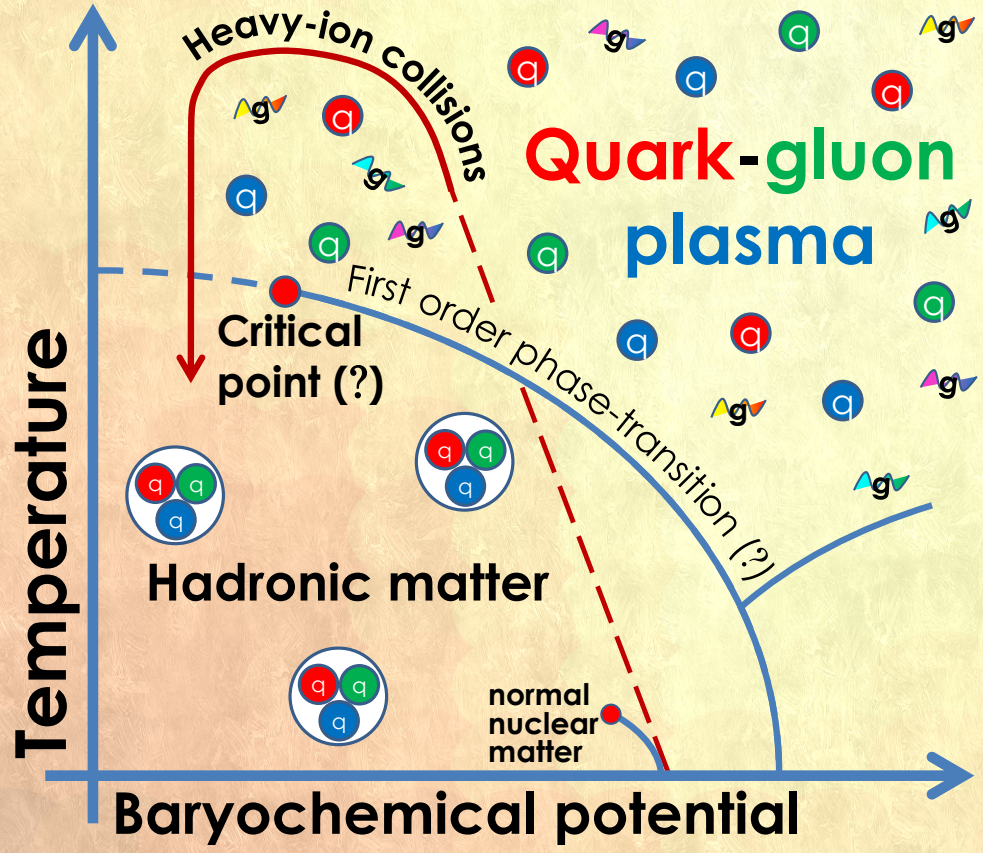
June 16, 2017

The phase-diagram of QGP

- Early stages of the Universe? High energy heavy-ion collisions!



- One of the most important still open questions: **Is there a critical point, and if there is, where?**
- How can we look for a critical point?

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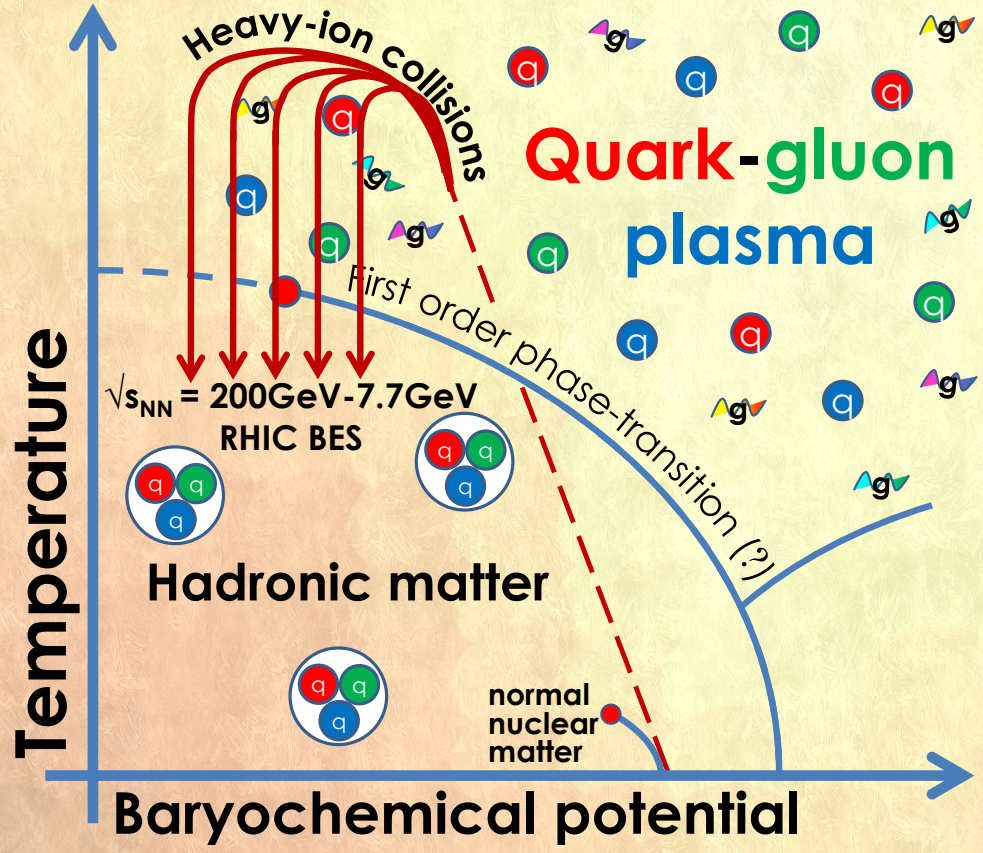
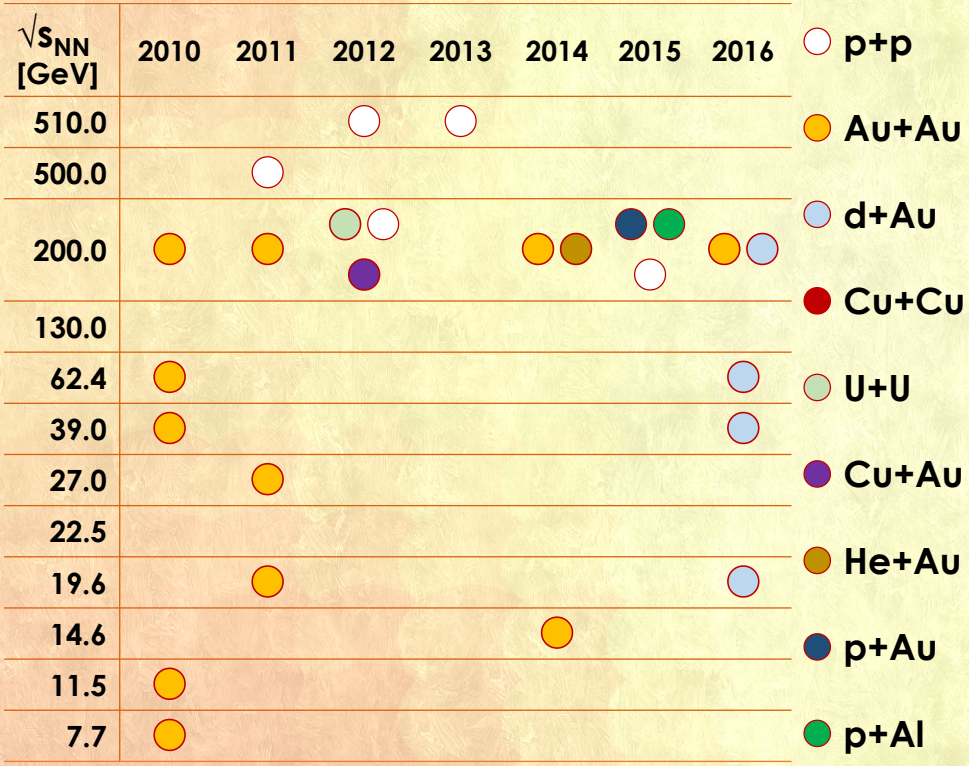


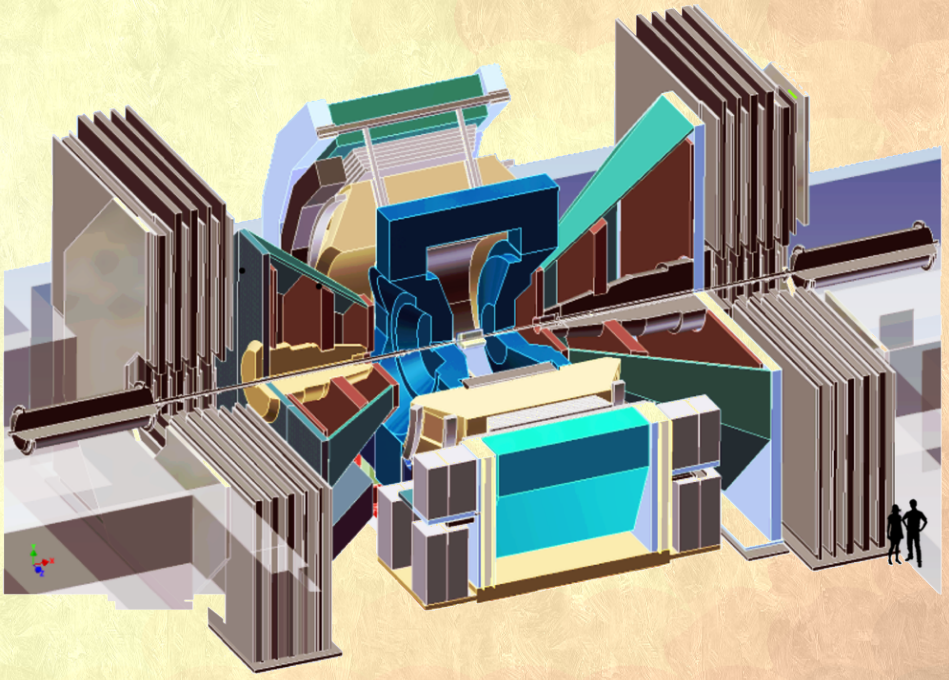
- One of the most important still open questions: **Is there a critical point, and if there is, where?**
- How can we look for a critical point?

$\Downarrow$

- Beam Energy Scan!

The PHENIX experiment and the RHIC BES





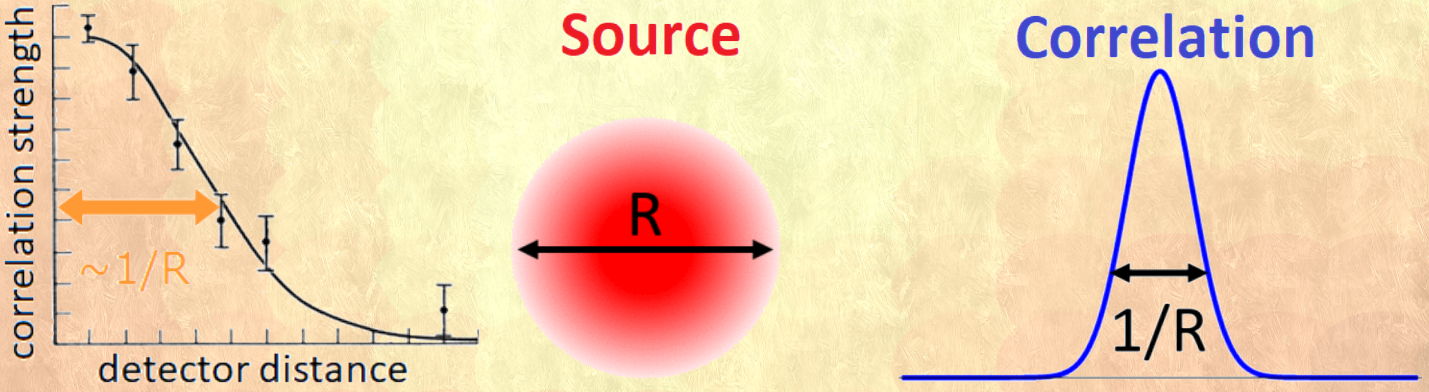
- **Au+Au collision energies: 200 GeV - 7.7 GeV**
- μ_B = 23.5 MeV - 422 MeV, T = 166 MeV - 139 MeV
- **How can we gain information about the Quark-Gluon Plasma?**

  Colliding nuclei → QGP → hadronization → detecting the particles → correlations/distributions of particles → information about the initial stage

The HBT-effect

- R. Hanbury Brown, R. Q. Twiss - observing Sirius with radio telescopes
- **Intensity correlations** as a func. of det. distance: $C(\Delta) = \frac{\langle I_A I_B \rangle}{\langle I_A \rangle \langle I_B \rangle}$
- They could measure the size of point-like sources!
- Correlation $\Longleftrightarrow$ Fourier-transform of $S(r)$ source distribution

$$C(q) \approx 1 + |\widetilde{S}(q)|^2, \qquad \widetilde{S}(q) = \int S(r) e^{iqr}$$



- High energy physics: **momentum correlations** of pions
- We can map out the particle-emitting source on the **femtometer scale**!

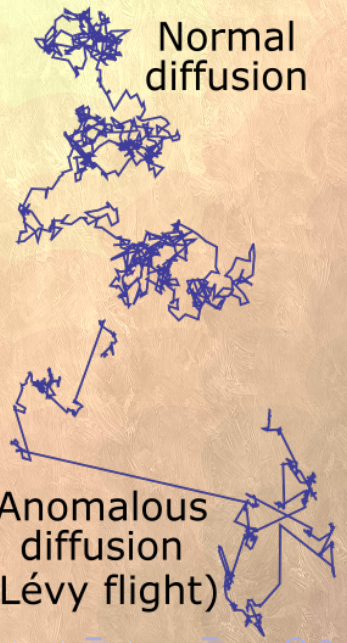
Lévy femtoscopy and the search for the CEP

- The assumed shape of the source distribution is usually Gaussian
- Generalization of Gaussian - **Lévy distribution**
  - Anomalous diffusion
  - Gen. Central Limit Th.

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

  - $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy
- Critical behavior $\rightarrow$ described by **critical exponents**
- At the crit. point the spatial corr. $\propto r^{-(d-2+\eta)}$
- In case of Lévy source $\rightarrow$ spatial corr. $\propto r^{-1-\alpha}$ $\Big\}\ \alpha = \eta$
- QCD universality class $\leftrightarrow$ (Rfd.) 3D Ising $\rightarrow \eta \leq 0.5$
- The shape of the corr. func. with Lévy source:

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



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$\alpha \equiv \eta$

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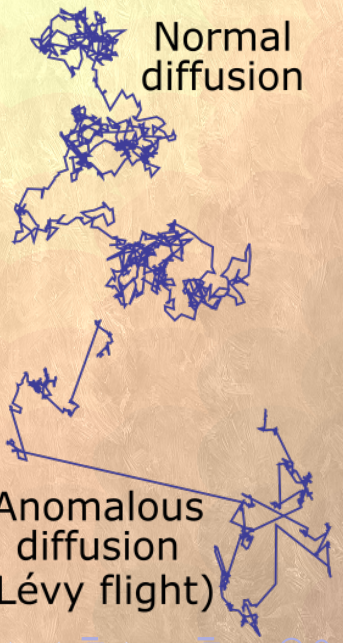
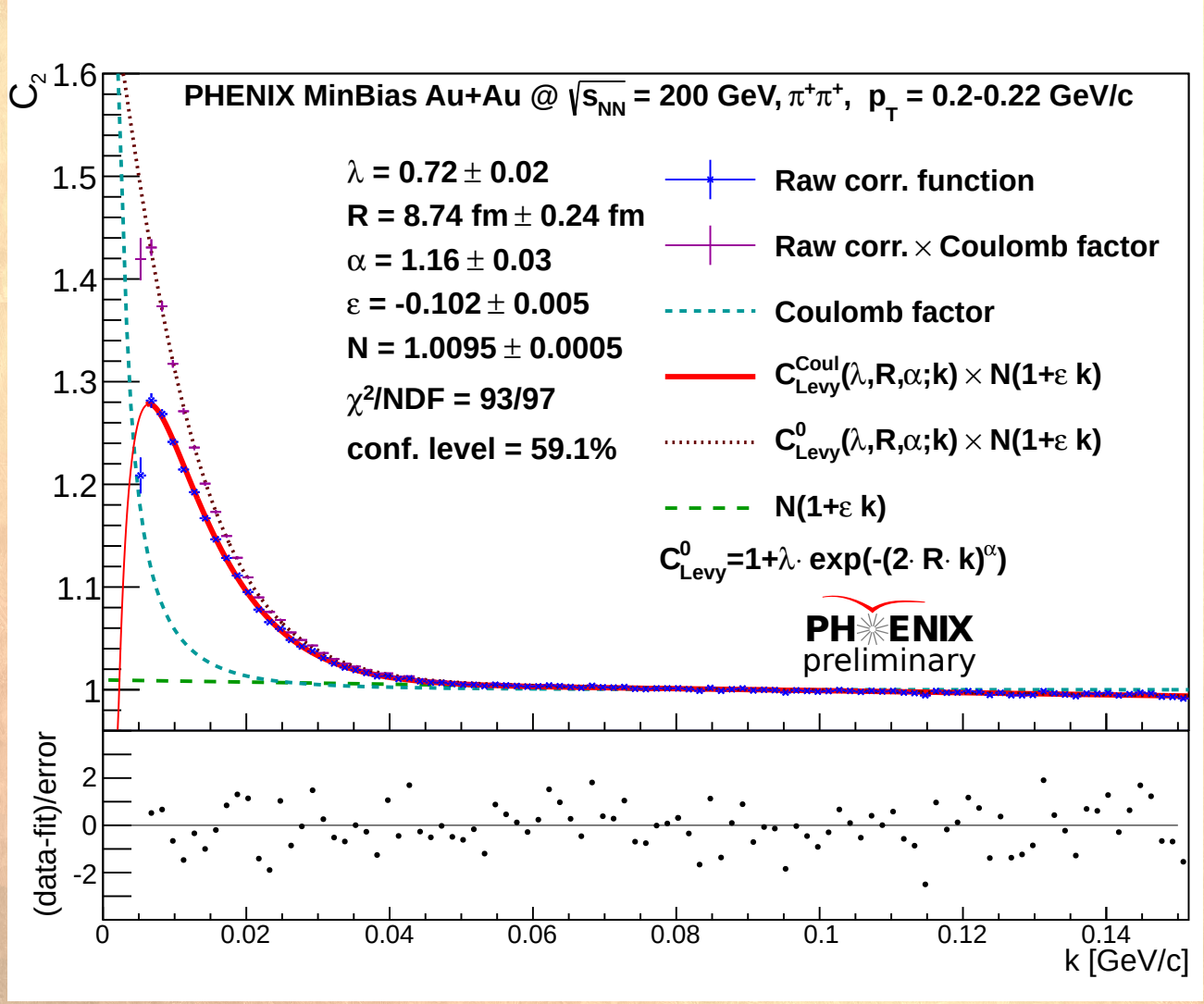


PHENIX Lévy HBT analysis - overview

- Data set: **$\sqrt{s_{NN}}$=200 GeV, 62 GeV, 39 GeV Au+Au**, identified pions
- Some details of the analysis:
  - **Measurement of 1D $\pi^{\pm}\pi^{\pm}$ corr. func.** as a function of m_T and centrality
  - Investigation of systematic uncertainties
    - One- and two-particle criteria (PID, matching, pair cuts)
    - Other sources of syst. uncertainties (e.g. fit stability)
  - Fitting the measured corr. func. with Lévy shape
  - **Investigation of the source parameters ($\lambda(m_T), \alpha(m_T), R(m_T)$)**
  - Publication from the first results already under collaboration review

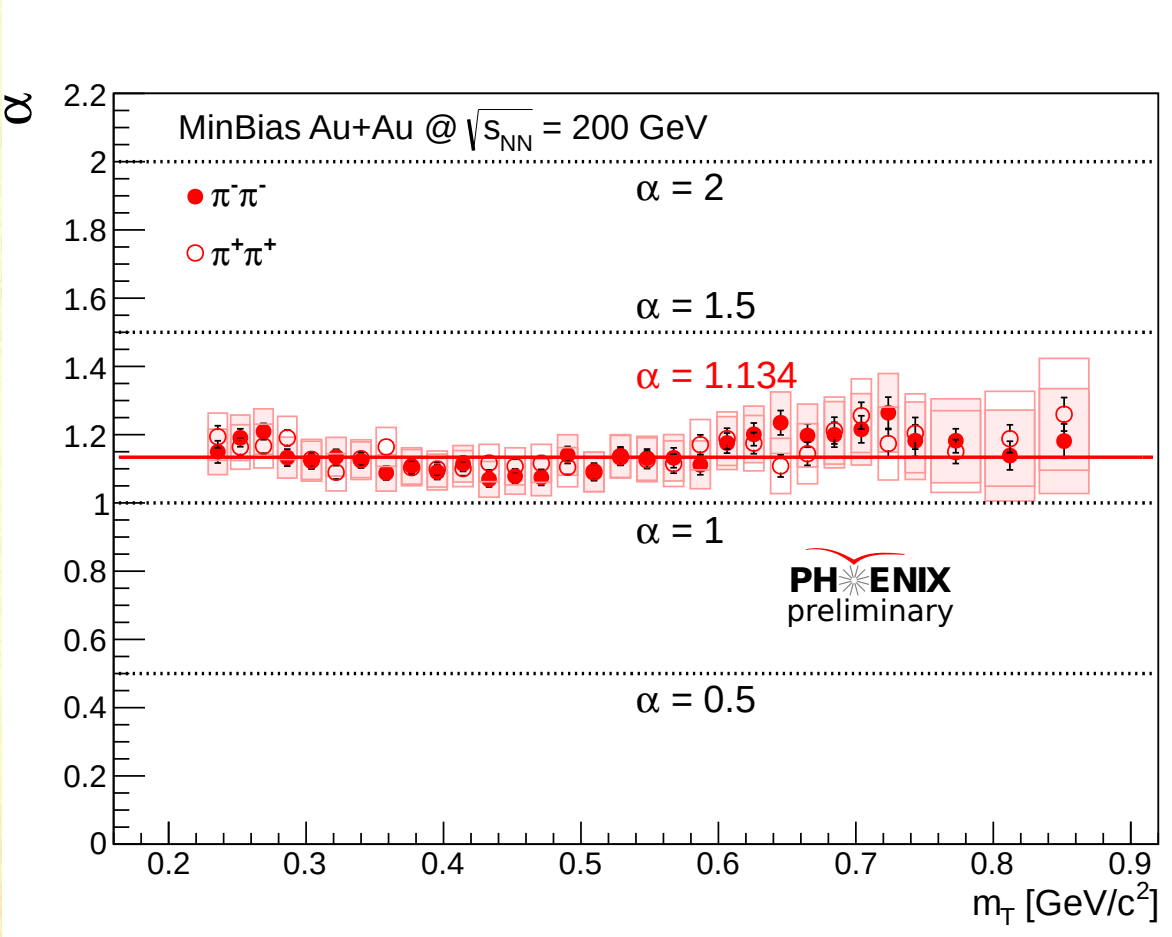
Example correlation function



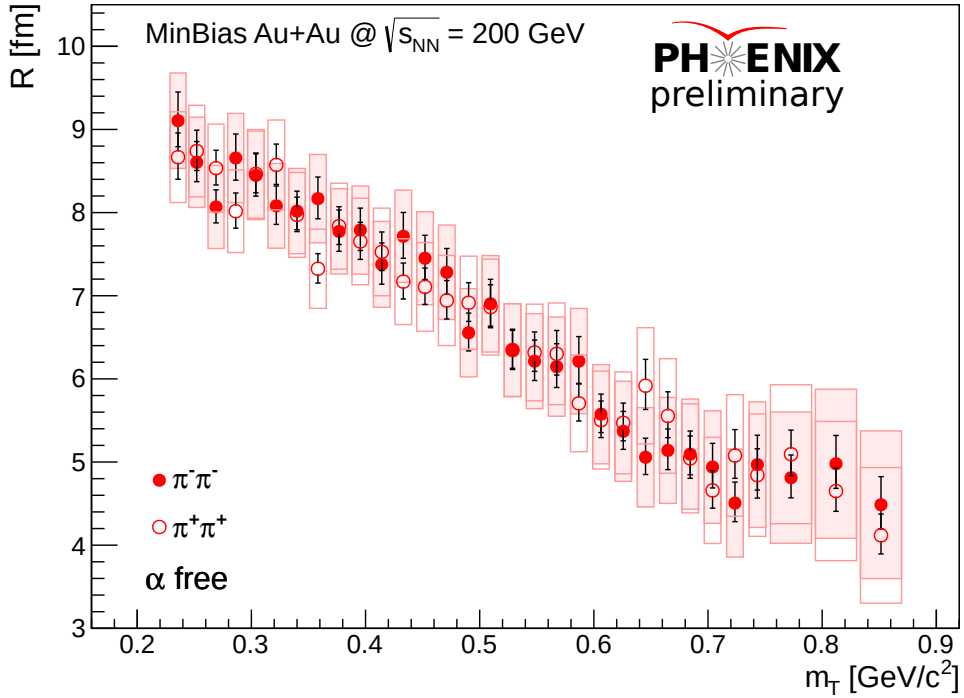
- $\pi^+\pi^+$ corr. func., $p_T = (0.2 - 0.22)$ GeV/c
- **Fitted function: HBT-correlation + Coulomb interaction + linear background**

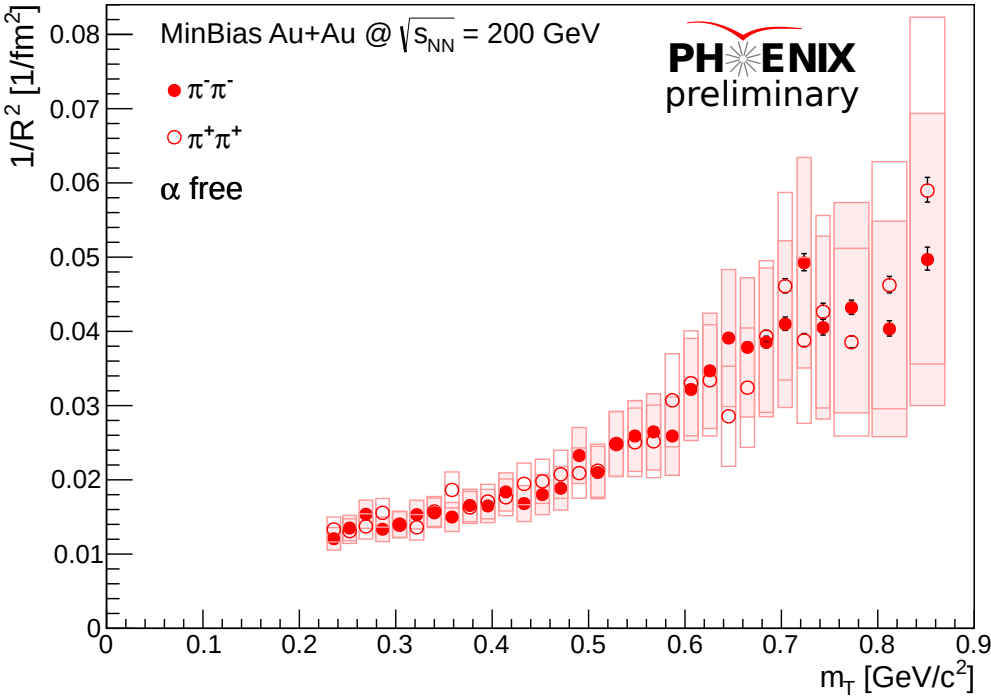
Lévy exponent α

- Hydrodynamics $\rightarrow \alpha = 2$
- **Measured value:** $\boldsymbol{\alpha \approx 1.134}$
- Measured value far from Gaussian ($\alpha = 2$) and exp. ($\alpha = 1$)
- Also far from rfd.3D Ising CEP value ($\alpha = 0.5$)
- More or less constant (within syst. err.)
- If we go to lower energies α vs. $\sqrt{s} \rightarrow$ CEP?



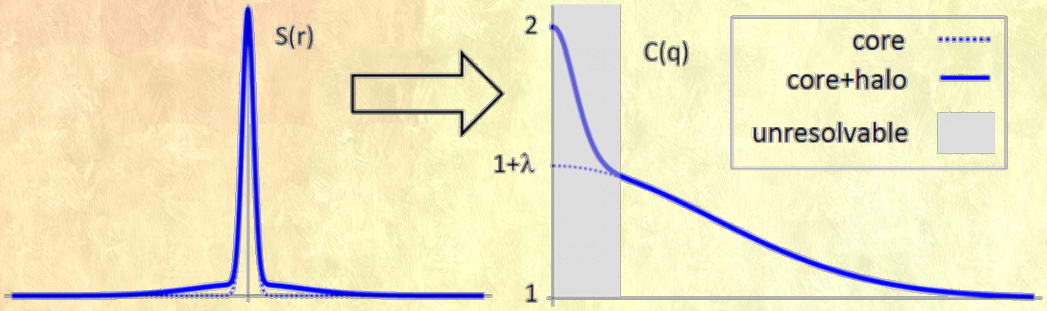
Lévy scale parameter R

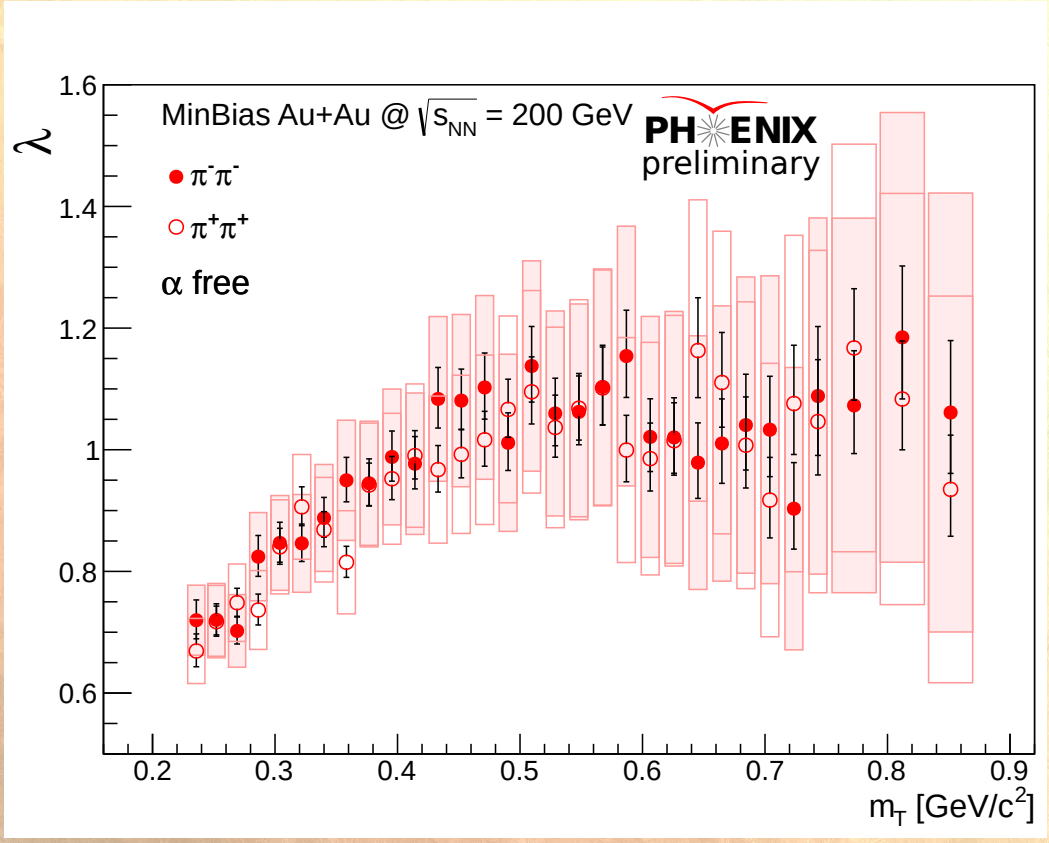




- Similar **decreasing trend** as Gaussian radii
- Hydro calculations for Gaussian radii $\rightarrow 1/R^2 \sim m_T$
- In case of low m_T, the linear scaling of $1/R^2$ holds

Correlation strength λ



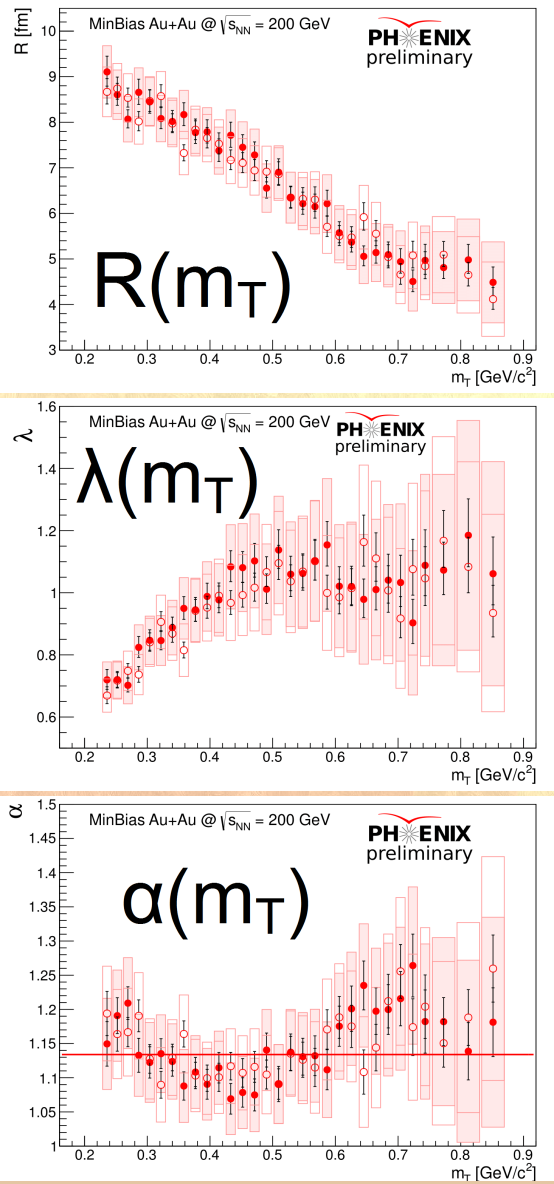


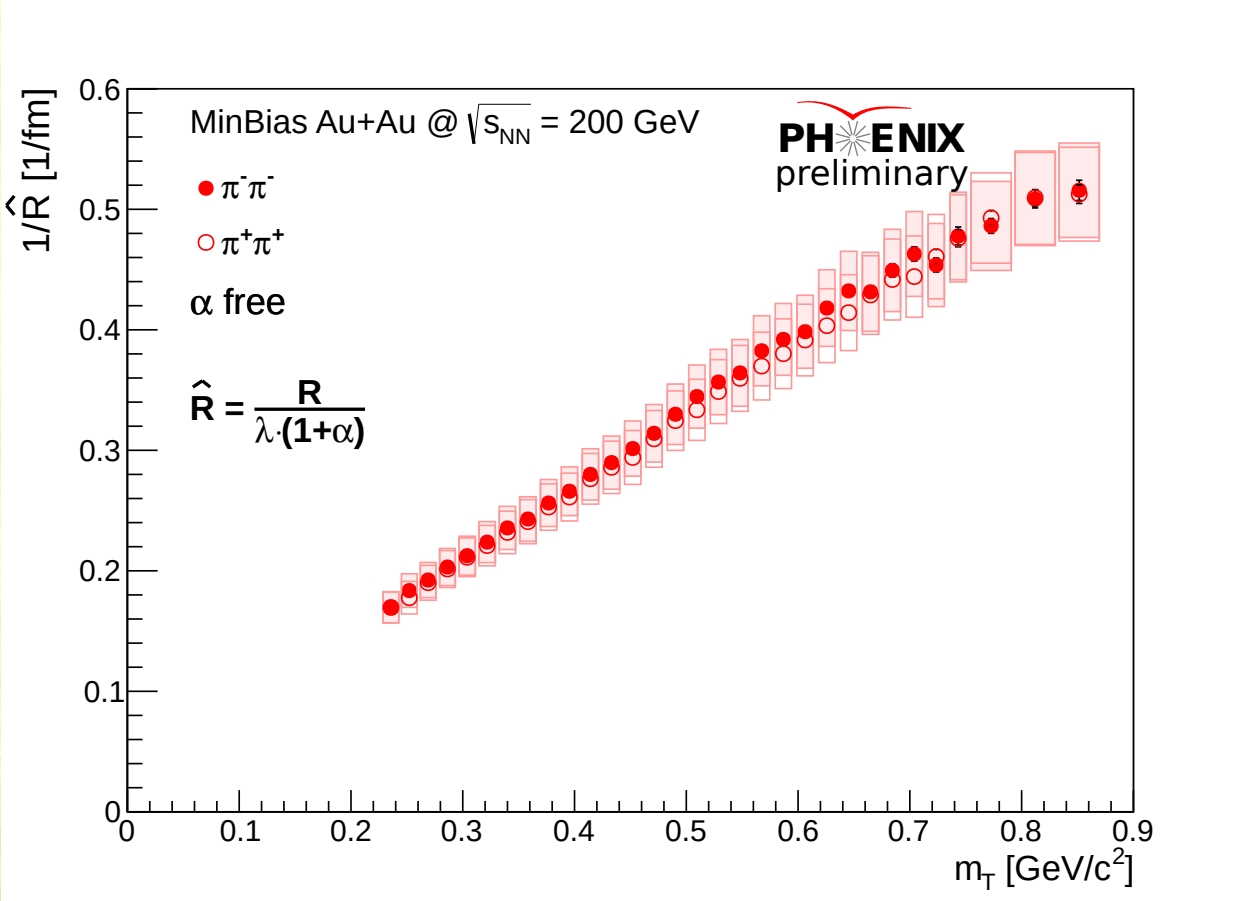
- **Core-Halo model:** $S = S_M + S_G$
- Primordial pions - Core $\lesssim$ 10 fm
- Resonance pions - Halo
- $C(q) \xrightarrow{q \to 0} 1 + \lambda$
- $\lambda = (N_M/(N_M + N_G))^2$

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

- **Decrease at small m_T: increase of halo fraction**
- Different effects can cause this:
  - Resonance effects
  - Partial coherence
  - Random fields
- Precise measurement is important

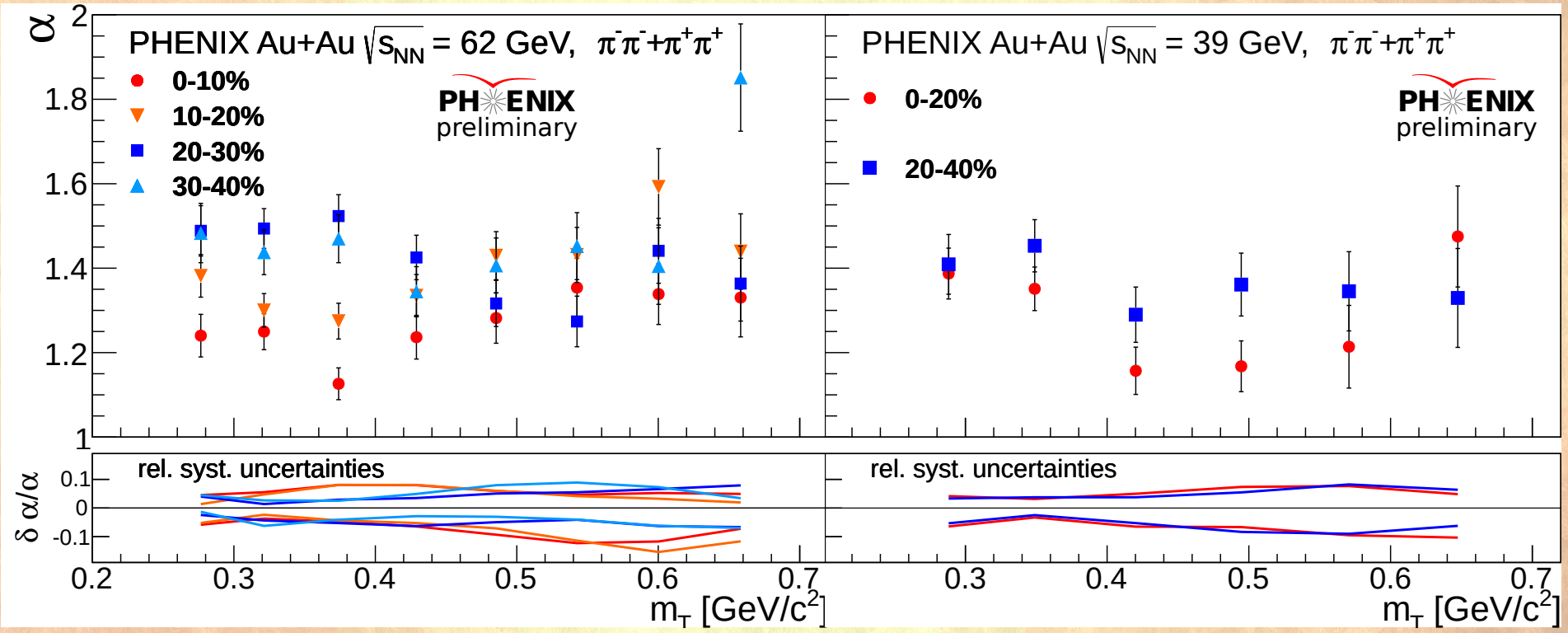
Newly found scaling parameter $\widehat{R}$





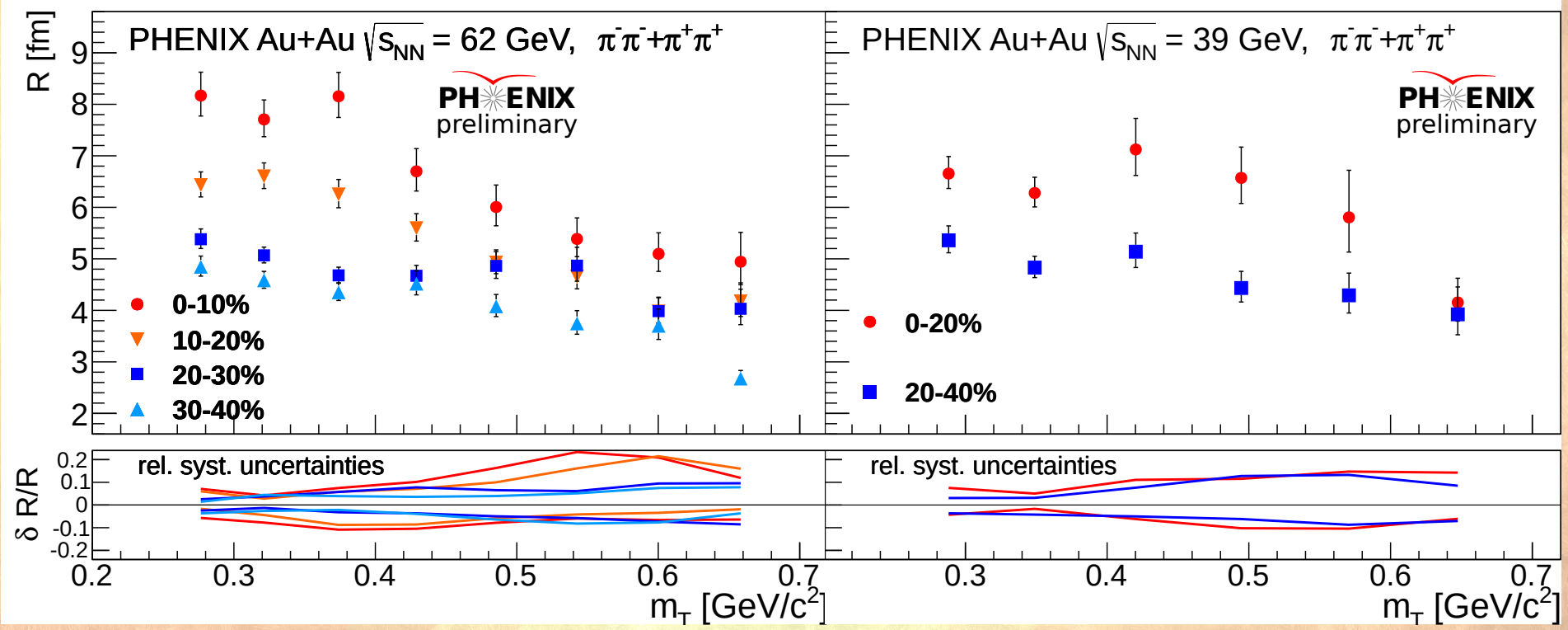
- Empirically found scaling parameter
- **$\widehat{R}^{-1}$ linear in m_T**
- Physical interpretation → open question

Results at 62 GeV, 39 GeV – $\alpha(m_T)$



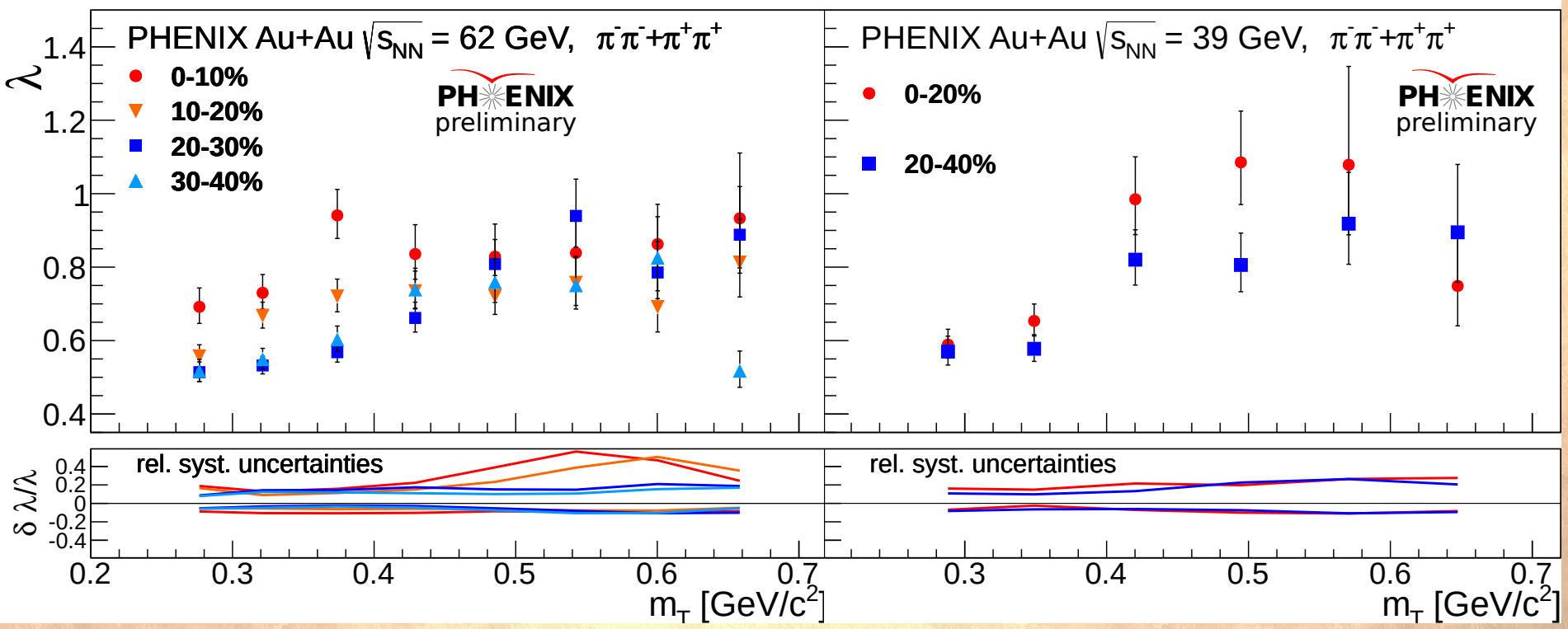
- Not really constant
- Values definitely above 0.5 (CEP limit)
- Values definitely under 2 (hydro limit)

Results at 62 GeV, 39 GeV – $R(m_T)$



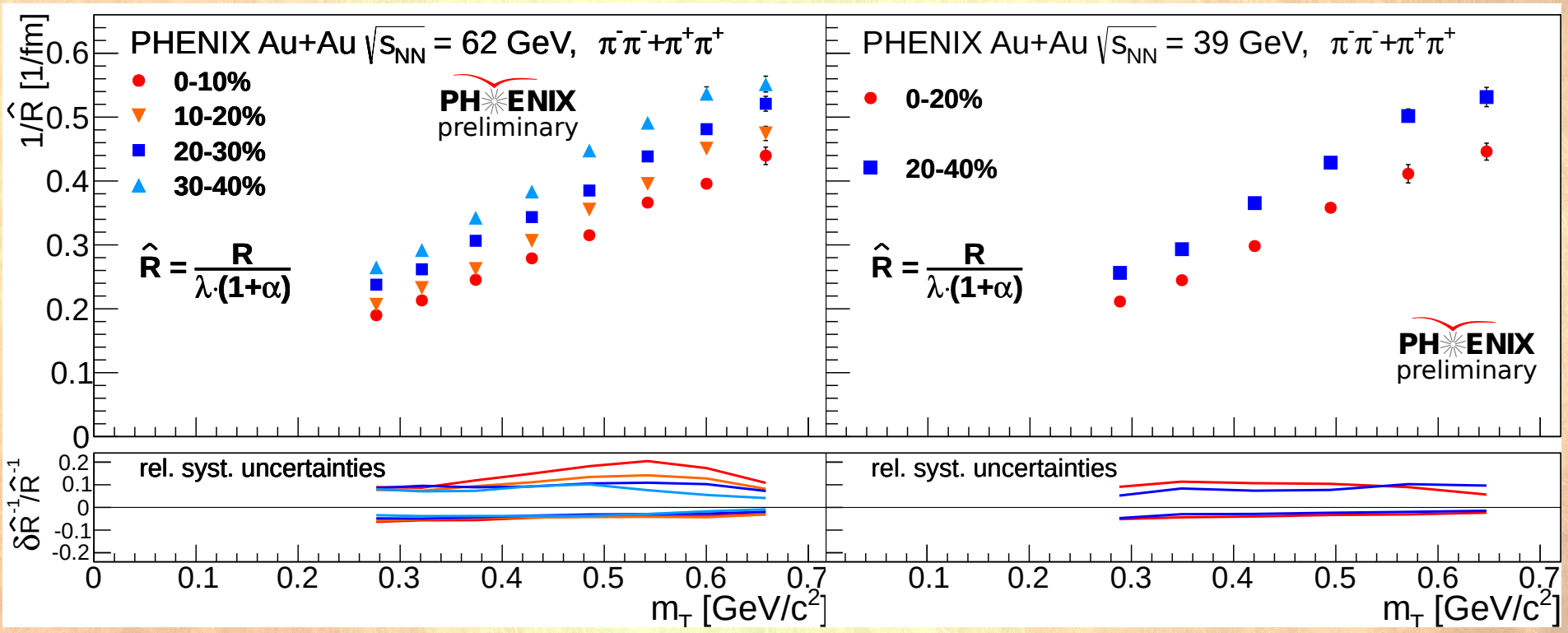
- Similar decreasing trend as at 200 GeV
- Magnitudes of R are similar in case of 200 GeV, 62 GeV, 39 GeV
- Geometrical centrality dependence (more central collision $\rightarrow$ greater R)

Results at 62 GeV, 39 GeV – $\lambda(m_T)$



- Suppression at low m_T is still present

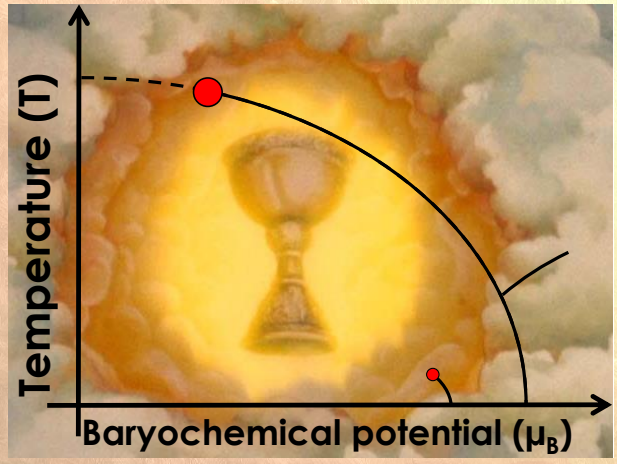
Results at 62 GeV, 39 GeV – $1/\widehat{R}(m_T)$



- Linear scaling holds
- Geometrical centrality dependence (more central collision $\rightarrow$ greater R)

Summary

- Data set: Run-10 200 GeV, 62 GeV, 39 GeV Au+Au, identified pions
- **precise measurement of Lévy source parameters (R, λ, α)**
  - At 200-62-39 GeV, $0.5 < \alpha < 2$
  - Hydro prediction ($\alpha = 2$) is not fulfilled, but $1/R^2 \sim m_T$ approximately holds
  - Decrease of λ at small $m_T \rightarrow$ increase of resonance fraction
- Empirically found scaling parameter: $\widehat{R} = R/(\lambda(1+\alpha))$, $\widehat{R}^{-1}$ linear in m_T
- The showed results are in the process of publication
- Current work: investigation of lower energies (27, 19, 15 GeV)



Thank you for your attention!

Emberi Erőforrások Minisztériuma

Supported by the ÚNKP-16-2 new national excellence program of the Hungarian Ministry of Human Capacities

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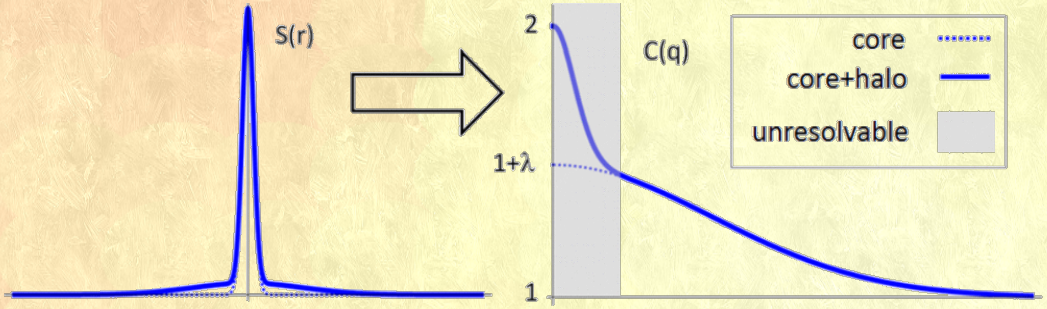

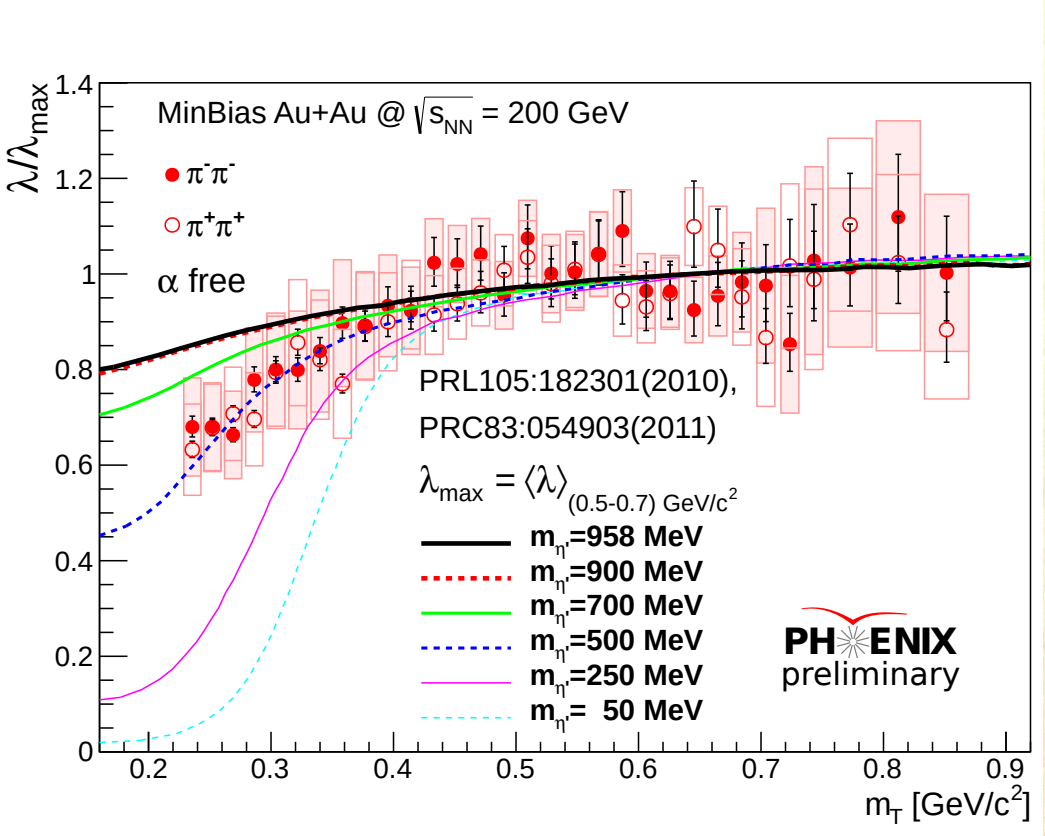

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- **Decrease at small m_T: increase of halo fraction**
- Different effects can cause this:
  - **Resonance effects:**
- **Indirect method for investigating the in-medium mass modification of η'**

Introduction to Bose-Einstein correlations

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

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

The invariant momentum distributions

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

- $S(x, p)$ 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. $\to S$

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

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

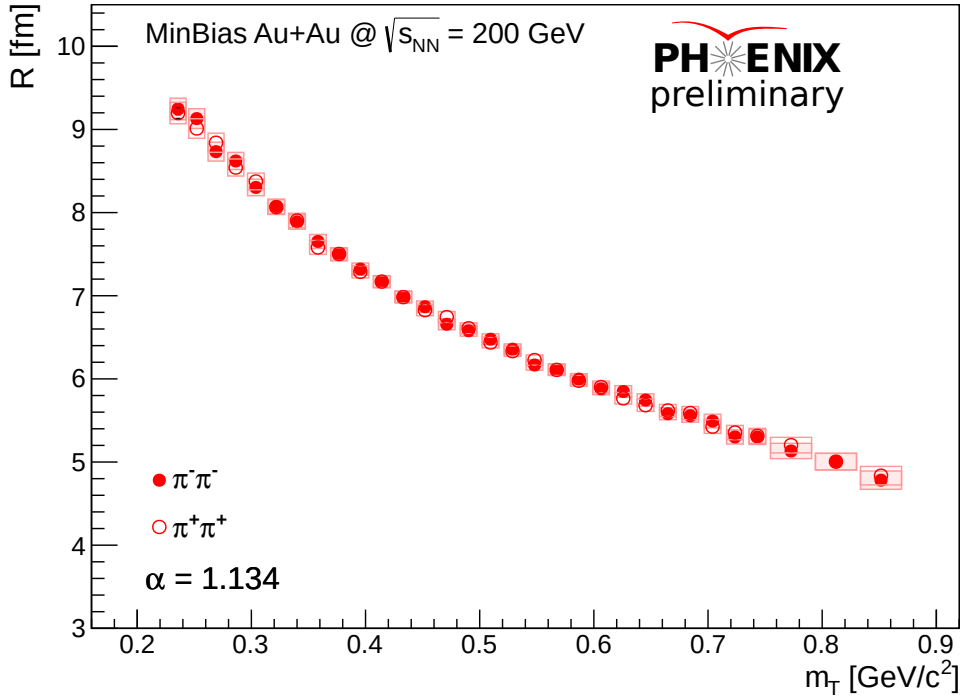
The out-side-long system, HBT radii

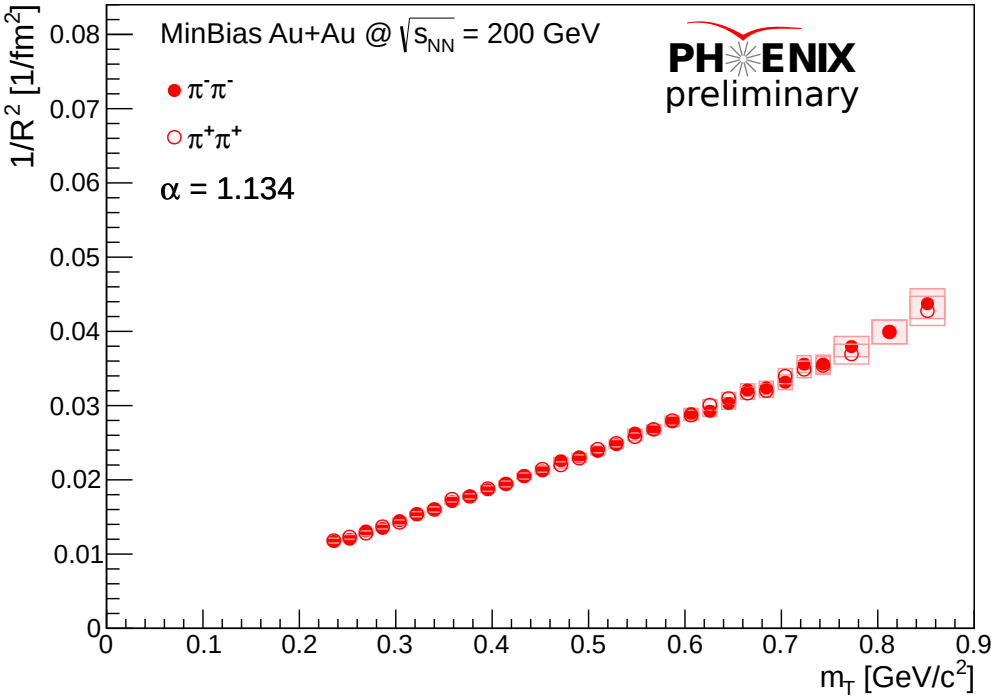
- Corr. func. (with Gaussian source): $C_2(q) = 1 + \lambda \cdot e^{-R^2_{\mu\nu} q^\mu q^\nu}$
- Bertsch-Pratt pair coordinate-system
  - out direction: direction of the average transverse momentum (K_t)
  - long direction: beam direction (z axis)
  - side direction: orthogonal to the latter two
- 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 1st order phase trans.

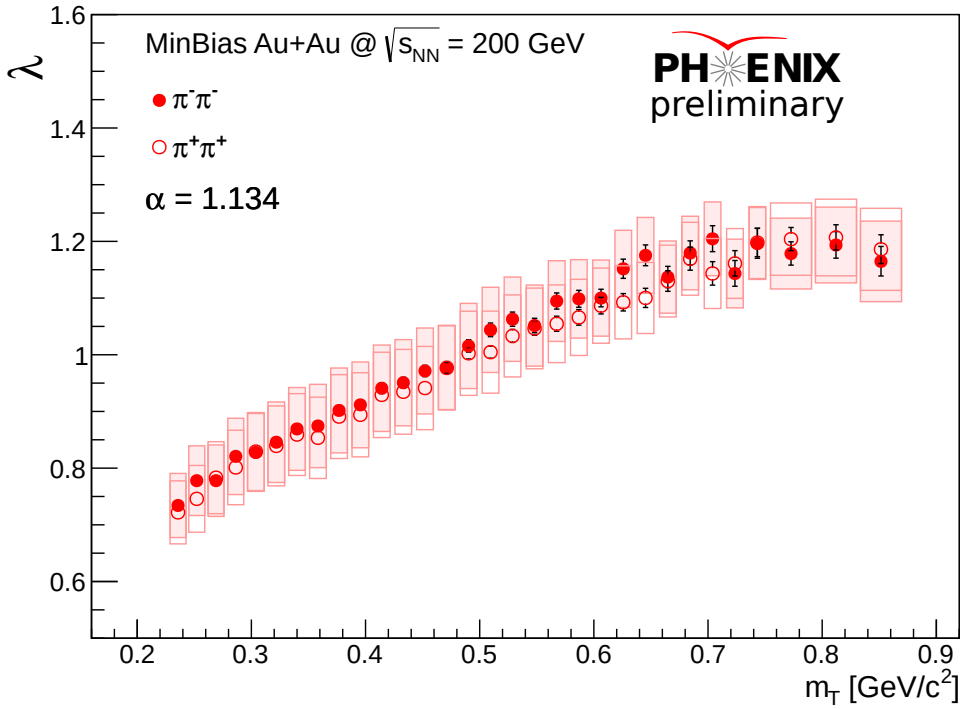
Lévy scale parameter R with fixed $\alpha = 1.134$

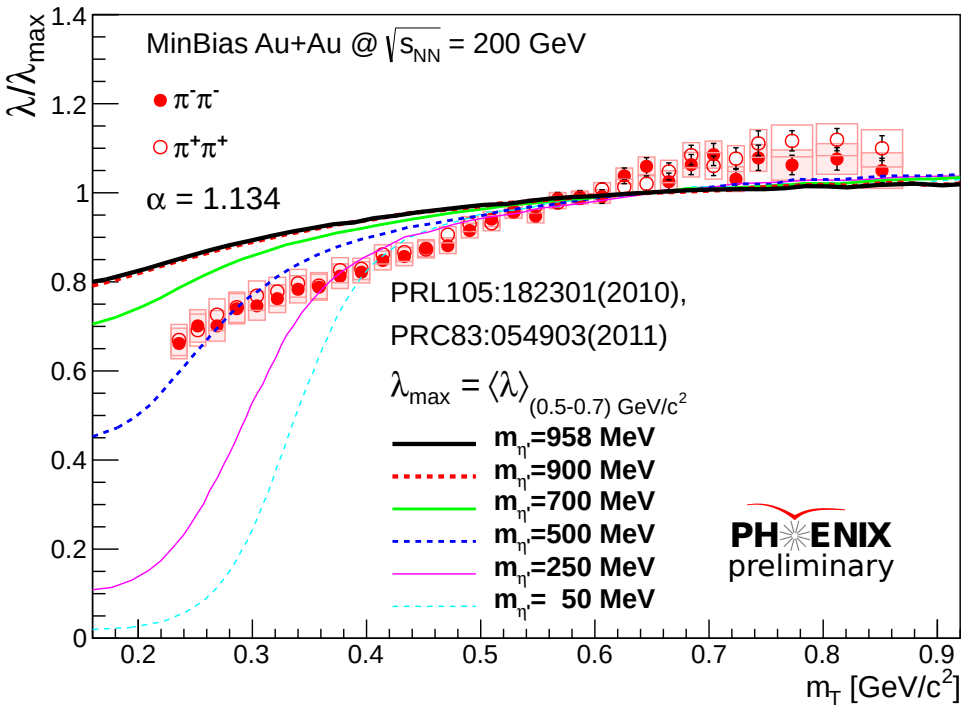




- More smooth trend
- Hydro behavior seems to be more valid
- The linearity of $1/R^2$ holds

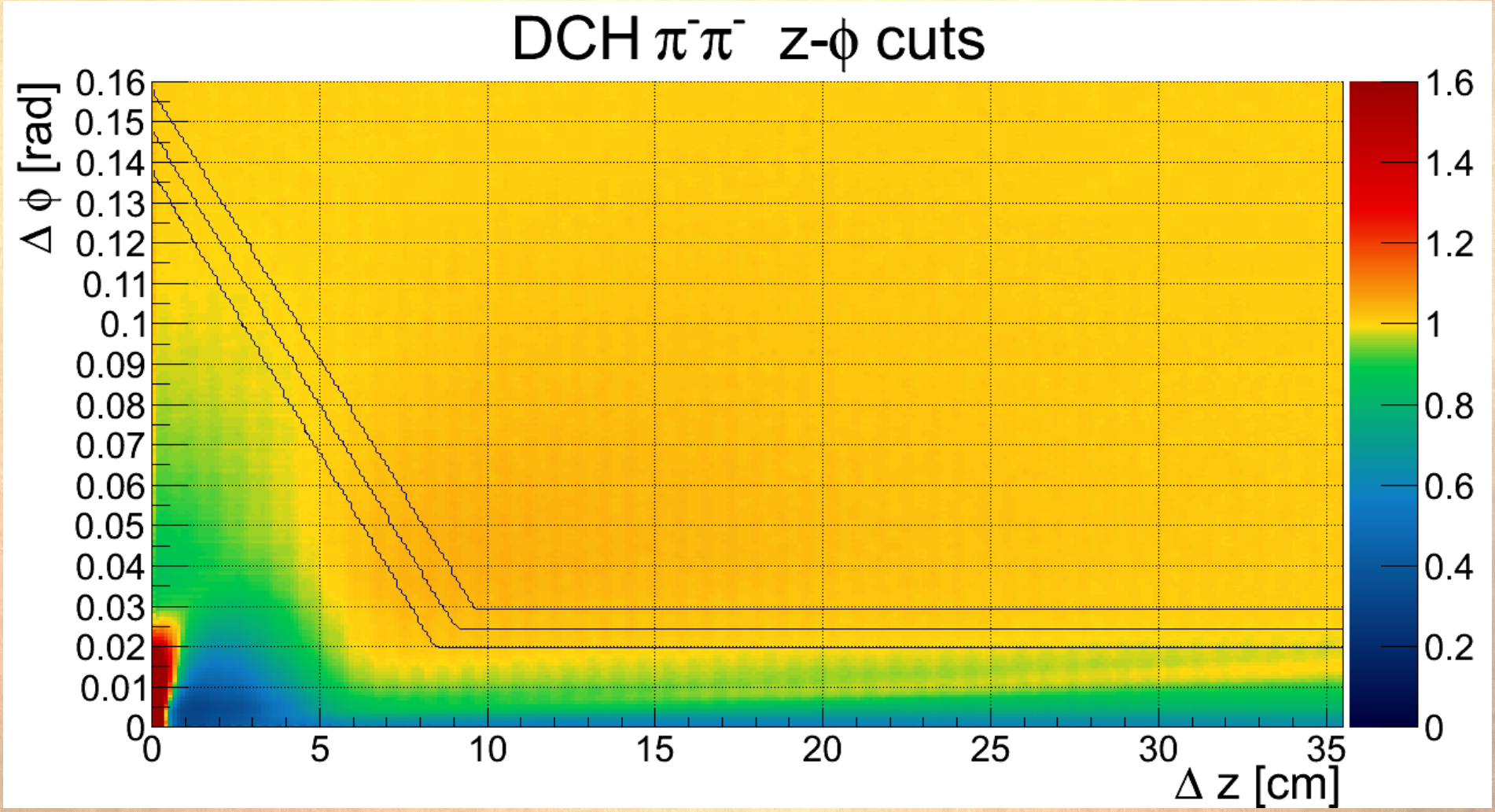
Correlation strength λ with fixed $\alpha = 1.134$



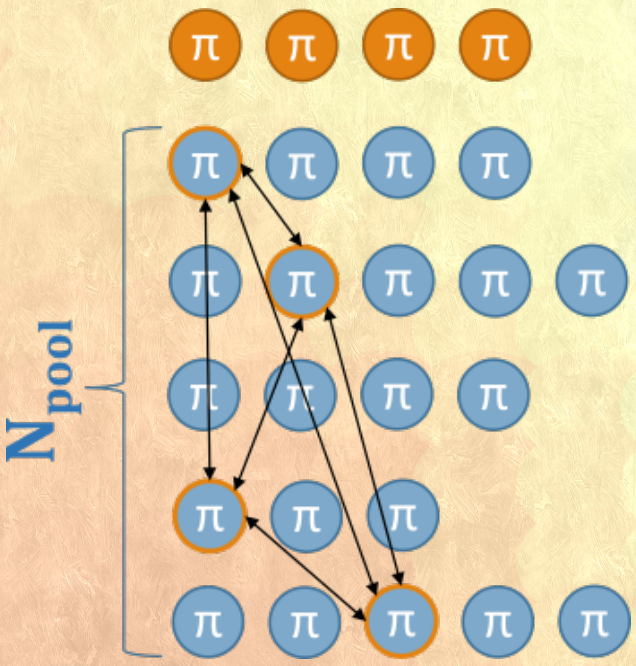


- More smooth trend
- Smaller systematic errors

An example for paircuts



Event mixing method



- Corr.func. from actual and background events
- $C(q) = A(q)/B(q)$
- 3% wide cent. and 6 cm wide zvtx classes
- Event mixing:
  - From the background pool we choose N evts., where N is the multiplicity of the act. evt.
  - From every chosen evt. we chose one pion randomly
  - Background distribution: from correlating the chosen pions

Fitting with iterative method

- The func. containing the Coulomb int. is pre-calculated and stored in a database $\rightarrow C_2(\lambda, R, \alpha; q)$
- Numerically fluctuating χ^2 map
- We need a second-round iterative afterburner:

$$C_2^{(0)}(\lambda, R, \alpha; q) \frac{C_2(\lambda_0, R_0, \alpha_0; q)}{C_2^{(0)}(\lambda_0, R_0, \alpha_0; q)} \times N \times (1 + \varepsilon q),$$

$$\text{ahol} \quad C_2^{(0)}(\lambda, R, \alpha; q) \equiv C_2^{(0)}(q) = 1 + \lambda \cdot e^{-(qR)^\alpha},$$

- As long as the new parameters differ significantly from the previous, we continue iterating

$$\Delta_{\text{iteration}} = \sqrt{\frac{(R_{\text{n+1}} - R_{\text{n}})^2}{R_{\text{n}}^2} + \frac{(\lambda_{\text{n+1}} - \lambda_{\text{n}})^2}{\lambda_{\text{n}}^2} + \frac{(\alpha_{\text{n+1}} - \alpha_{\text{n}})^2}{\alpha_{\text{n}}^2}} < 0.01.$$