Centrality dependent Levy HBT at PHENIX

SANDOR LOKOS (MATE KRC & IFJ PAN)

ZIMANYI WINTER WORKSHOP 2024

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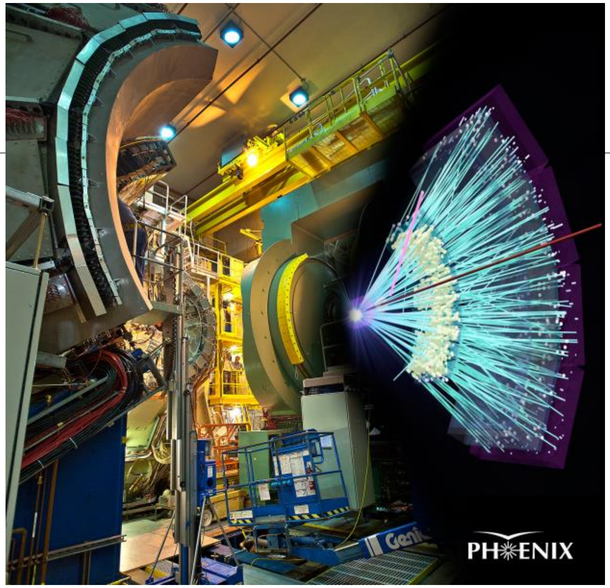
The PHENIX and the BES

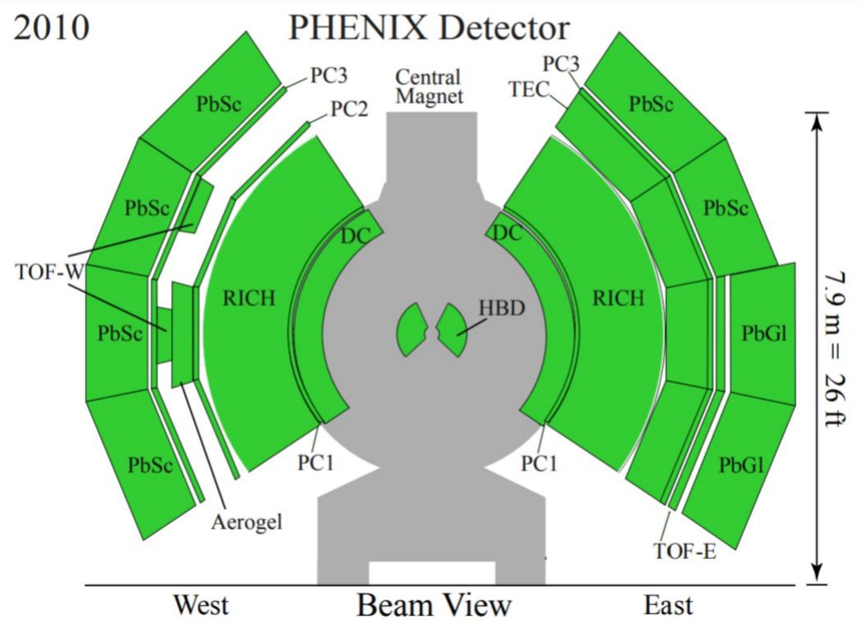
Collision energies: 7.7 to 200 GeV

20-400 MeV in μ_B, 140-170 MeV in T

This talk: 200 GeV Au+Au

$\sqrt{s_{NN}}$ [GeV]		Al	Au	Au	Au	Cu Cu	Cu Au	Au Au	U U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	





Femtoscopy – introduction

Originates from radio astronomy

- Hanbury-Brown and Twiss observed intensity correlation
- In high energy physics, Goldhaber, Goldhaber, Lee and Pais

Technique to access the spatio-temporal structure of the particle emitting source

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

where we can use the Yano-Koonin formula to relate the mom. dists. to the source:

$$\boldsymbol{N_2(p_1, p_2) = \int dx_1 dx_2 S(x_1, p_1) S(x_2, p_2) |\Psi_2(x_1, x_2)|^2}$$

S: source function, Ψ_2 two-particle wavefunction

Femtoscopy – two approaches

Assume the source shape: **S ~ Gaussian**

Measure in a clean environment, e. g. in pp

Learn about the final state interactions encoded into the wave function

Program in ALICE:

$p-K, p-p, p-\Lambda, \Lambda-\Lambda, p-\Xi, p-\Omega,$

$p-\Sigma, p-\phi, N-\Sigma, N-\Lambda$

Assume the **wave function**: free planewave

$$|\Psi_2|^2 = 1 + \cos\left((p_1 - p_2)x\right)$$

Not to realistic: Coulomb (and strong) FSI

What is the interacting wave function?

$$\Psi_2 \sim \frac{\Gamma(1+i\eta)}{e^{\frac{\pi\eta}{2}}}\left[e^{i\boldsymbol{kr}}F\left(-i\eta, 1, i(kr - \boldsymbol{kr})\right)\right]$$

$$+\boldsymbol{r} \to -\boldsymbol{r}$$

(more complicated with strong interaction)

Learn about the **source size** and **shape**

Final state interactions

Like-charged pions → Coulomb correction

Strong final state interaction may play a role

Effect of the resonances: core-halo model

- Long-lived resonances contribute to the halo
- In-medium mass modifications could cause specific m_T dependence

Partially coherent particle production (core-halo model)

Aharonov-Bohm like effect: the hadron gas acts as a background field, the correlated bosons paths are the closed loop

Levy parametrization of the C_2

Generalized Gaussian – Levy distribution

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

$\alpha = 2$: Gaussian, $\alpha = 1$: Cauchy, $0 < \alpha \leq 2$: Levy

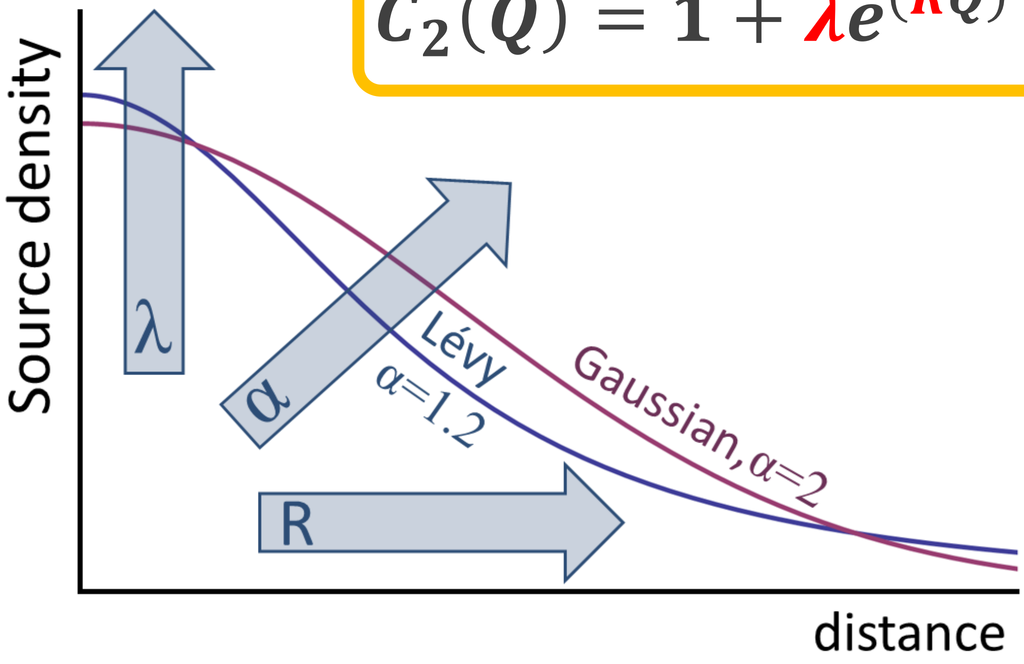
Assume the source to be Levy!

$\lambda(K)$: core-halo parameter

$R(\mathrm{K})$: Levy-scale parameter

$\alpha(K)$: Levy index of stability

$$C_2(Q) = 1 + \lambda e^{(RQ)^\alpha}$$



Csörgő, Hegyi, Zajc *Eur.Phys.J.C* 36,67

Physics in the parameters

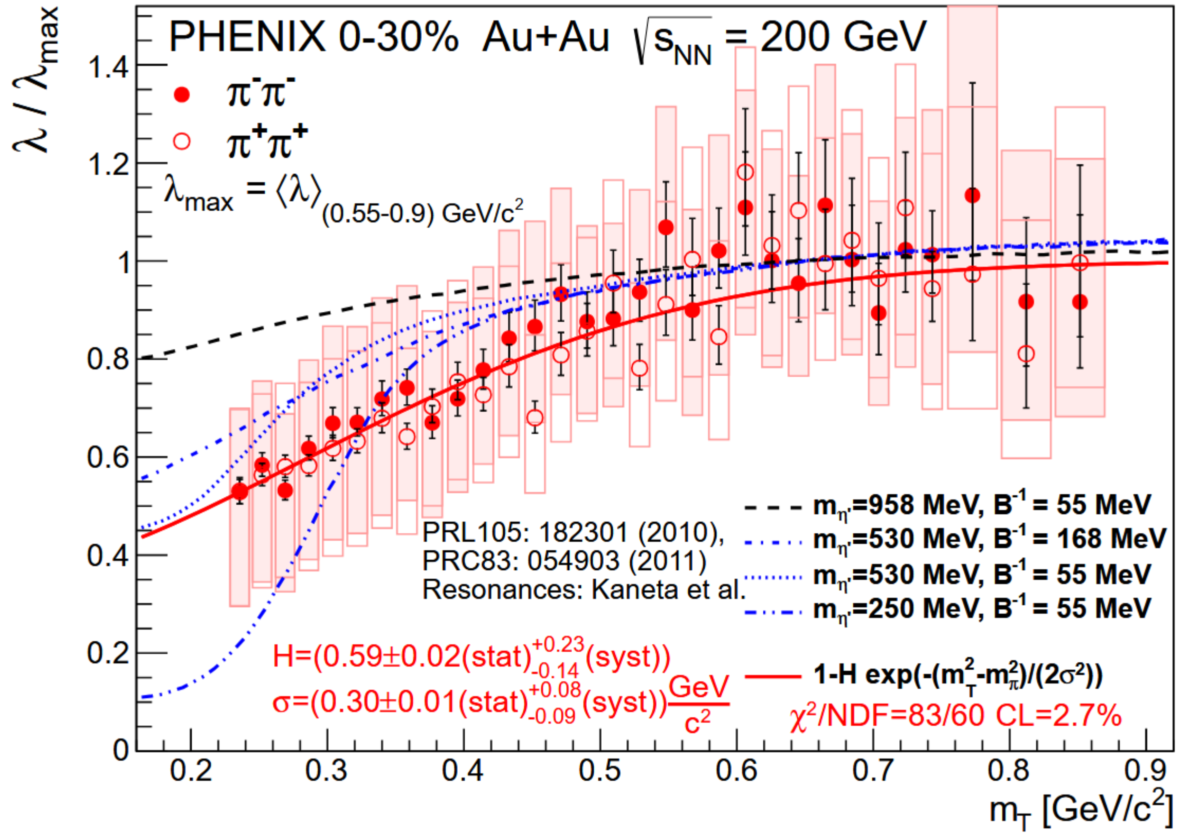
Possible interpretations of the λ:

1. Specific m_T suppression linked to chiral restoration:
   - $\rightarrow$ decreased η' mass
   - $\rightarrow$ more η' produced
   - $\rightarrow$ more decay pions
   - $\rightarrow$ m_T specific suppression of λ

   $\Rightarrow 2^{nd}$ transition besides the free quarks

2. Measuring two- and three particle correlations could shed light on partially coherent particle production (see core-halo model)

PHENIX, *Phys.Rev.C* 108, 4



Physics in the parameters

Possible interpretation of the R:

- Important: $R_{Levy} \neq R_{Gauss}$
- Is it related to the size? Check hydro-like scaling: $\frac{1}{R^2} = A\, m_T + B$
- Seen in Gaussian parametrizations
- In 3D it is especially important to measure it precisely!

Possible interpretation of the α:

- Surprising similarity with the critical exponent of the spatial correlation in 3D

$$\text{spatial corr.} \sim r^{-1-\eta} \qquad \text{symm. Levy dist.} \sim r^{-1-\alpha}$$

- Sudden change in α might be a sign for critical behavior
- Could be the sign of anomalous diffusion or jets

MEASURE HBT WITH THE PROPER PARAMETRIZATION

Centrality dependent HBT analysis from PHENIX

Au+Au @ 200 GeV from Run 10, $\pi^+\pi^+ + \pi^-\pi^-$

$\alpha, R, \lambda, \frac{1}{R^2}, \frac{1}{\hat{R}}, \frac{\lambda}{\lambda_{max}}$ in 6 cent bin (0-10% … 50-60%) and 24 m_T bins

1D variable $Q = |q_{LCMS}|$ (instead of $q_{inv} = |q_{PCMS}|$)

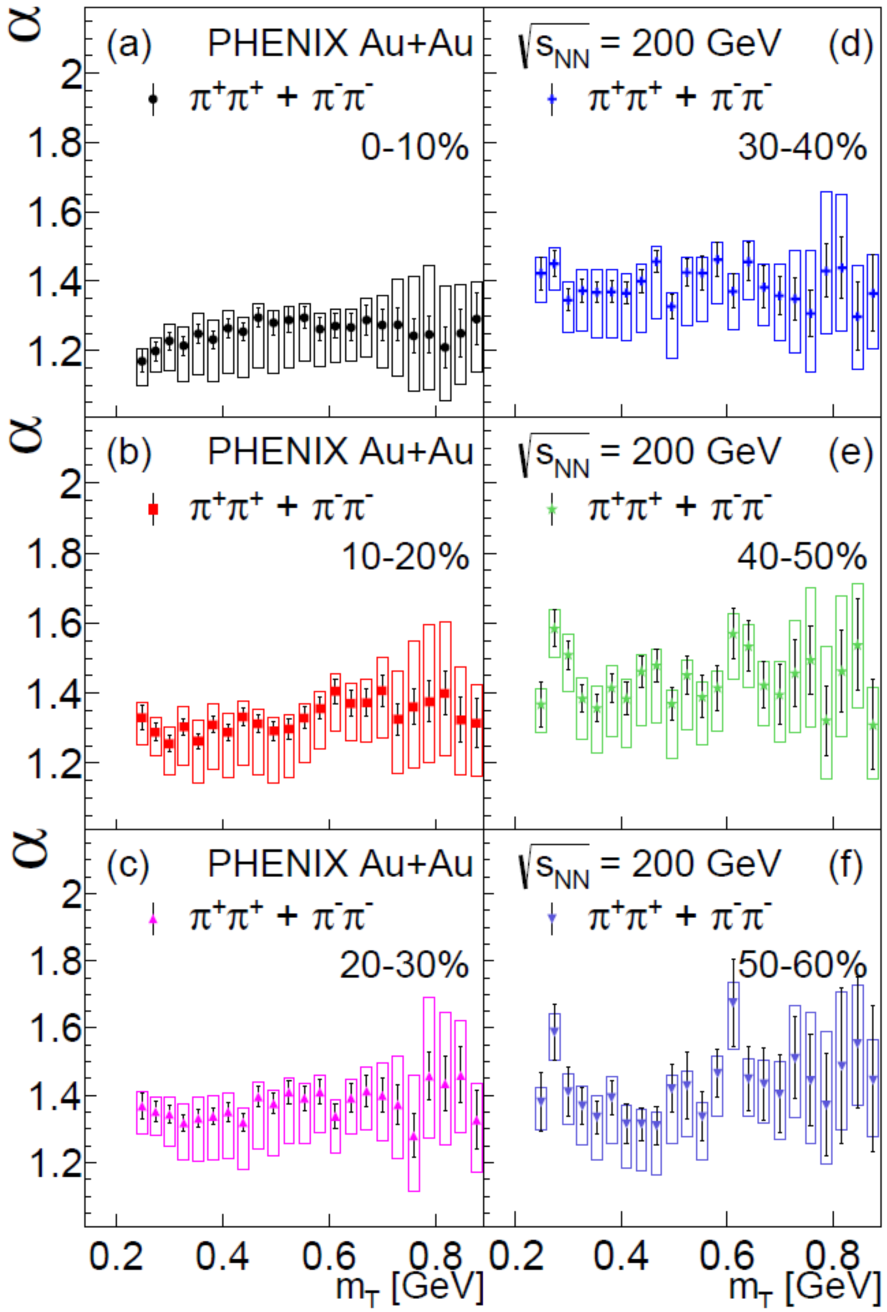
Fit function incorporates CC FSI (weighting for var. change)

Costume track and pair cuts to obtain clean sample

Check Levy shape validity: 1^{st} order corr. zero (*APP.Supp.* 9 (2016) 289)

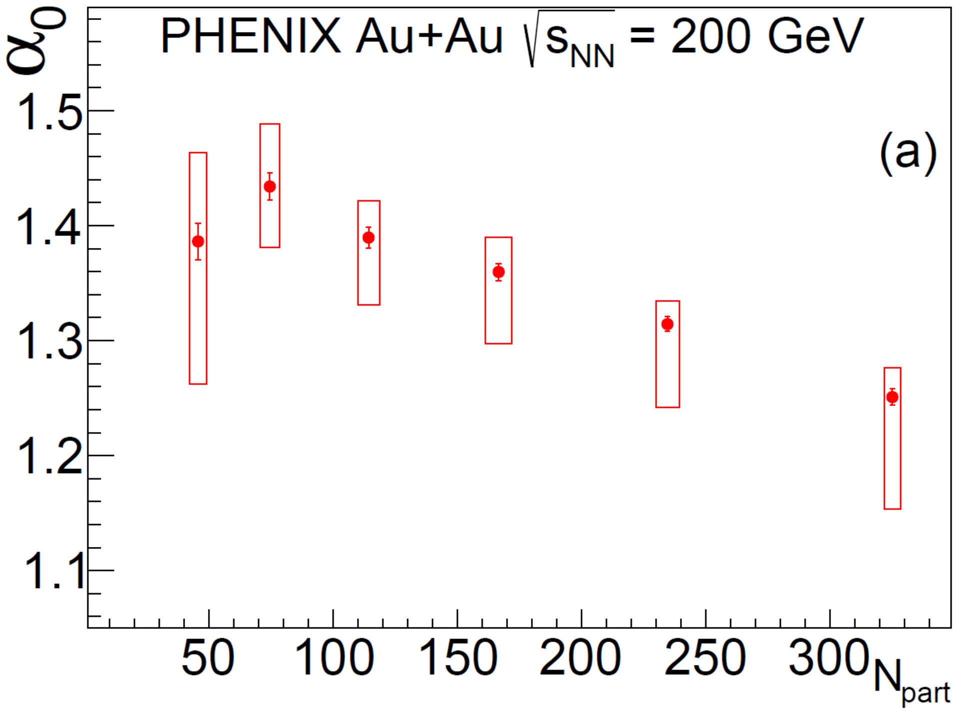
Accepted for publication in PRC, draft available at arXiv:2407.08586

Let’s see the results!

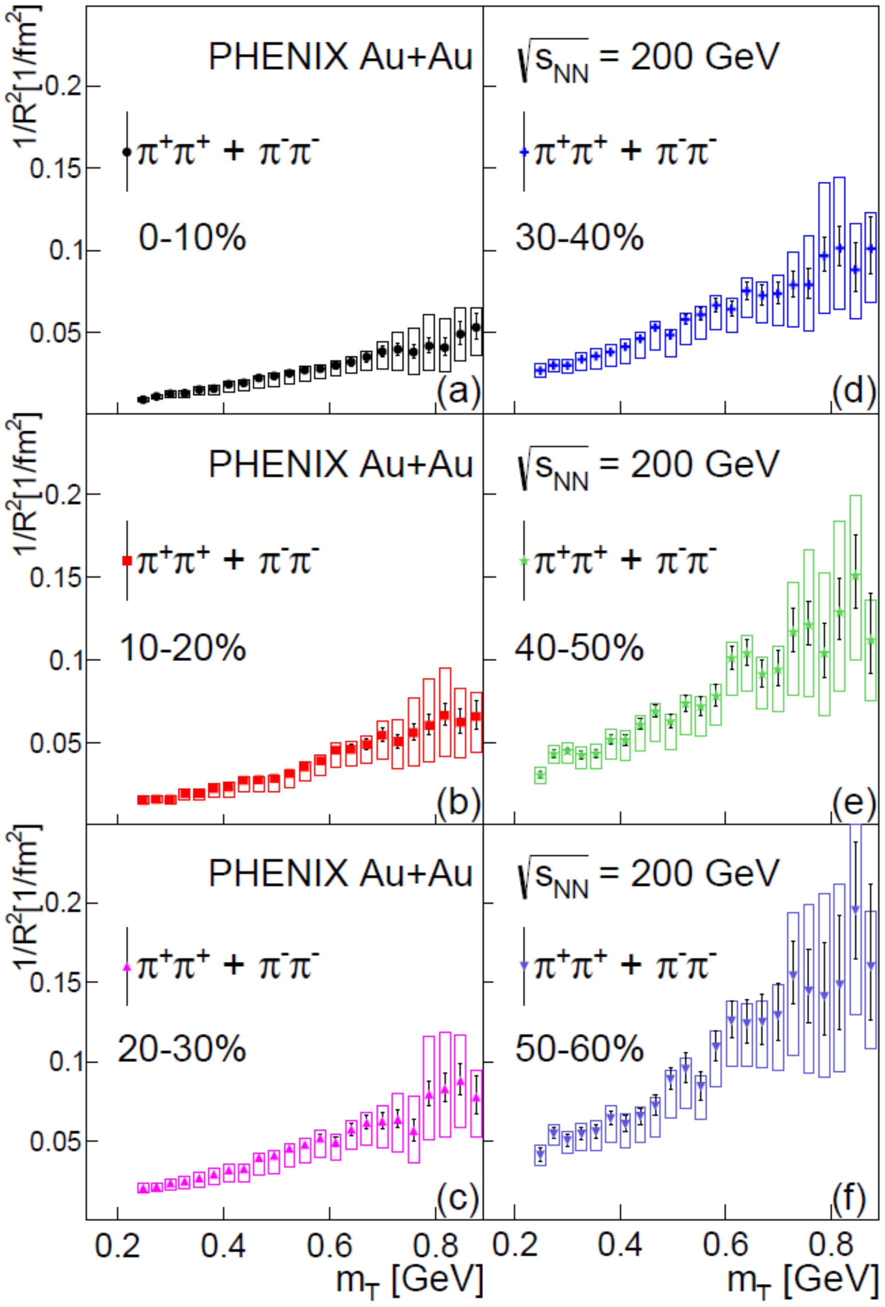


$\alpha(m_T, N_{part})$

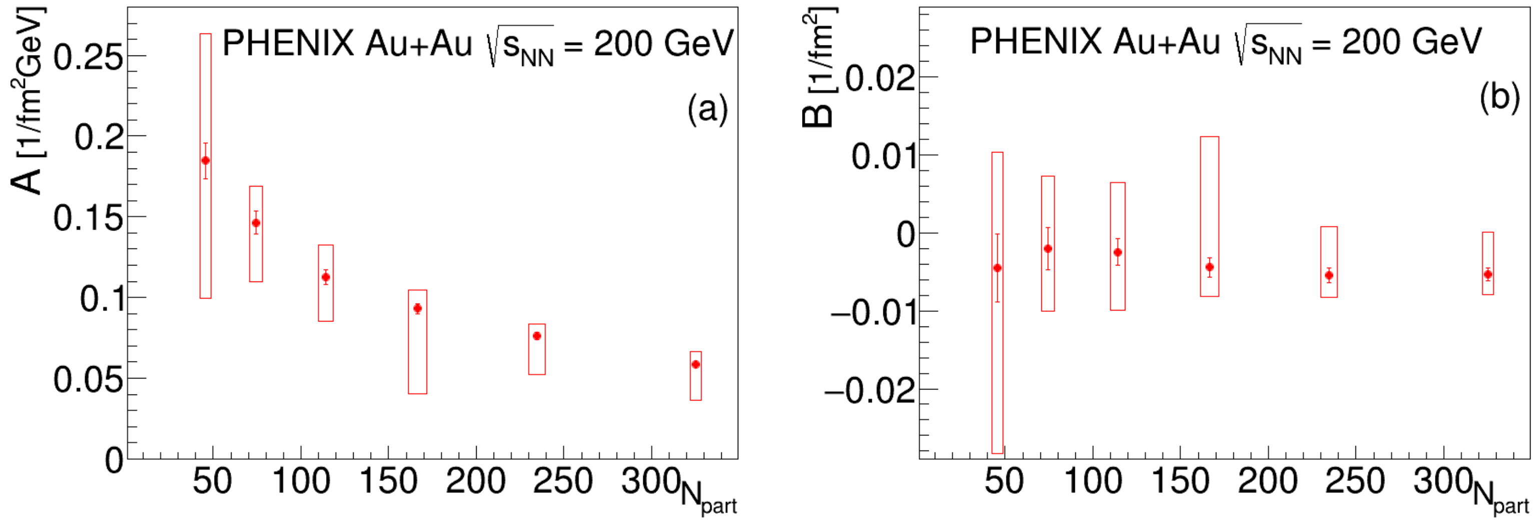
- Does not depend on m_T, does depend on N_{part}
- N_{part} dep. has model selection power
- Anomalous diffusion, QCD jets, resonances???
- (03.12. Csanad, 05. 12. Kincses, Kovacs, Arpasi, Molnar (poster))



$R(m_T, N_{part})$

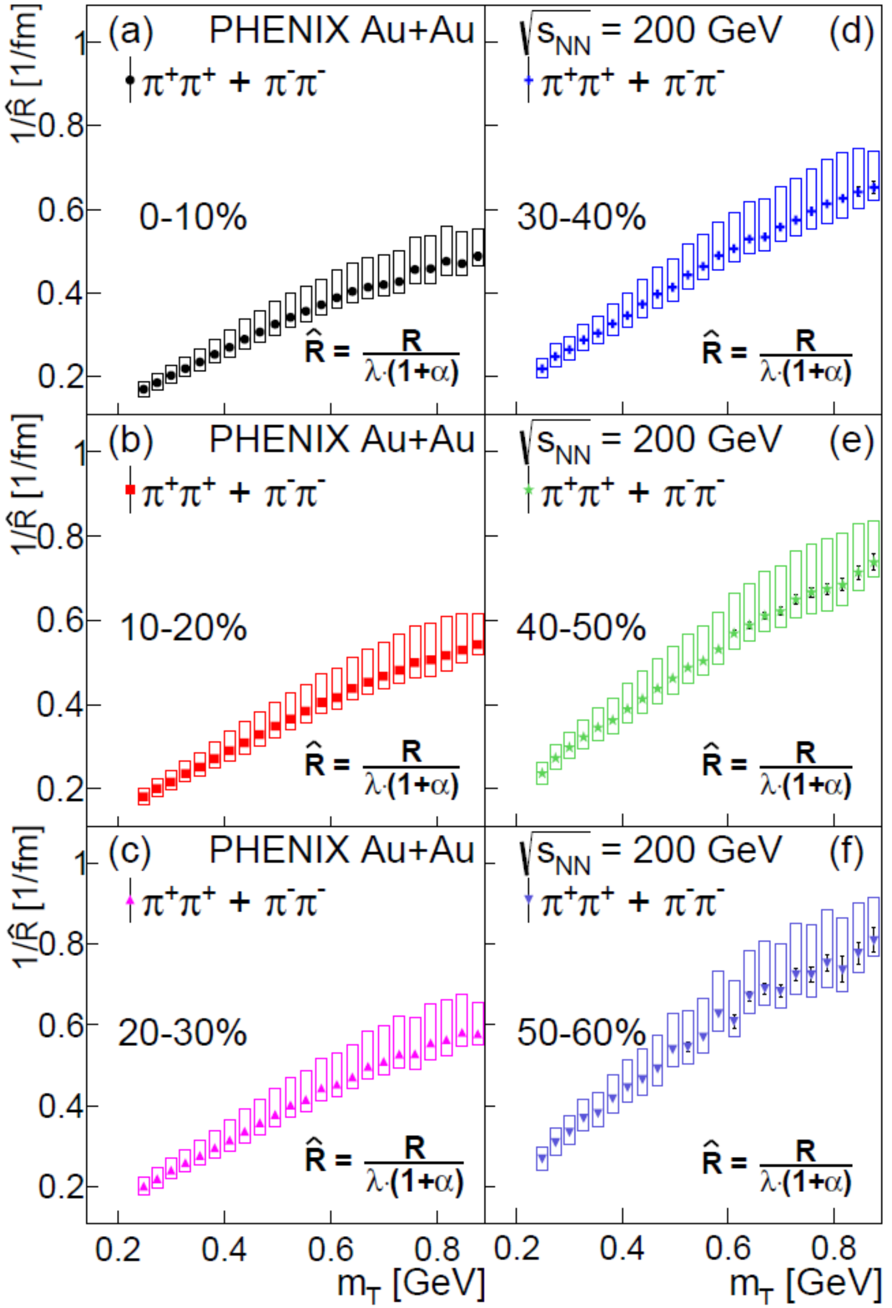


- Unexpected hydro scaling but not RMS
- Centrality ordering, monotonic behavior
- Related to the size?

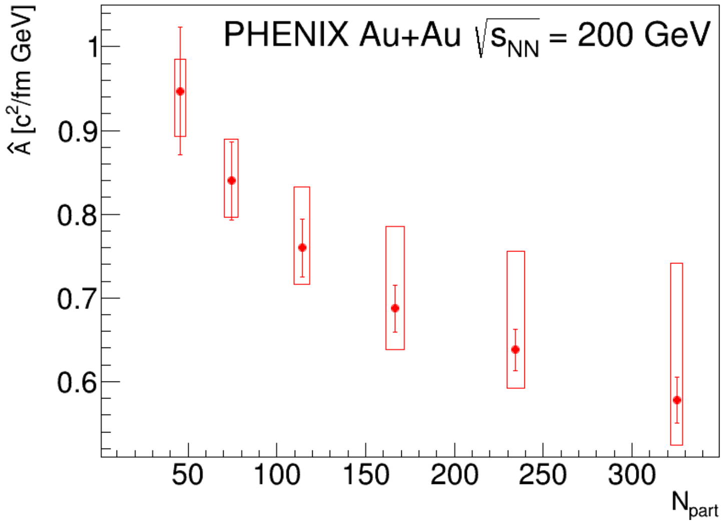


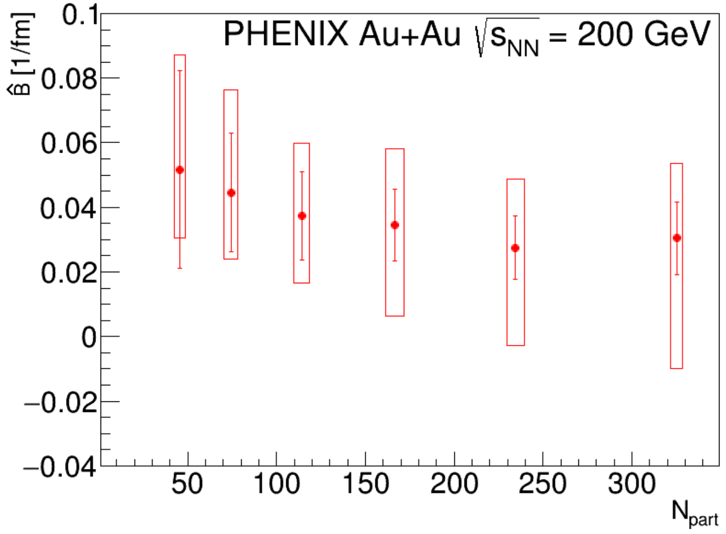
$$\frac{1}{R^2} = Am_T + B$$

$\hat{R}(m_T, N_{part})$



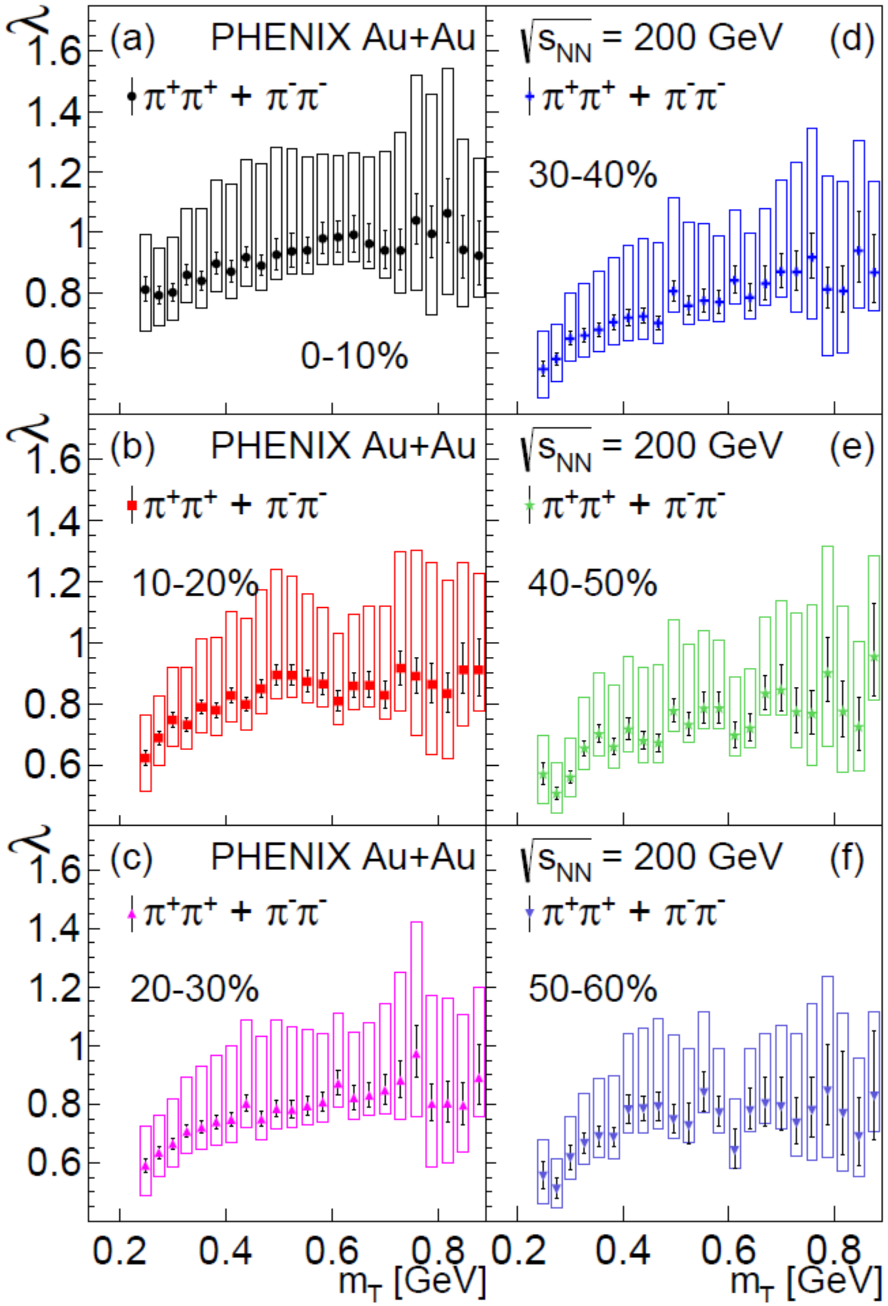
- Empirical parameter, surprisingly linear
- Centrality ordering, monotonic behavior
- Related to the size?



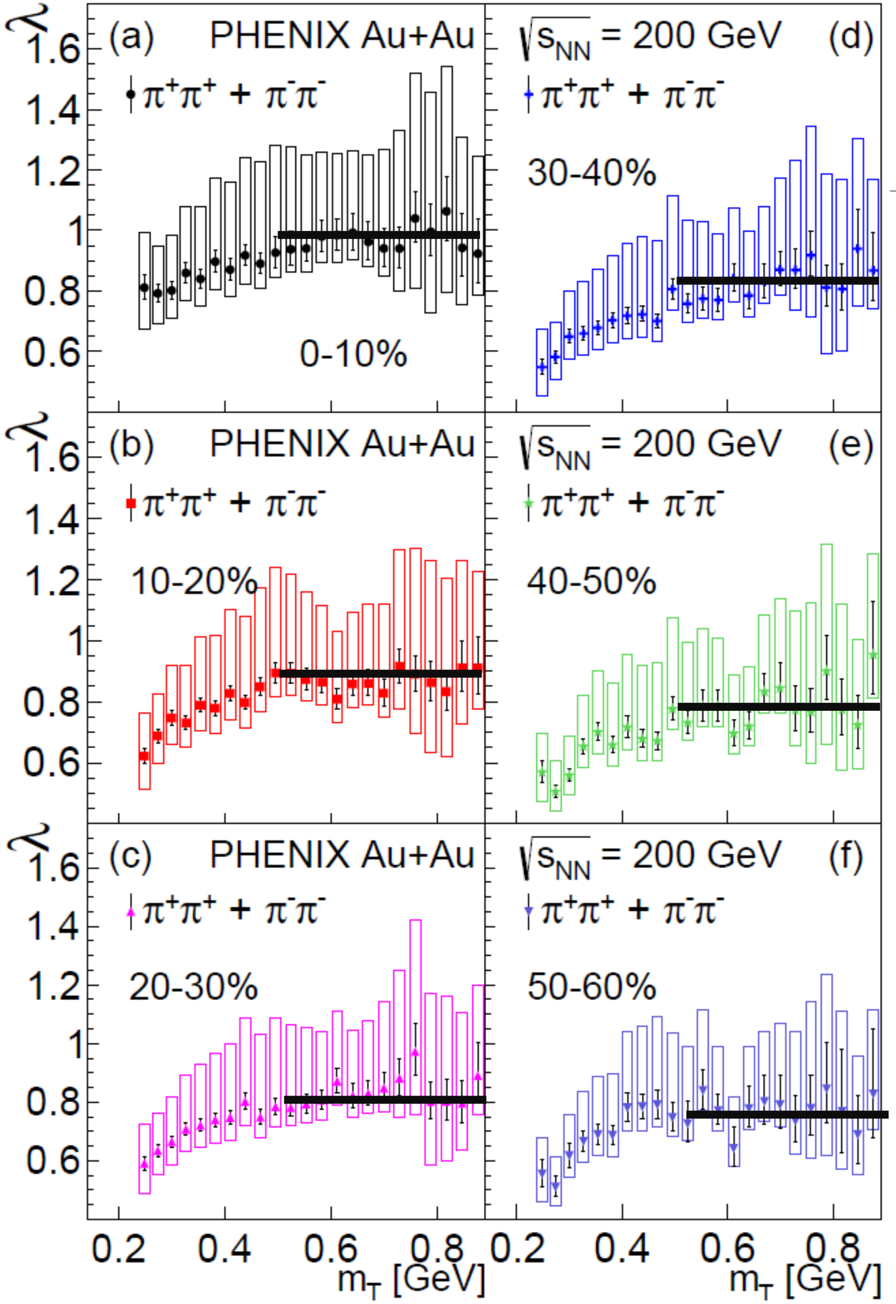


$$\frac{1}{\hat{R}} = \hat{A} m_T + \hat{B}$$

$\lambda(m_T, N_{part})$



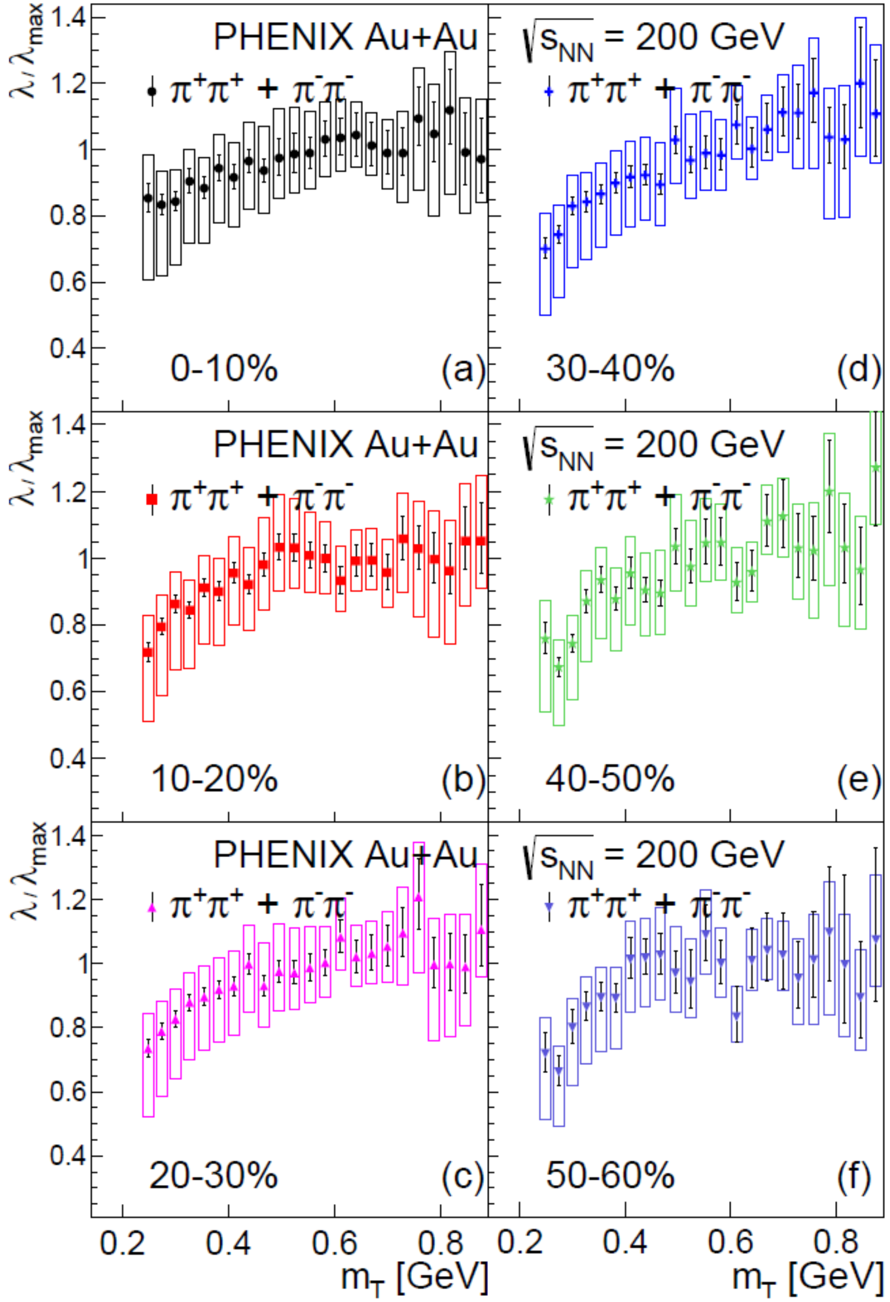
- Suppression on every centrality



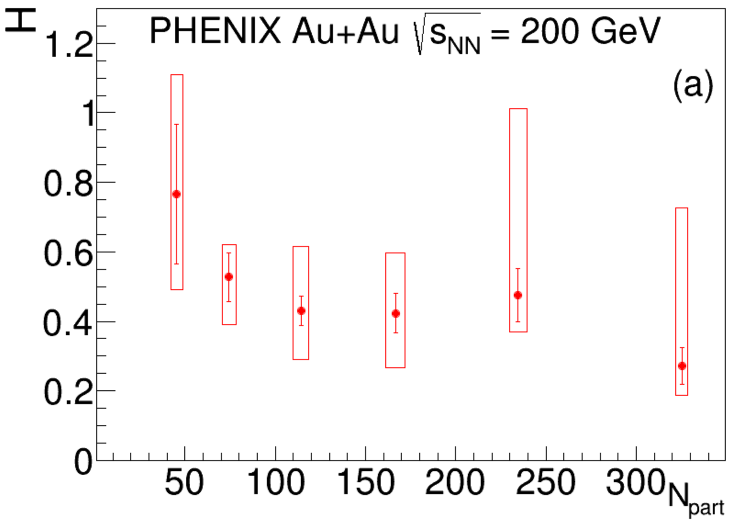
$\lambda(m_T, N_{part})$

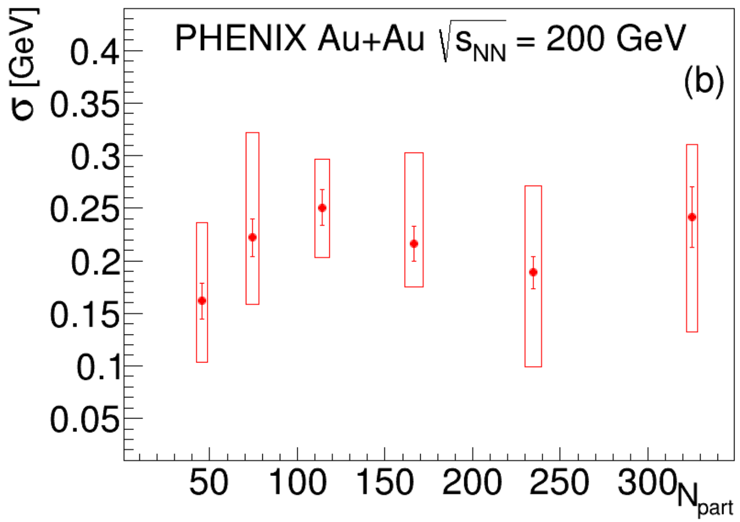
- Suppression on every centrality
- Normalized to 1

$\lambda/\lambda_{max}(m_T, N_{part})$



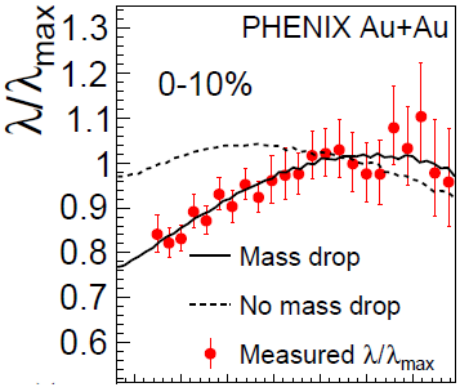
- Suppression on every centrality
- Normalized to 1 ⇒ centrality independent!
- Sign of the η' in medium mass modification?
- Let's compare the results to Monte Carlo simulations





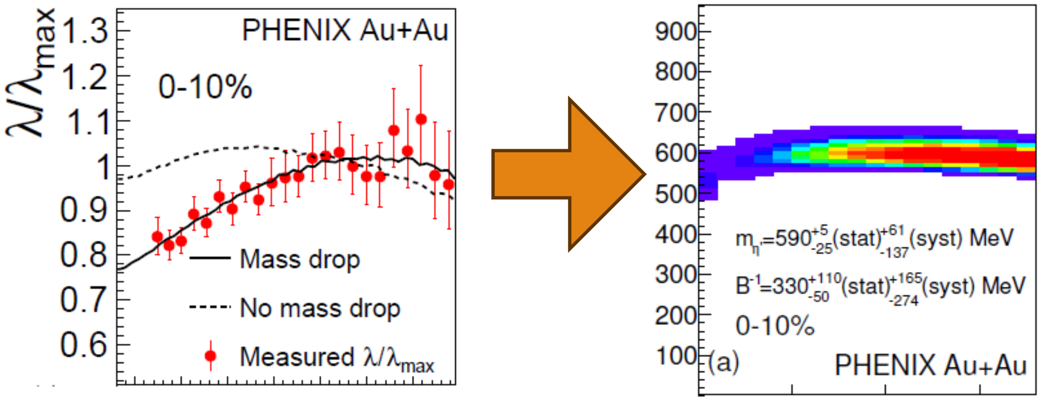
$$\frac{\lambda}{\lambda_{max}} = 1 - H\exp\left(-\frac{m_T^2 - m_\pi^2}{2\sigma^2}\right)$$

η' mass modification and $U_A(1)$ restoration ?



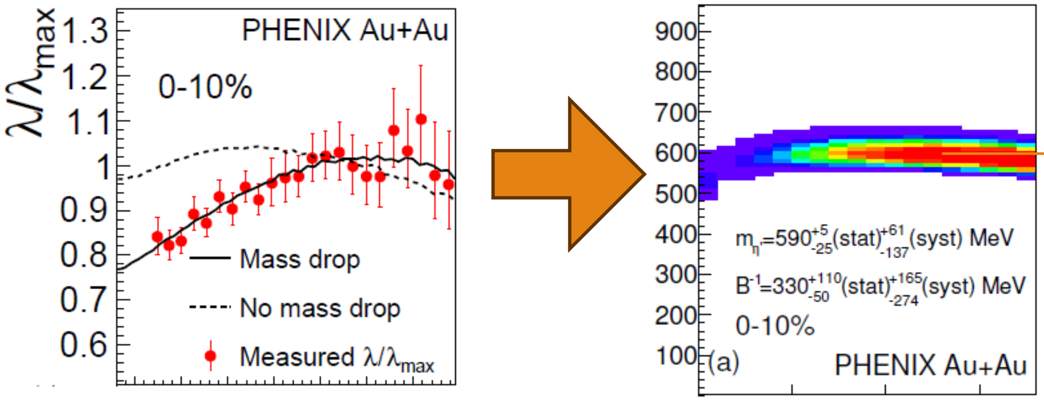
- Calculate λ from SHAREv3 for resonance production
- Resonance chain decay included

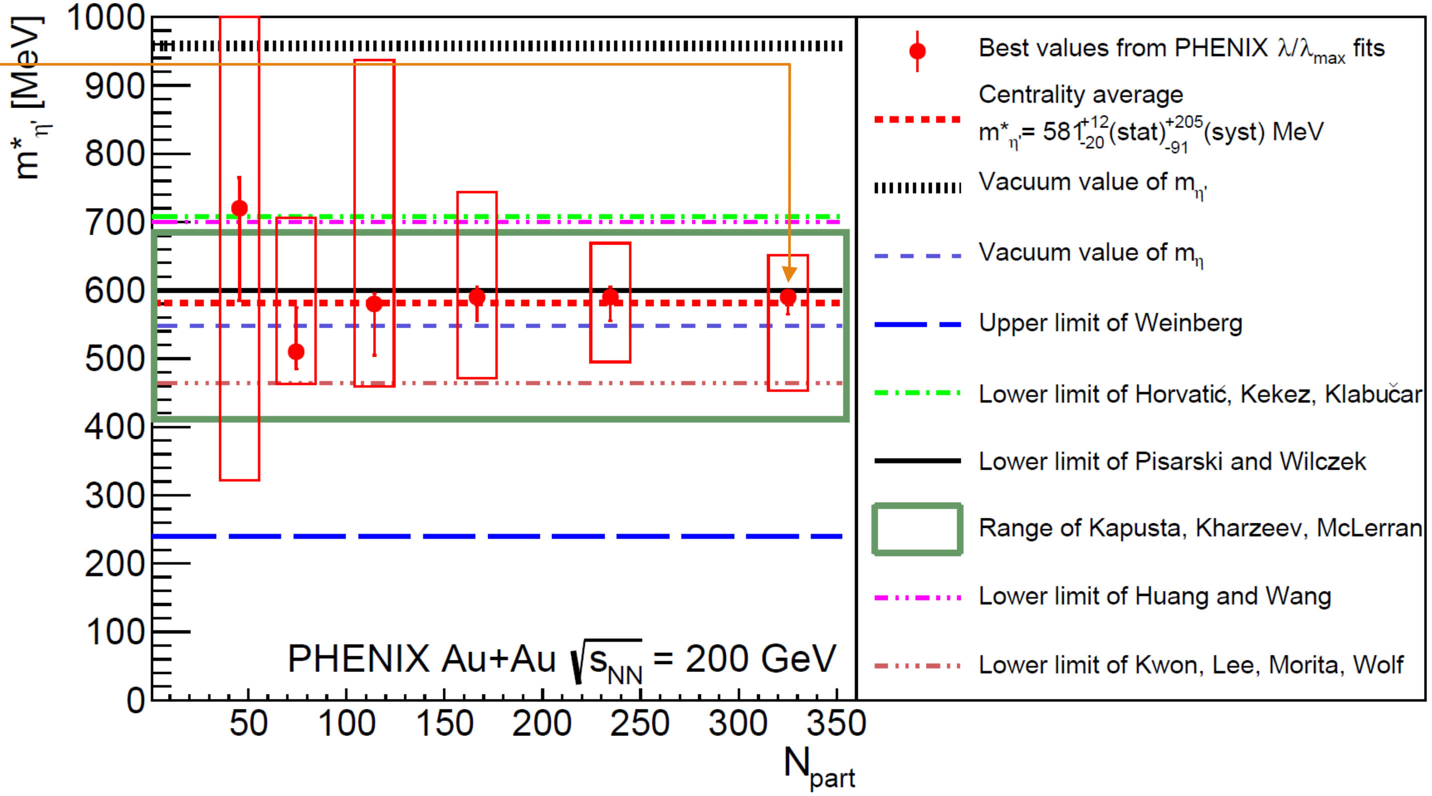
η' mass modification and $U_A(1)$ restoration ?



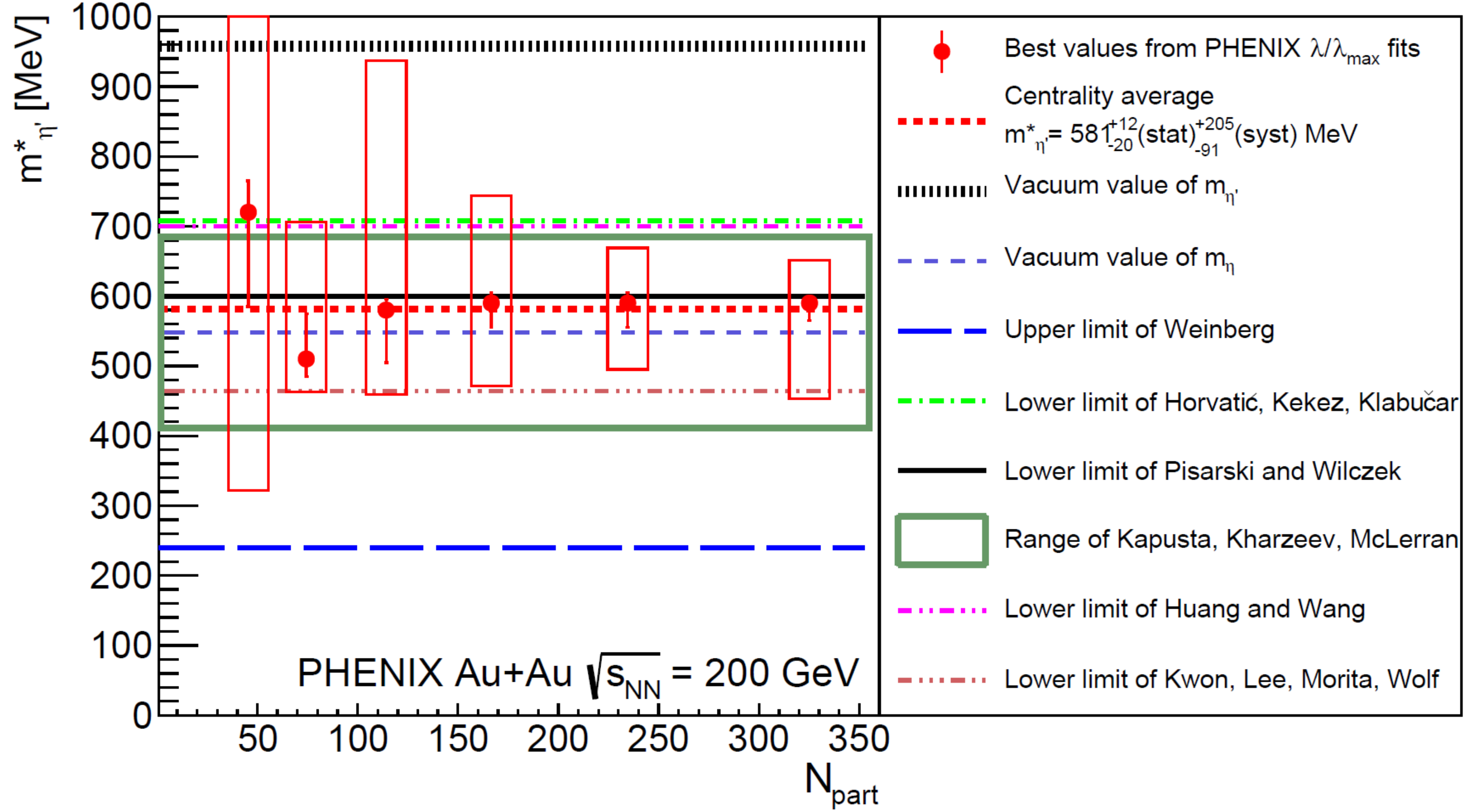
- Calculate λ from SHAREv3 for resonance production
- Resonance chain decay included
- Scan the CL with different η' masses

η' mass modification and $U_A(1)$ restoration ?



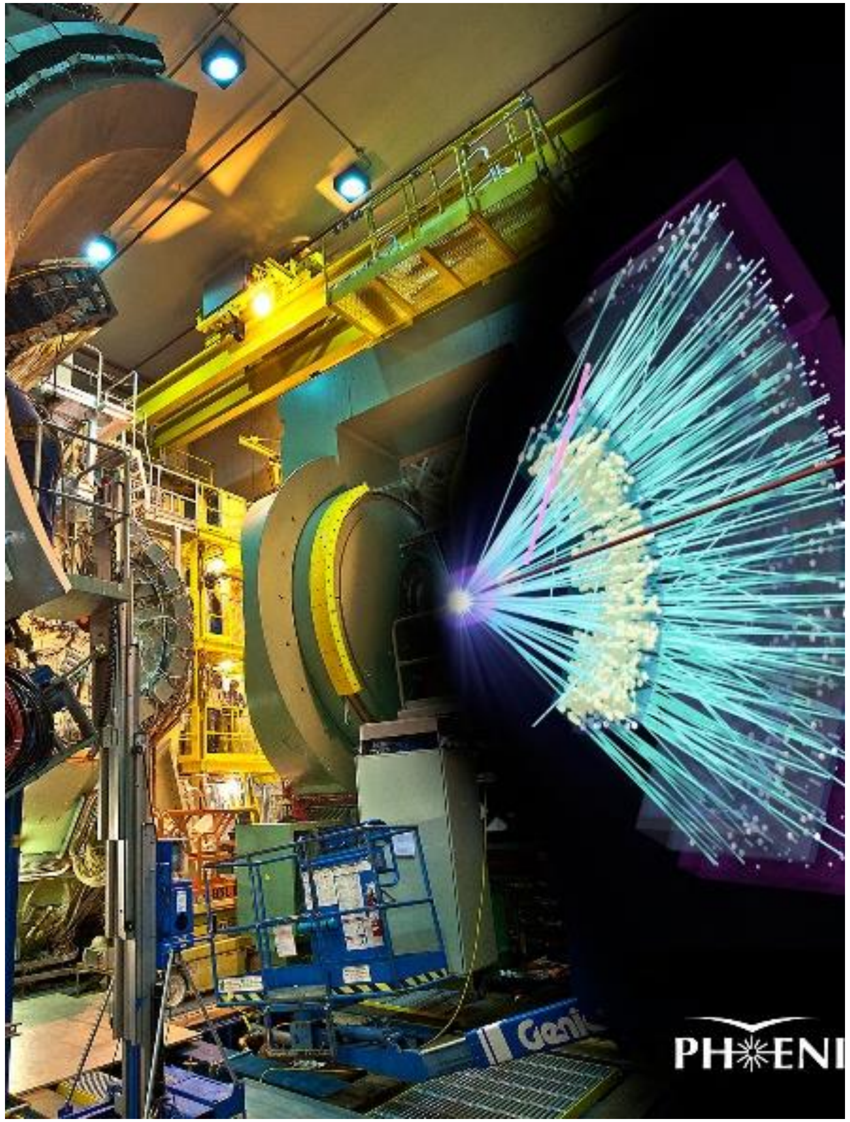


- Calculate λ from SHAREv3 for resonance production
- Resonance chain decay included
- Scan the CL with different η' masses



Results suggest in-medium $U_A(1)$ restoration: $m_\eta \approx m_{\eta'}$

Sign of a second transition!



Summary and outlook

Precise measurement of BEC requires Levy-exponent

$$\mathbf{1 < \alpha < 2}$$

Levy scale R exhibits hydro scaling → size?

Levy scale $\hat{R}$ linear scaling → size?

Strength parameter λ indicates a second, chiral transition

Significant in medium mass modification of η' meson

Editor's suggestion in PRC : [arXiv:2407.08586]

THANK YOU FOR YOUR ATTENTION!

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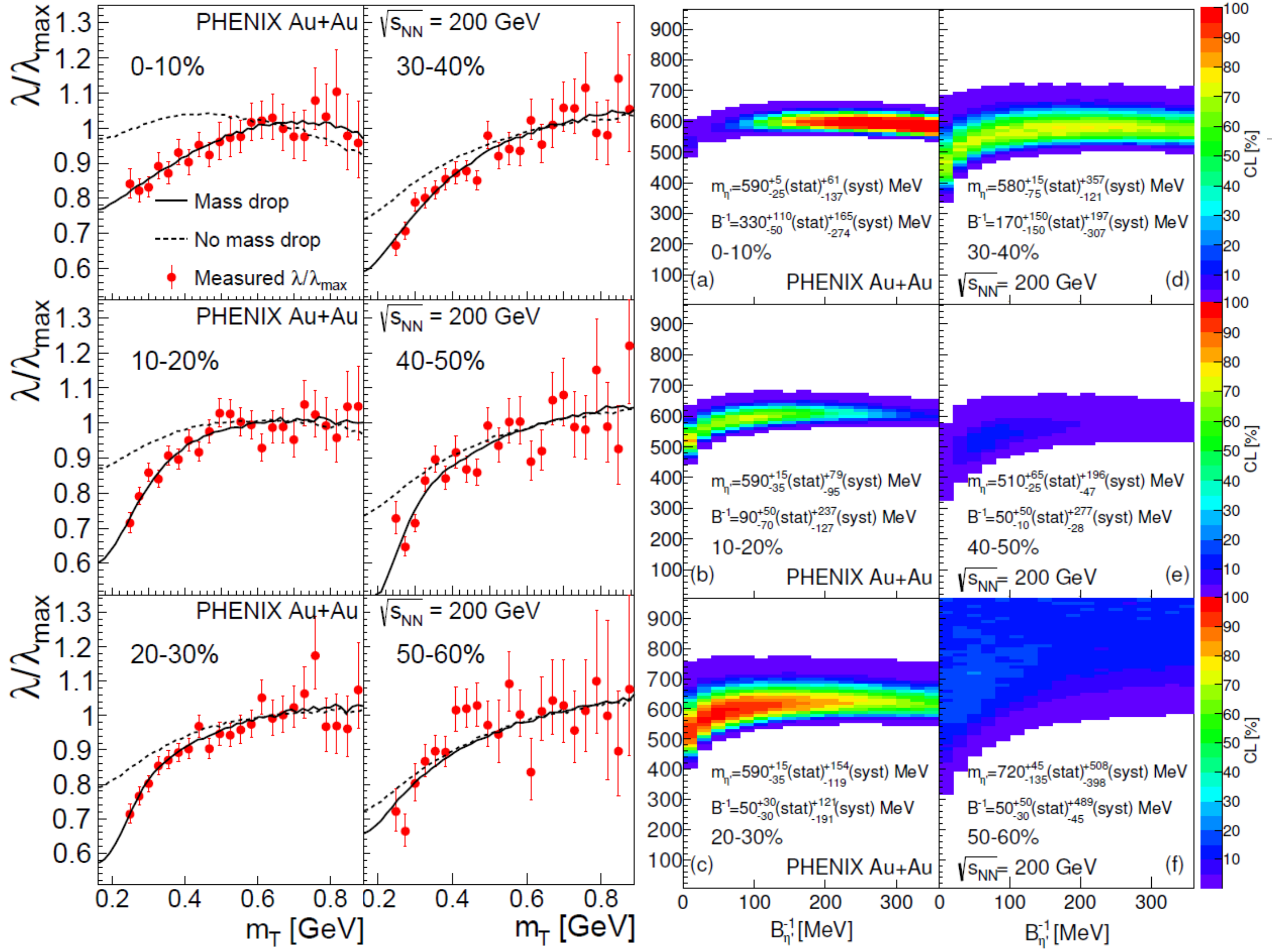
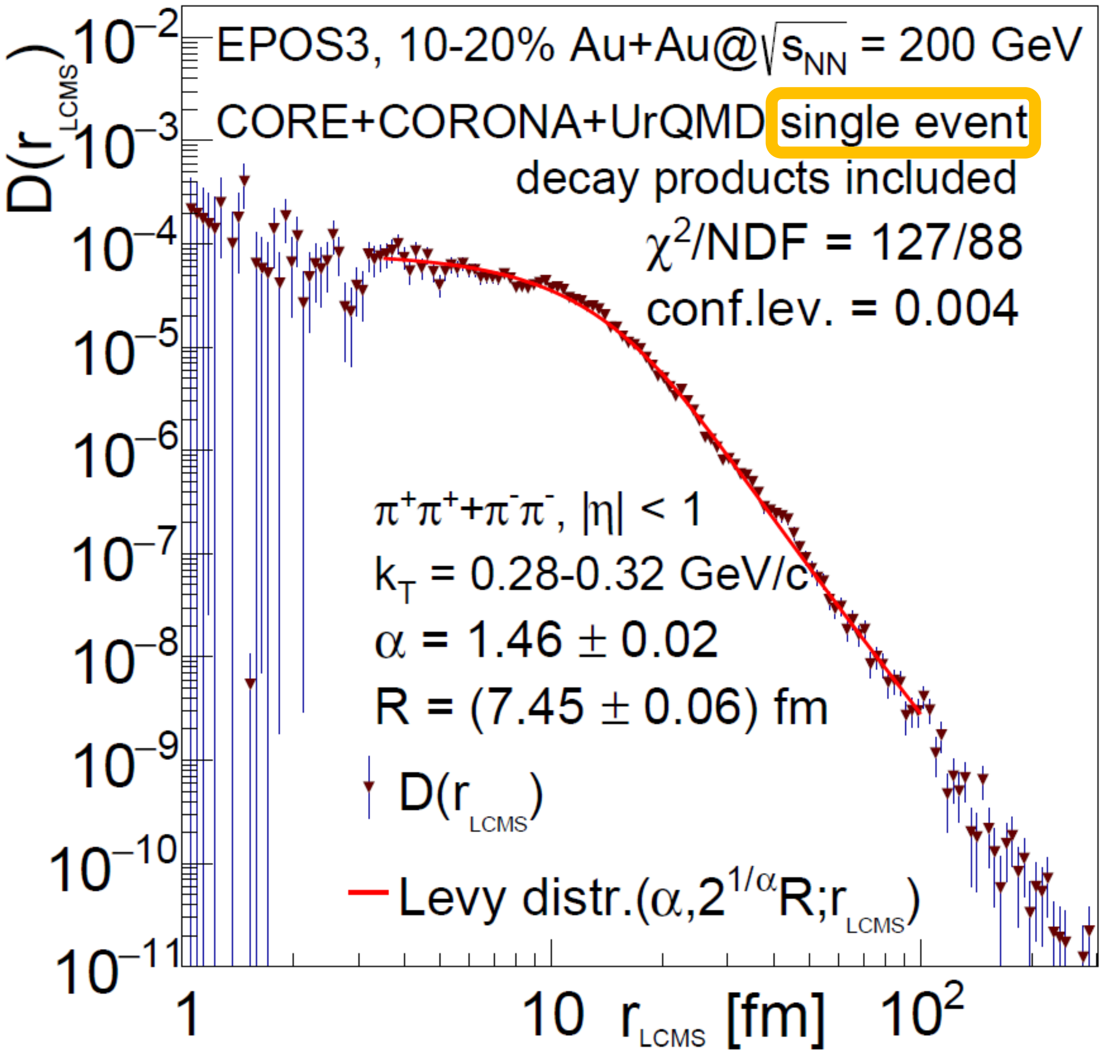
https://arxiv.org/abs/2407.08586

Comparison to MC



- Calculate λ from SHAREv3 for resonance production
- Resonance chain decay included
- Scan the CL with different η' masses

EPOS simulation – event-by-event correlation



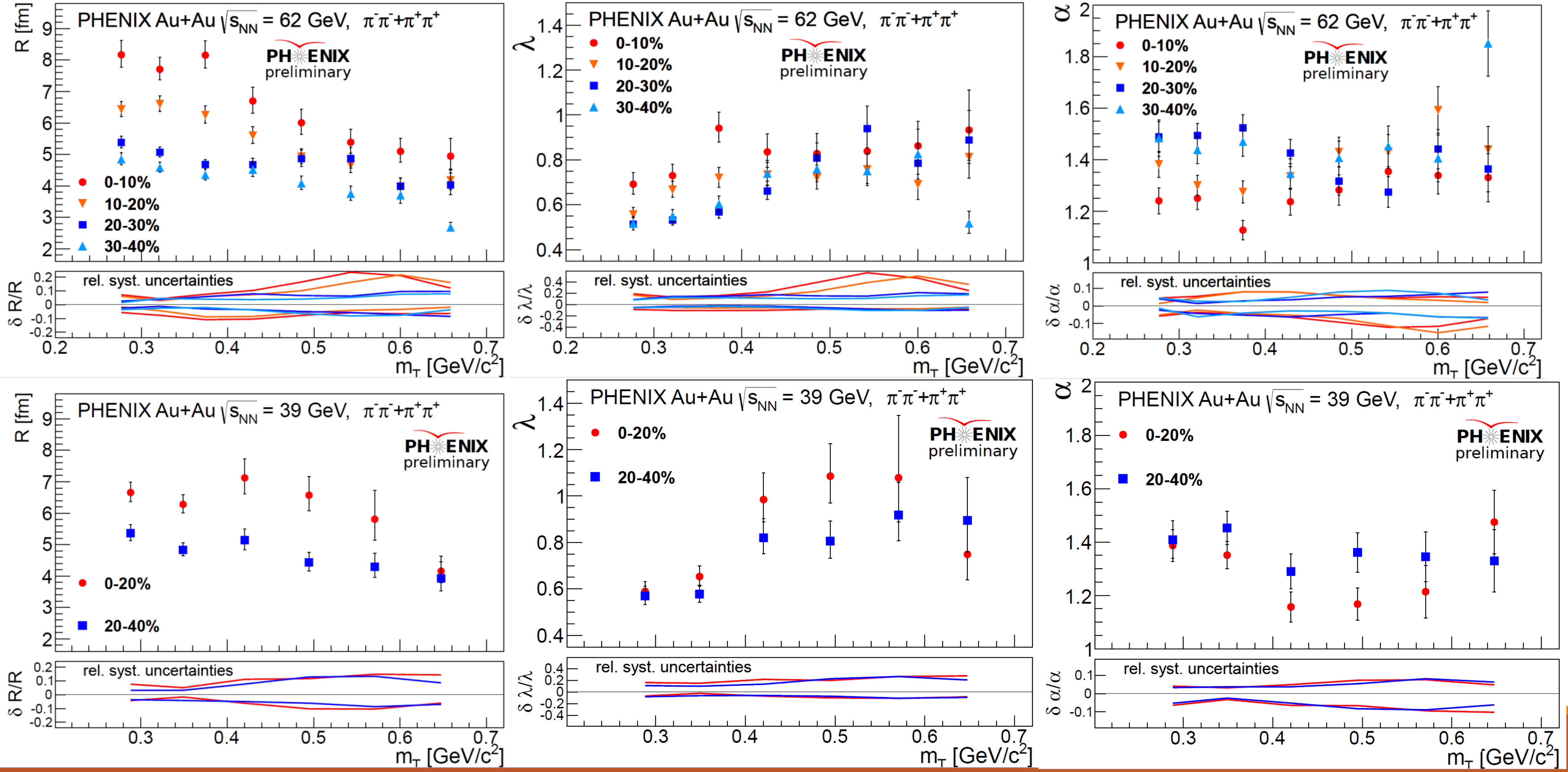
- Core-halo picture is included
- UrQMD for the hadronic cascade

- Levy gives the good description

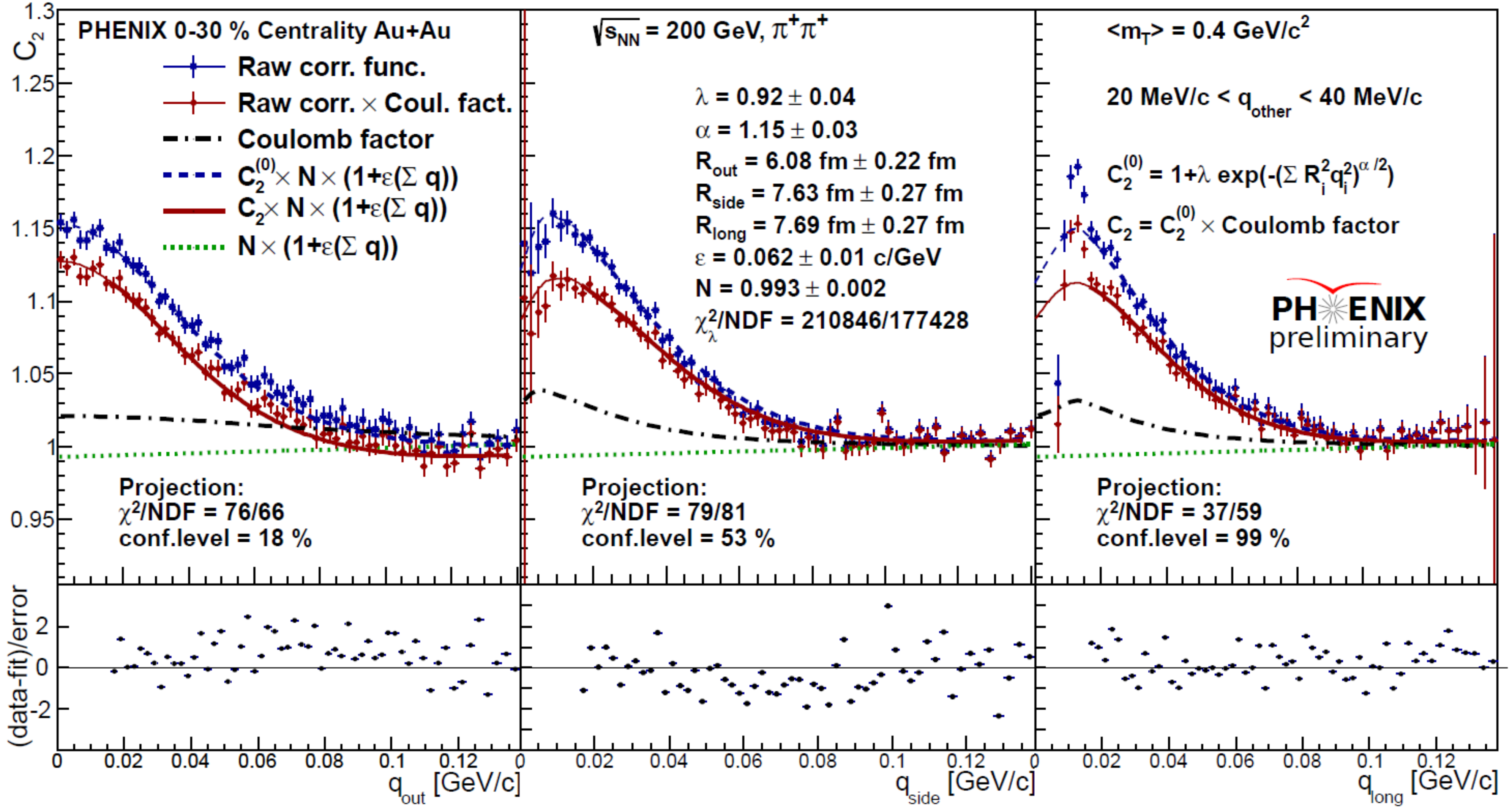
- It is a single event!
- This analysis support that the origin of the Levy shape could be explained only with the experimental averaging
- This analysis also support the role of the resonances, i.e., the anomalous diffusion

- With this confidence let's look at other experiments

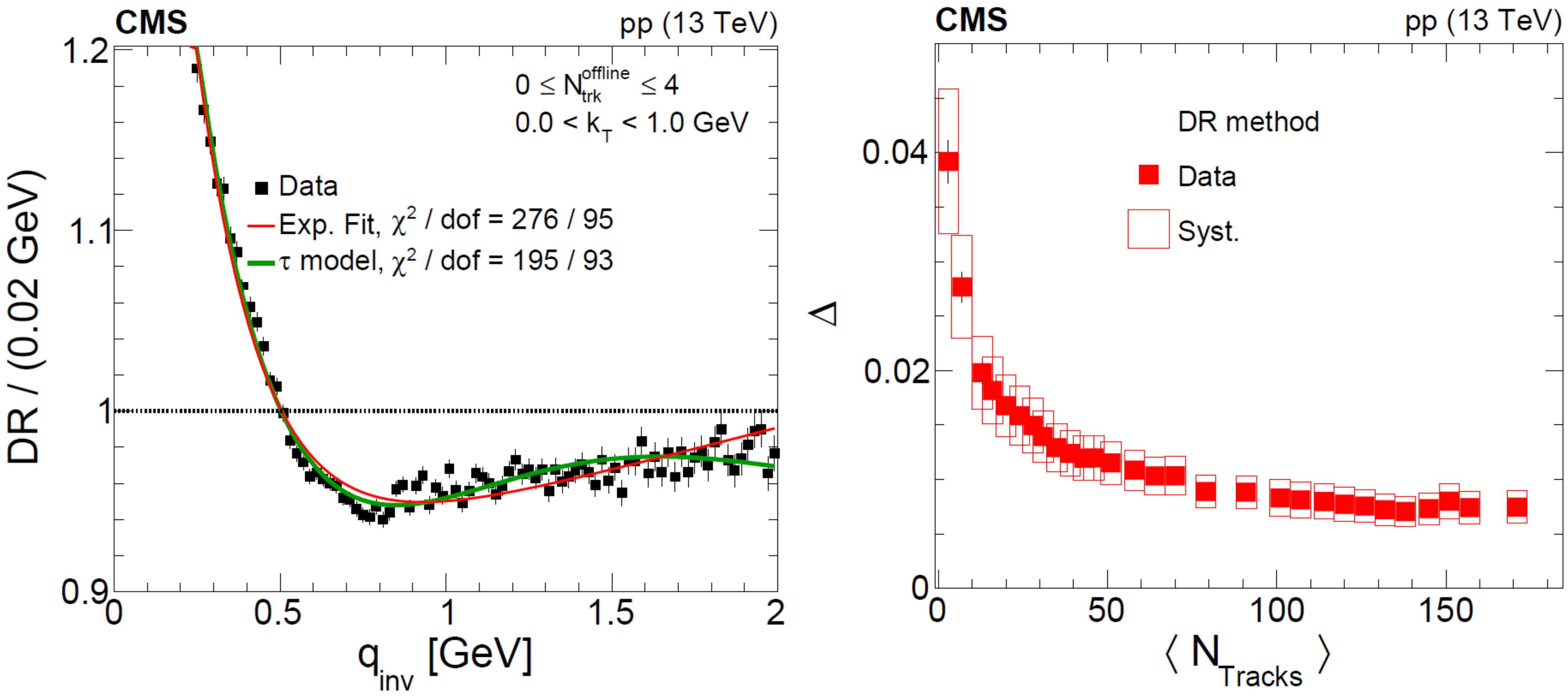
Backup slides



Backup slides



Backup slides



Backup slides

$$Q = \sqrt{(p_{1x} - p_{2x})^2 + (p_{1y} - p_{2y})^2 + q^2_{\mathrm{long,LCMS}}},$$

$$\text{where} \quad q^2_{\mathrm{long,LCMS}} = \frac{4(p_{1z}E_2 - p_{2z}E_1)^2}{(E_1 + E_2)^2 - (p_{1z} + p_{2z})^2}$$

Femtoscopy – the core-halo model

Usually pions, kaons, protons are measured

Resonance contributions are considerable: core-halo model

$$S(x,p) = \sqrt{\lambda}\, S_{core}(x,p) + \left(1-\sqrt{\lambda}\right) S_{halo}^{R_h}(x,p)$$

Let's introduce the pair source function as

$$D_{AB}(x,p) = \int d^3R \;\; S_A\left(R+\frac{x}{2},p\right) S_B\left(R-\frac{x}{2},p\right)$$

With this the pair source function in the core-halo model:

$$D(x,p) = \lambda D_{cc}(x,p) + \underbrace{2\sqrt{\lambda}\left(1-\sqrt{\lambda}\right) D_{ch}(x,p) + \left(1-\sqrt{\lambda}\right)^2 D_{hh}(x,p)}_{\text{Notation: } D_{(h)}/(1-\lambda)}$$

Femtoscopy – general form

With $K = 0.5(p_1 + p_2)$ and $Q = p_1 - p_2$! Also assume that $p_1 \approx p_2$

$$C_2(Q,K) \approx \lambda \int d^3r D_{cc}(r,K) \left|\Psi_2^{(Q)}(r)\right|^2 + (1-\lambda) \int d^3r D_{(h)}(r,K) \left|\Psi_2^{(Q)}(r)\right|^2$$

If we take the $R_h \to \infty$ limit the Bowler-Sinyukov formula is given:

$$C_2(Q,K) \approx 1 - \lambda + \lambda \int d^3r D_{cc}(r,K) \left|\Psi_2^{(Q)}(r)\right|^2$$

The simple planewave case (i.e. no FSI):

$$C_2^{(0)}(Q,K) = 1 + \lambda \frac{\widetilde{D}_c(Q,K)}{\widetilde{D}_c(Q=0,K)}$$

On the **3D** variable of the correlation function

$$C_2(Q,K) \approx 1-\lambda+\lambda\int d^3r D_{cc}(r,K)\left|\Psi_2^{(Q)}(r)\right|^2$$

The K dependence is much smoother than the Q dependence

Use the Q as a variable and the measure the K dep. of the params.

$$Q\cdot K=(p_1-p_2)(p_1+p_2)=p_1^2-p_2^2=0\rightarrow Q_0=\vec{Q}\frac{\vec{K}}{K_0}$$

$C_2(Q)$ can be transformed to $C_2(\vec{Q})$

Go to LCM system where $\vec{Q}=\left(Q_{out},Q_{side},Q_{long}\right)$

On the **1D** variable of the correlation function

What about in 1D? Could be necessary due to the lack of statistics

Usual choice: $q_{inv} = \sqrt{-Q^{\mu}Q_{\mu}}$, arguable choice!

$$q_{inv} = (1 - \beta_t^2)Q_{out}^2 + Q_{side}^2 + Q_{long}^2$$

But q_{inv} could be very small even if $Q_{out}^2 \approx Q_{side}^2 \approx Q_{long}^2 \neq 0$

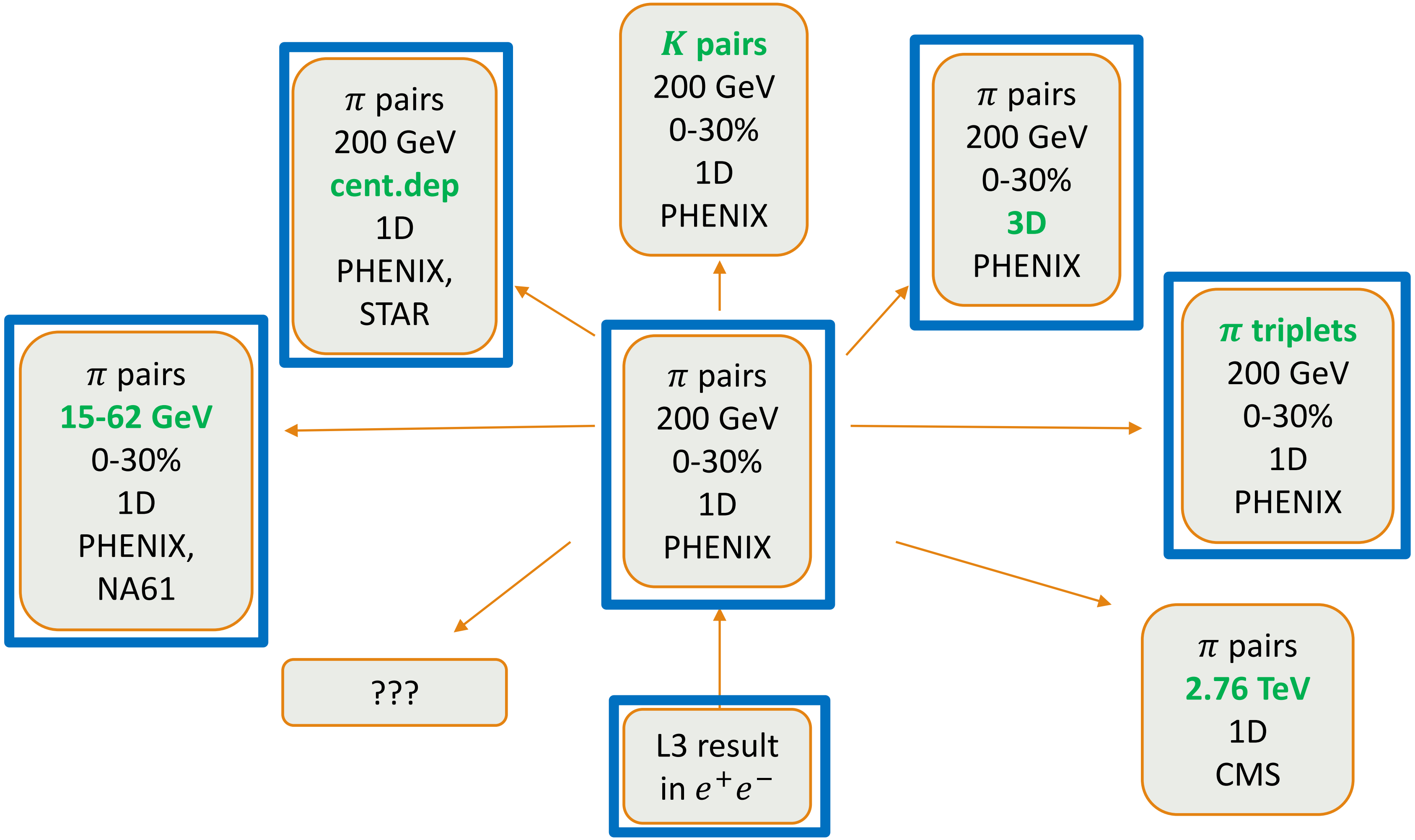
It is also known that the source approximately spherical at RHIC

1D variable!

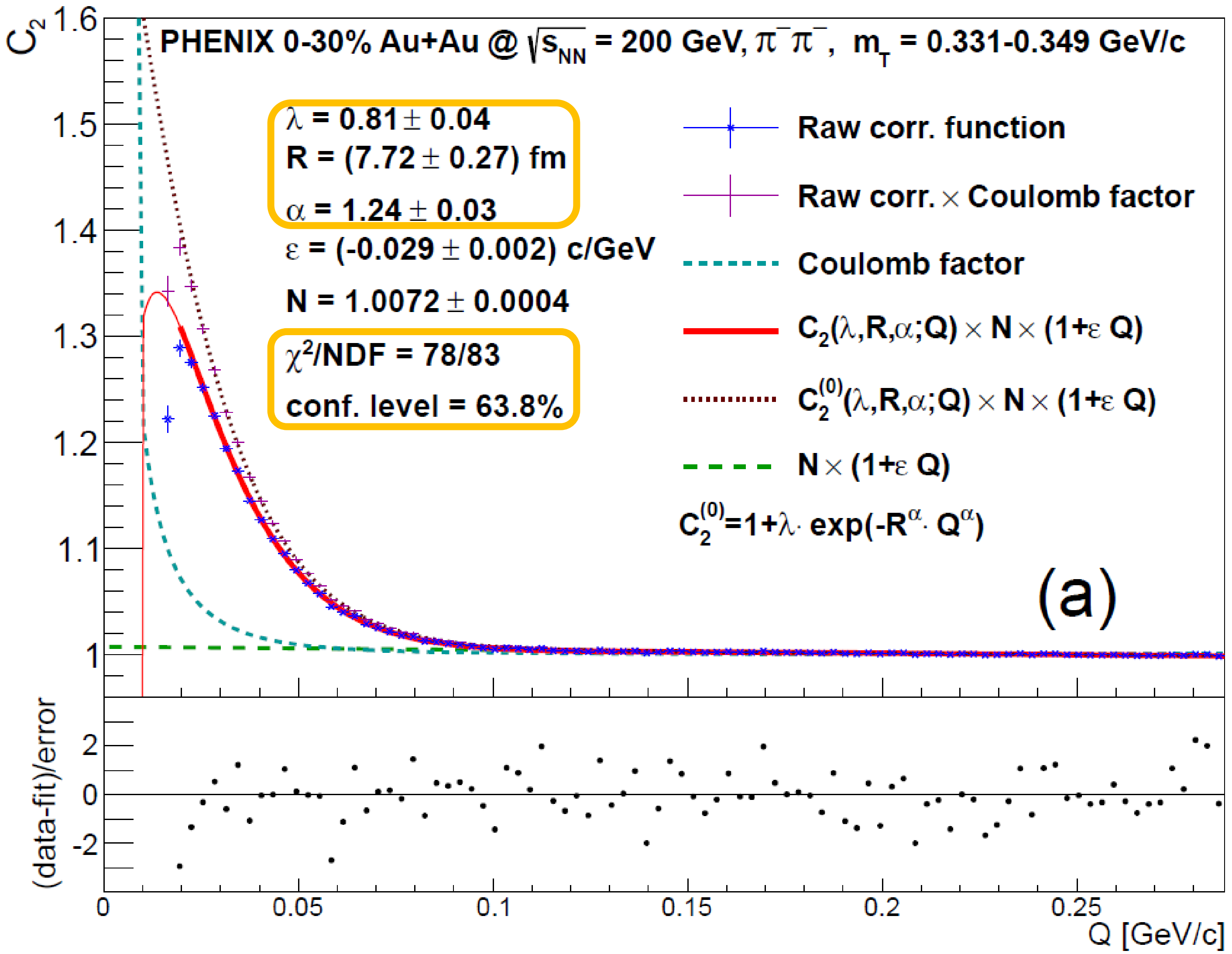
$$q_{inv} = |q_{PCMS}| \quad \Rightarrow \quad Q = |q_{LCMS}|$$

Here, sphericity preserved, so Q independent of the direction of q_{LCMS}

The tree of the Levy analyses

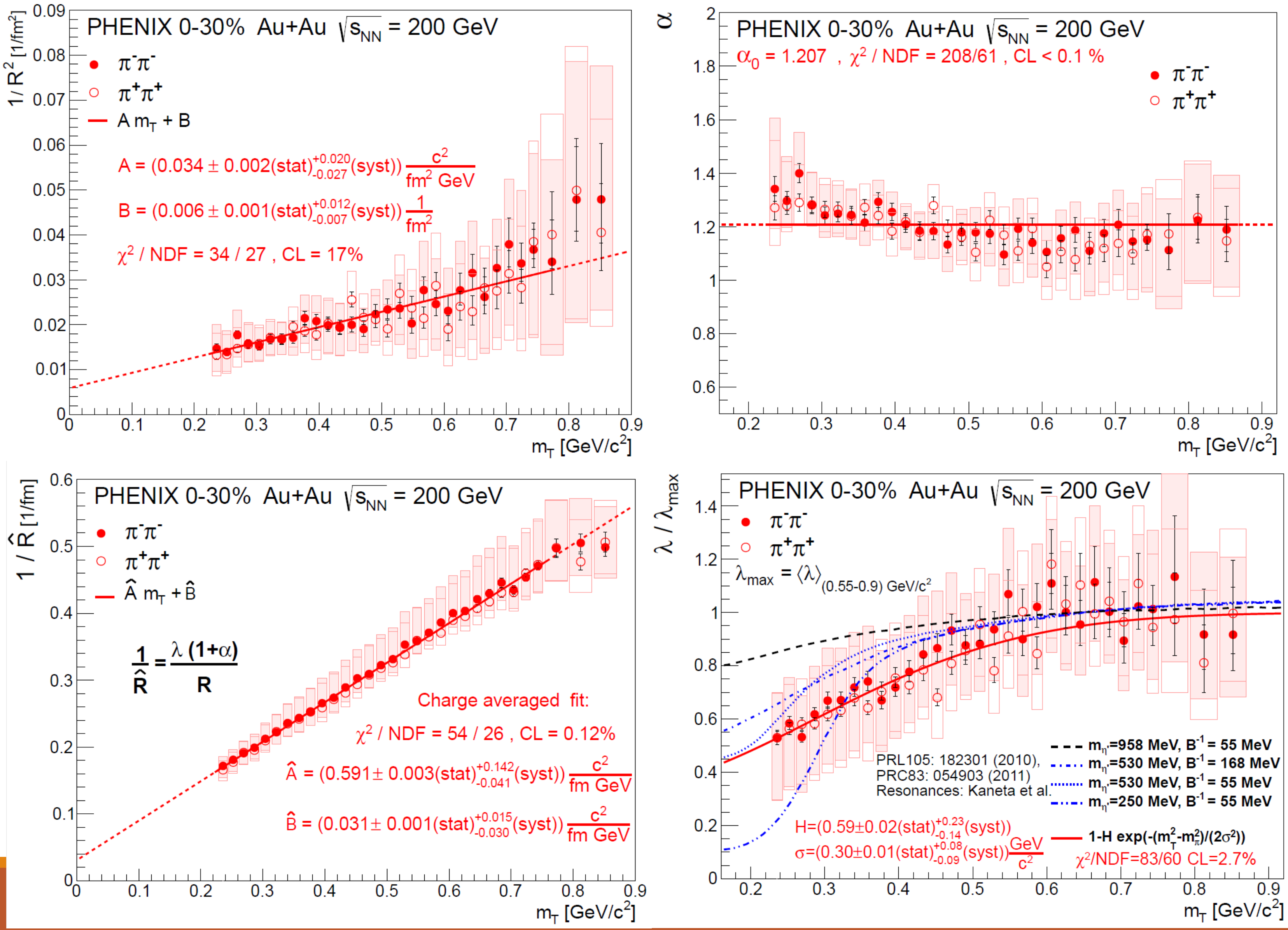


The first results – PHENIX 0-30% Au+Au



- Measured correlation function in 31 m_T bin with 0-30% cent.
- Coulomb correction incorporated into the fit function
- $\alpha \neq 2$ nor $\alpha \neq 1$
- The fits are acceptable in terms of confidence level and χ^2/NDF
- Gaussian parametrization cannot describe the data

The first results – PHENIX 0-30%, Au+Au

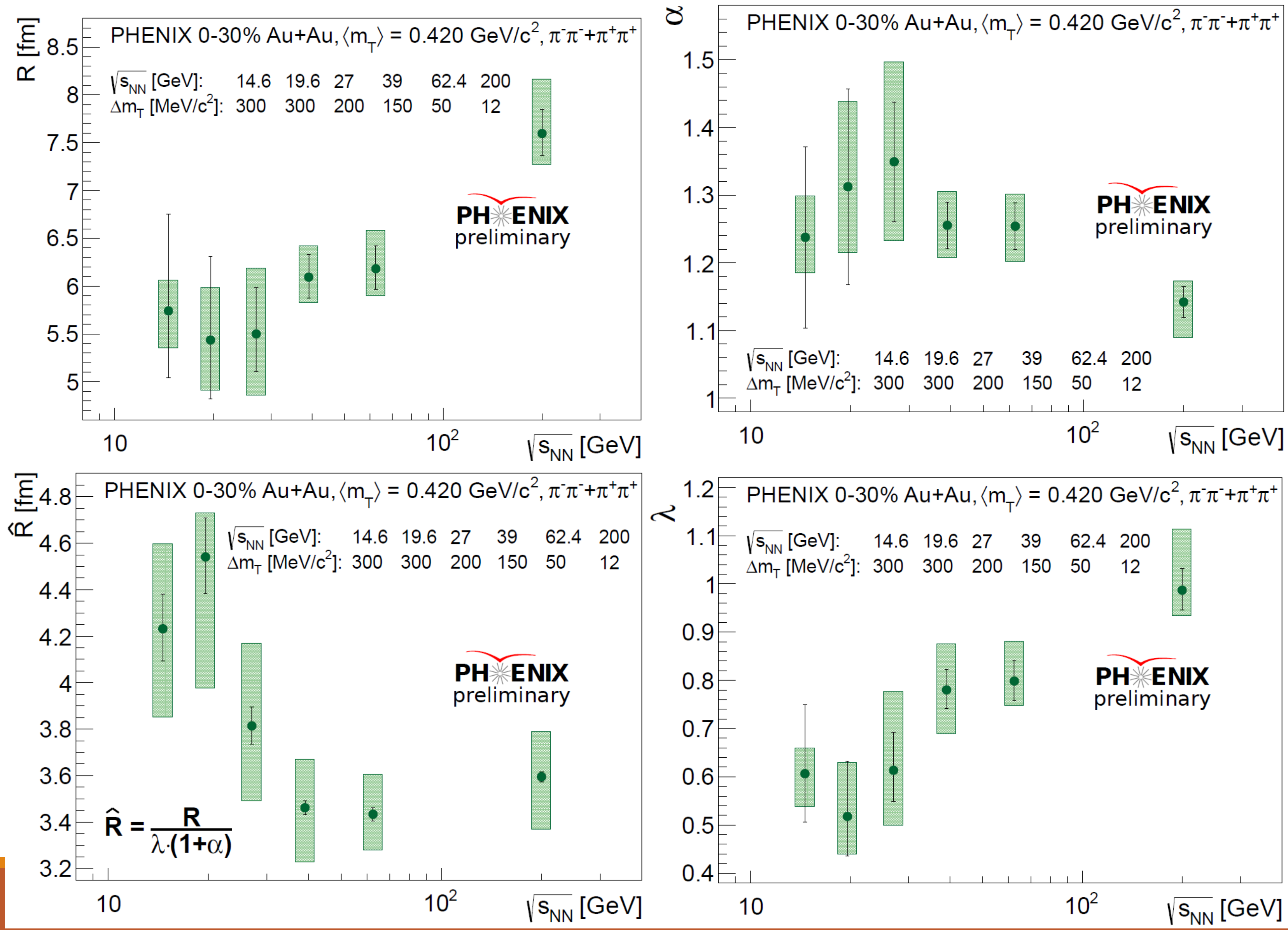


- R exhibits hydro scaling
- $1 < \alpha < 2\,, \langle\alpha\rangle \approx 1.2$
- $\lambda(m_T)$ suppressed which compatible with modified η' mass in the medium (compared with a resonance model)

- New scaling parameter
  - Interpretation?
- Interpretation of α ?

- Let's see the N_{part} and $\sqrt{s_{NN}}$ dependence

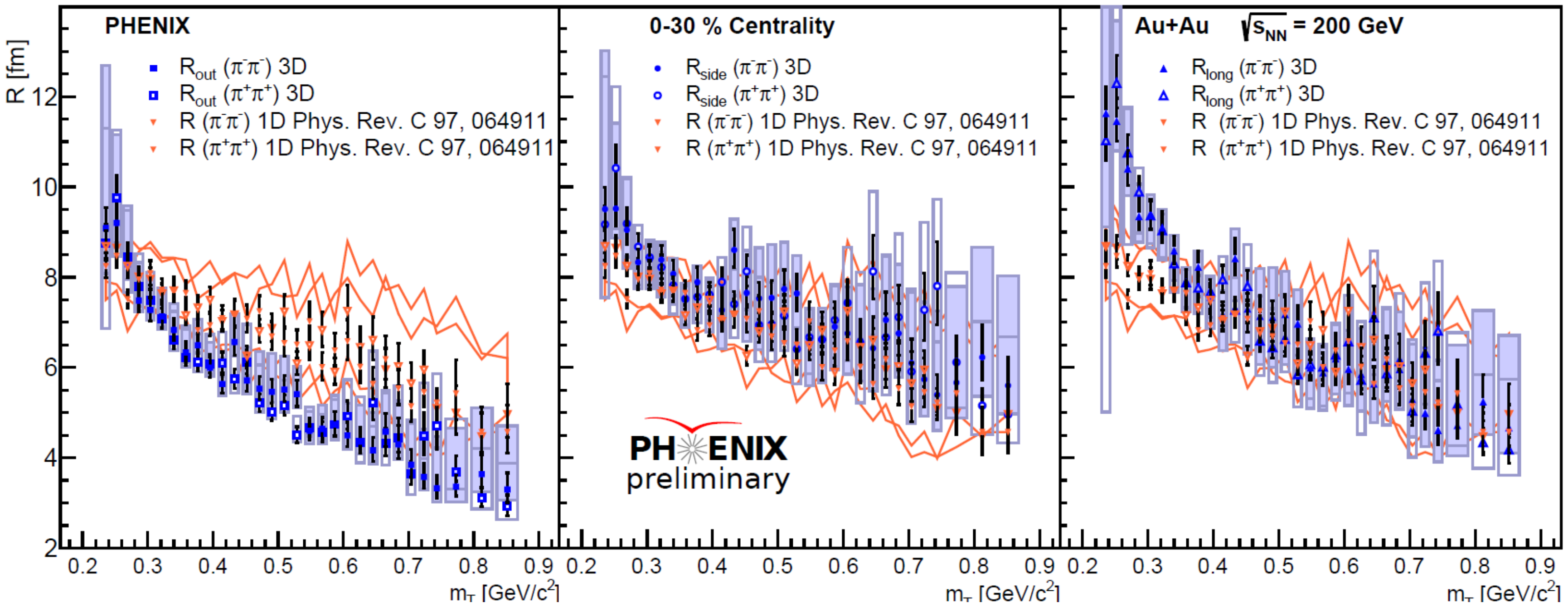
$\sqrt{s_{NN}}$ dependence – PHENIX Au+Au

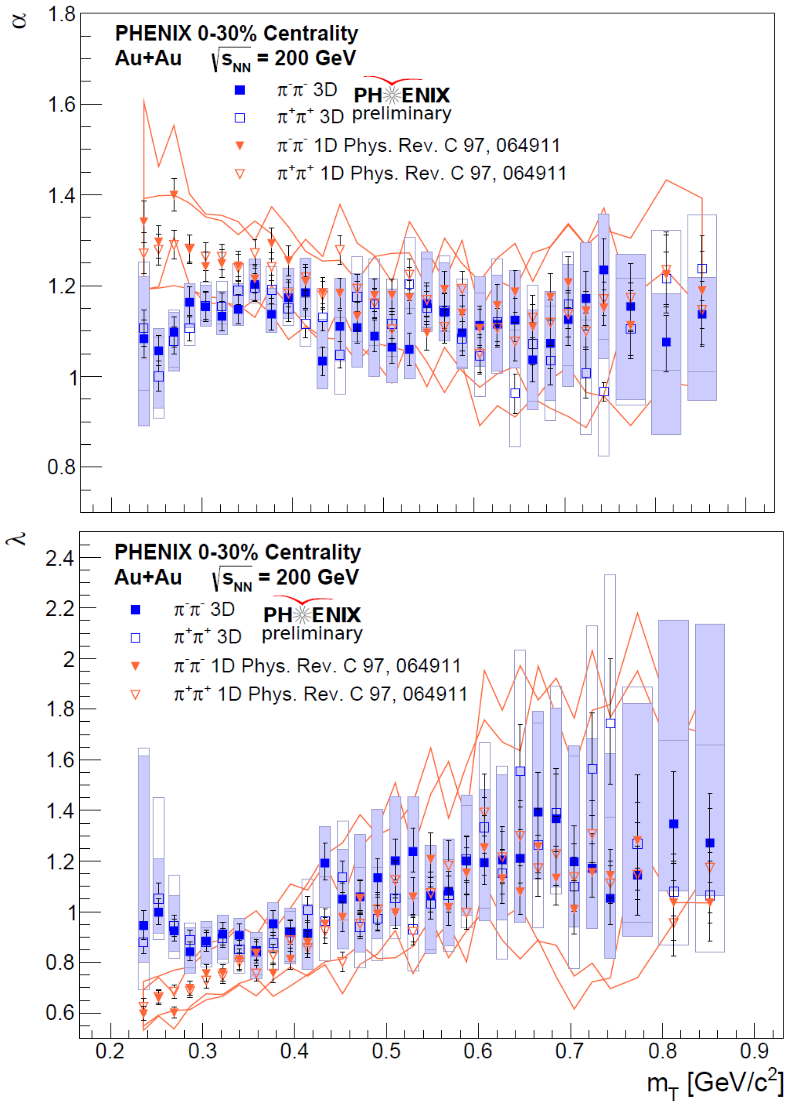


- Integrated in m_T due to the lack of statistics
- α does not really depend on $\sqrt{s_{NN}}$
- Non-monotonic behavior of $\hat{R}$ observed
  - Interpretation?

- For $\sqrt{s_{NN}} \geq 39$ GeV there are m_T dependent analysis but the trends are not clear

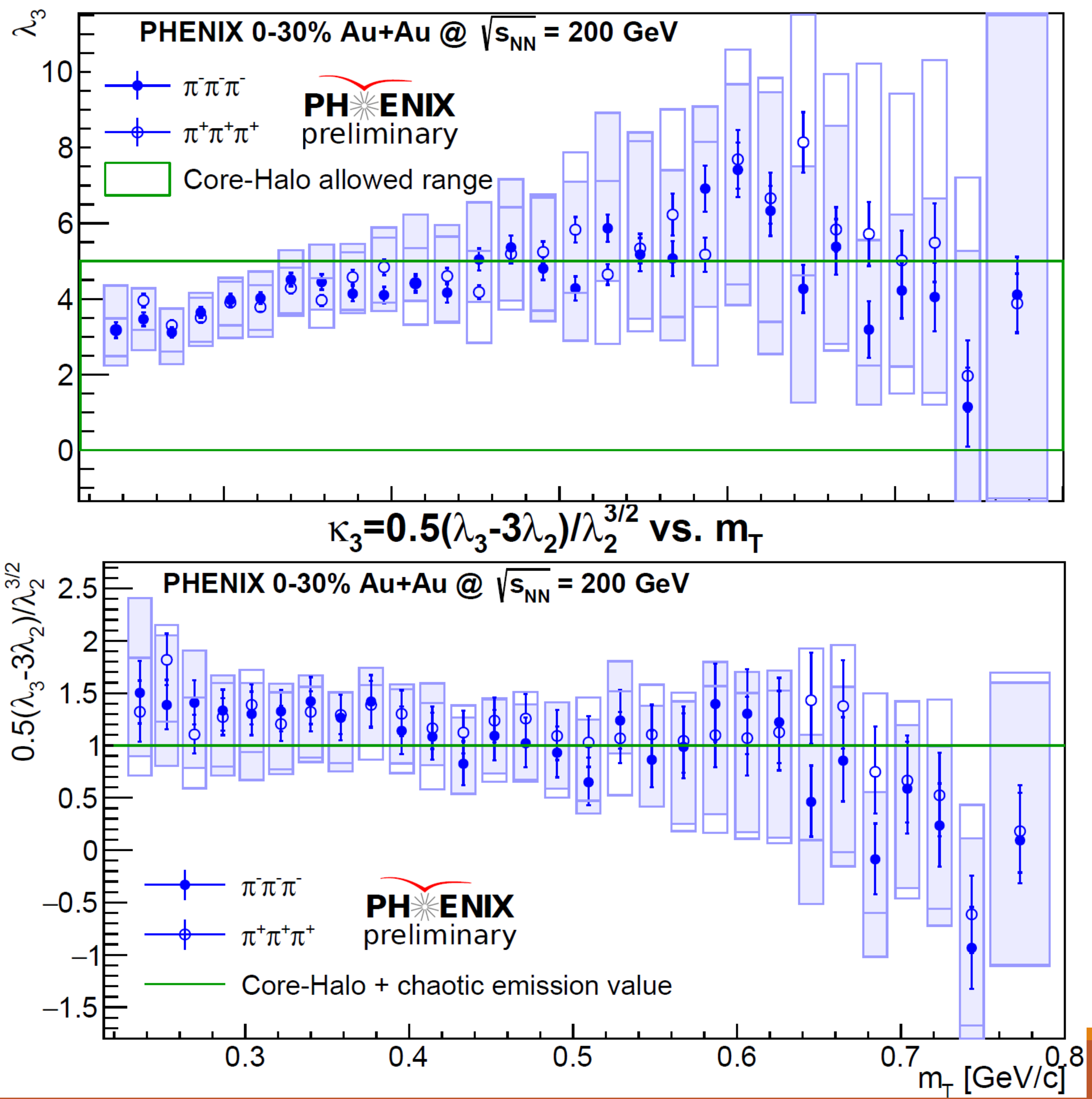
3D correlation – PHENIX 0-30% Au+Au





- 3D measurement gives very similar results compared to 1D
- The source appears to be spherical
- λ suppression is there in 3D too, with small discrepancy
- Preliminary data!

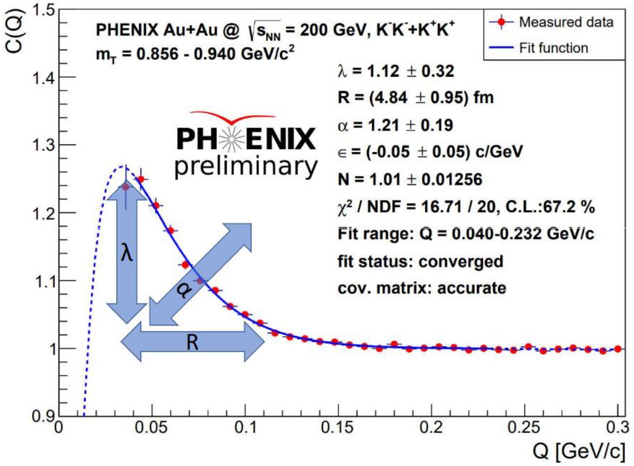
3 particle correlation – PHENIX 0-30% Au+Au

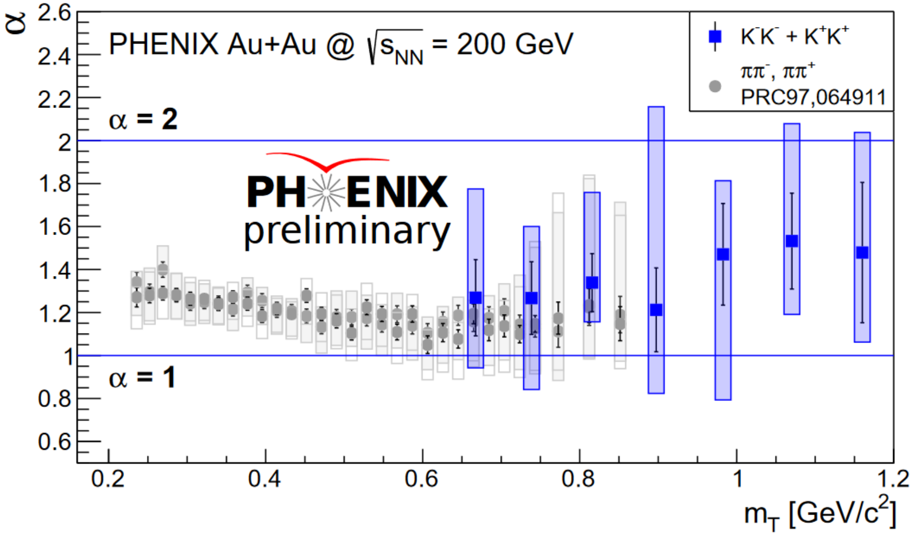


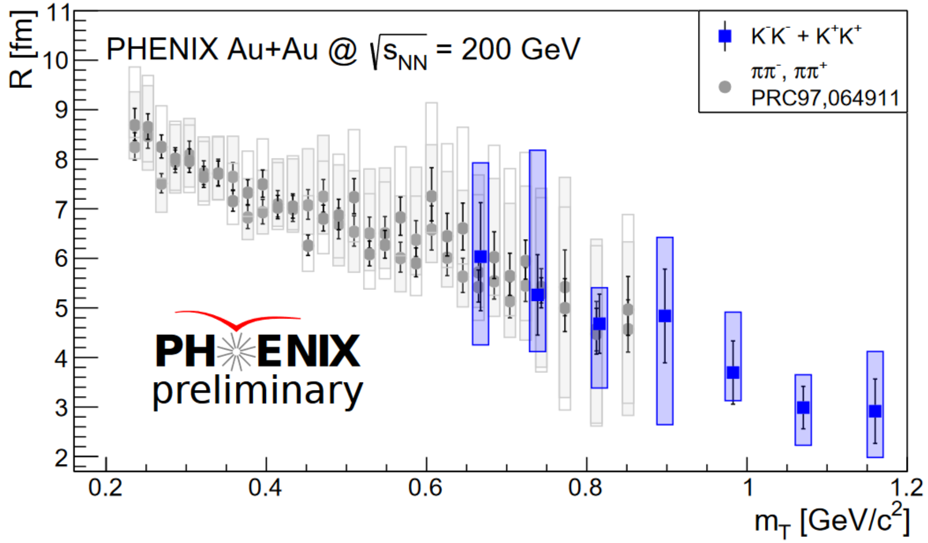
$$\kappa_3 = \frac{(\lambda_3 - 3\lambda_2)}{2\sqrt{\lambda_2^3}}$$

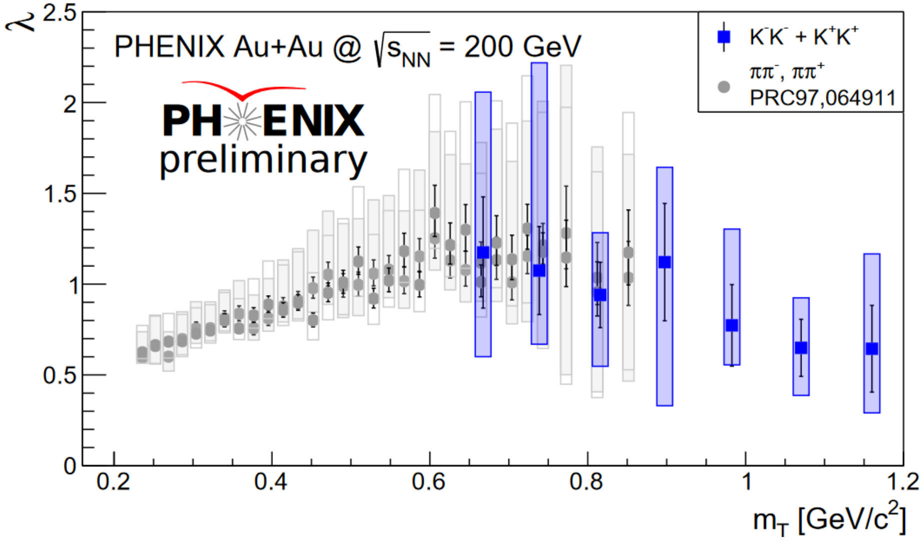
- From the definition:
  - No coherence: $p_c = 0 \Rightarrow \kappa = 1$
  - Coherence: $p_c > 0 \Rightarrow \kappa < 1$
- The source seems to be chaotic

PHENIX @ 200 GeV – kaon correlation in Au+Au









- $\alpha_K \approx \alpha_\pi$ underlying Levy process?
- λ exhibits decreasing trends – unidentified hadrons
- R supports its geometrical interpretation as before
- Preliminary results