



Centrality dependent Levy HBT at PHENIX

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WPCF 2024

MATE

PHENIX

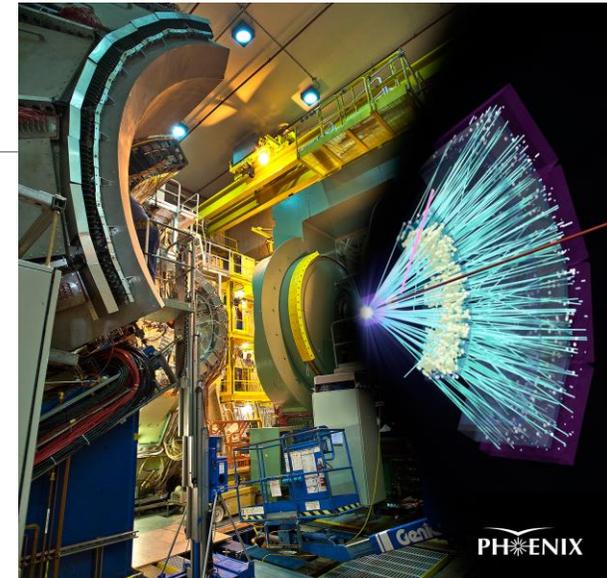


The PHENIX and the BES

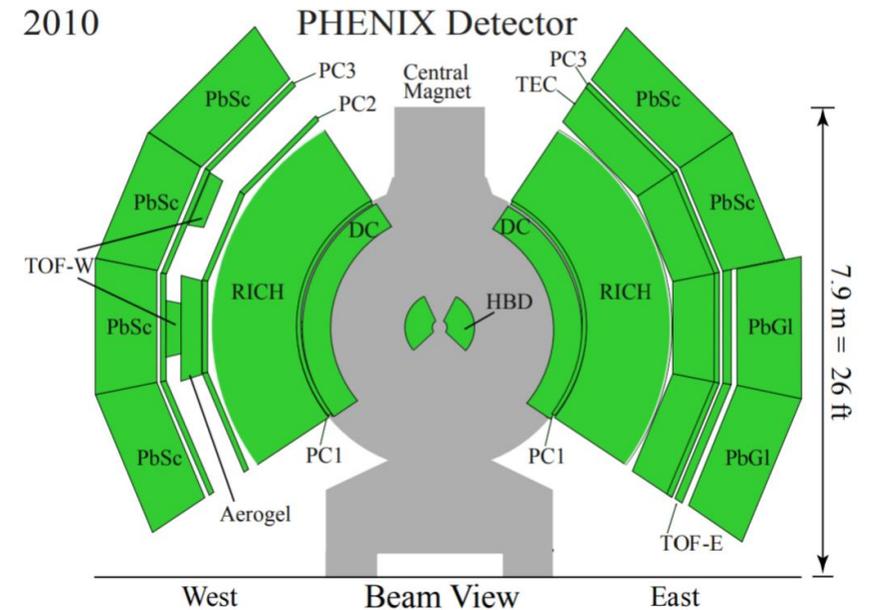
Collision energies: 7.7 to 200 GeV

20-400 MeV in μ_B , 140-170 MeV in T

This talk: 200 GeV Au+Au



$\sqrt{s_{NN}}$ [GeV]											
510	<input checked="" type="checkbox"/>										
200	<input checked="" type="checkbox"/>										
130									<input checked="" type="checkbox"/>		
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Femtoscscopy – 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:

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

S : source function, Ψ_2 two-particle wavefunction

Femtoscscopy – two approaches

Assume the source shape: $S \sim \text{Gaussian}$

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

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

Not too realistic: Coulomb (and strong) FSI

What is the interacting wave function?

$$\Psi_2 \sim \frac{\Gamma(1+i\eta)}{e^{\frac{\pi\eta}{2}}} [e^{ikr} F(-i\eta, 1, i(kr - \mathbf{k}\mathbf{r}))] \\ +\mathbf{r} \rightarrow -\mathbf{r}$$

(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

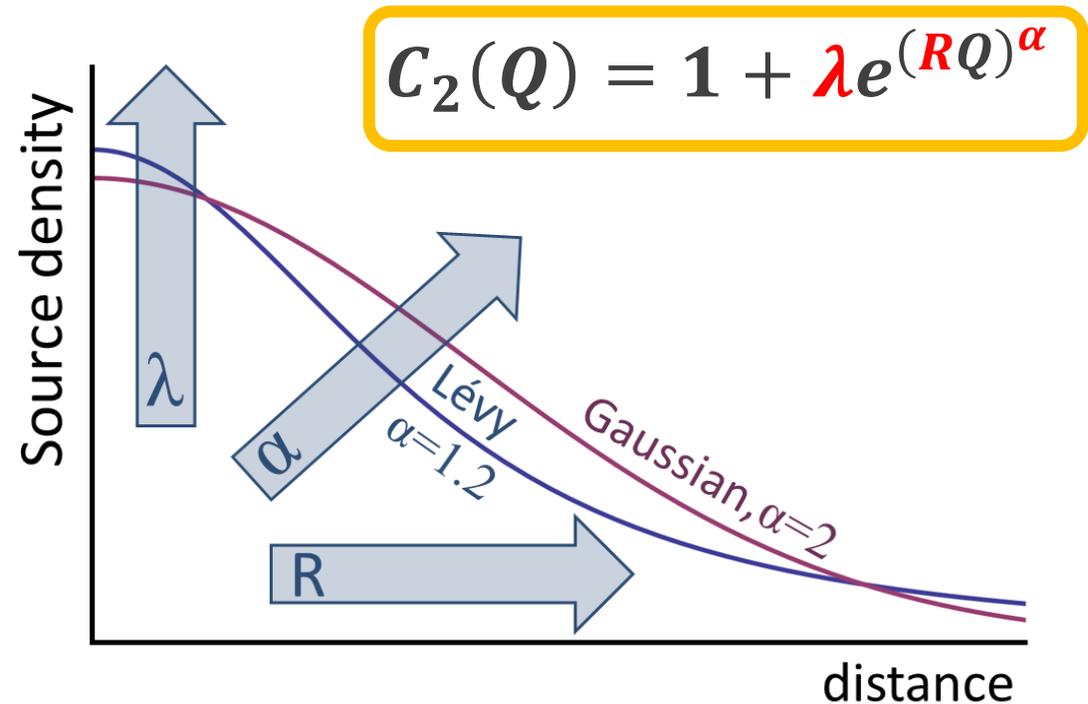
Assume the source to be Levy!

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

$R(K)$: Levy-scale parameter

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

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

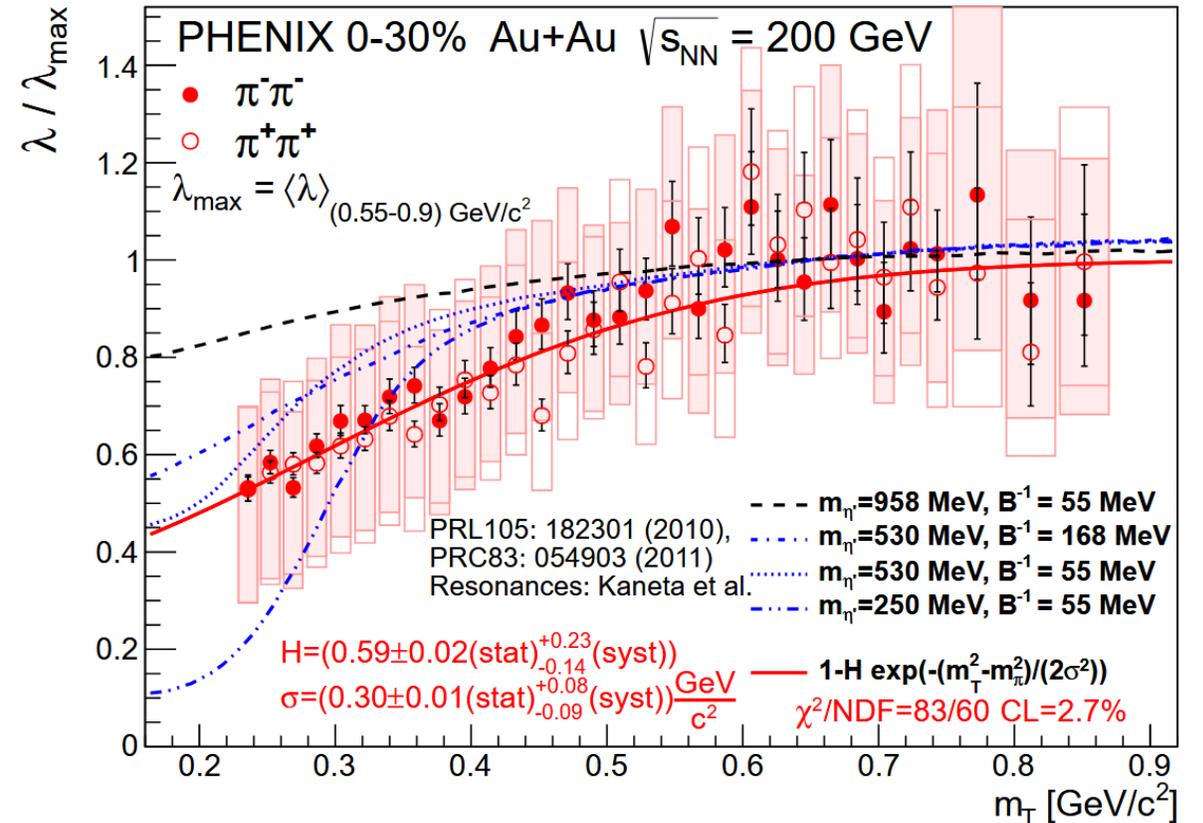


Physics in the parameters

Possible interpretations of the λ :

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

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

- 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 $q_{inv} = |q_{PCMS}|$)

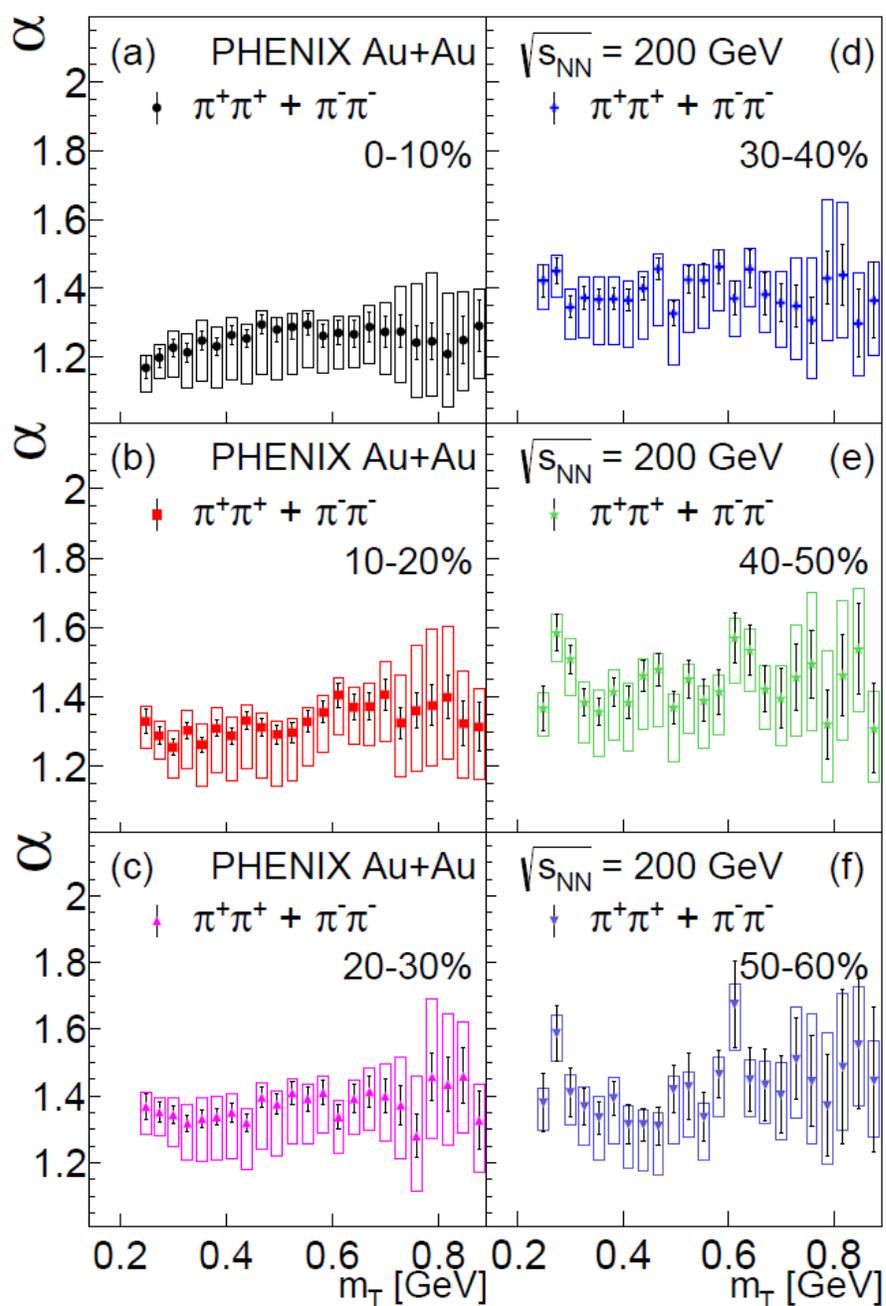
Fit function incorporates CC FSI (weighting for var. change)

Costume track and pair cuts to obtain clean sample

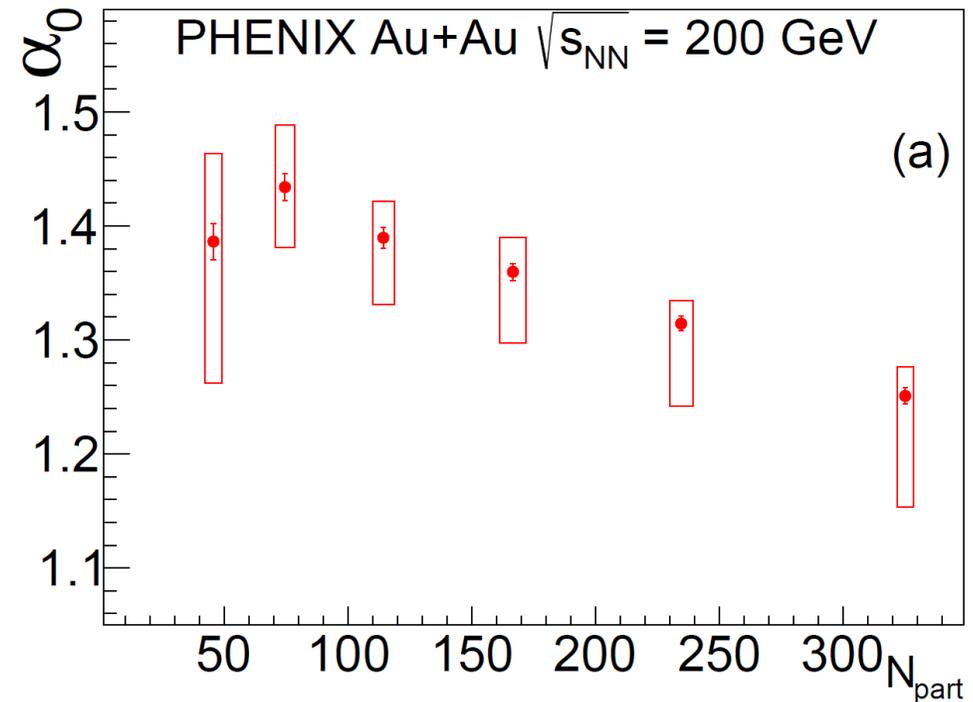
Accepted for publication in PRC, available at [arXiv:2407.08586](https://arxiv.org/abs/2407.08586)

Let's see the results!

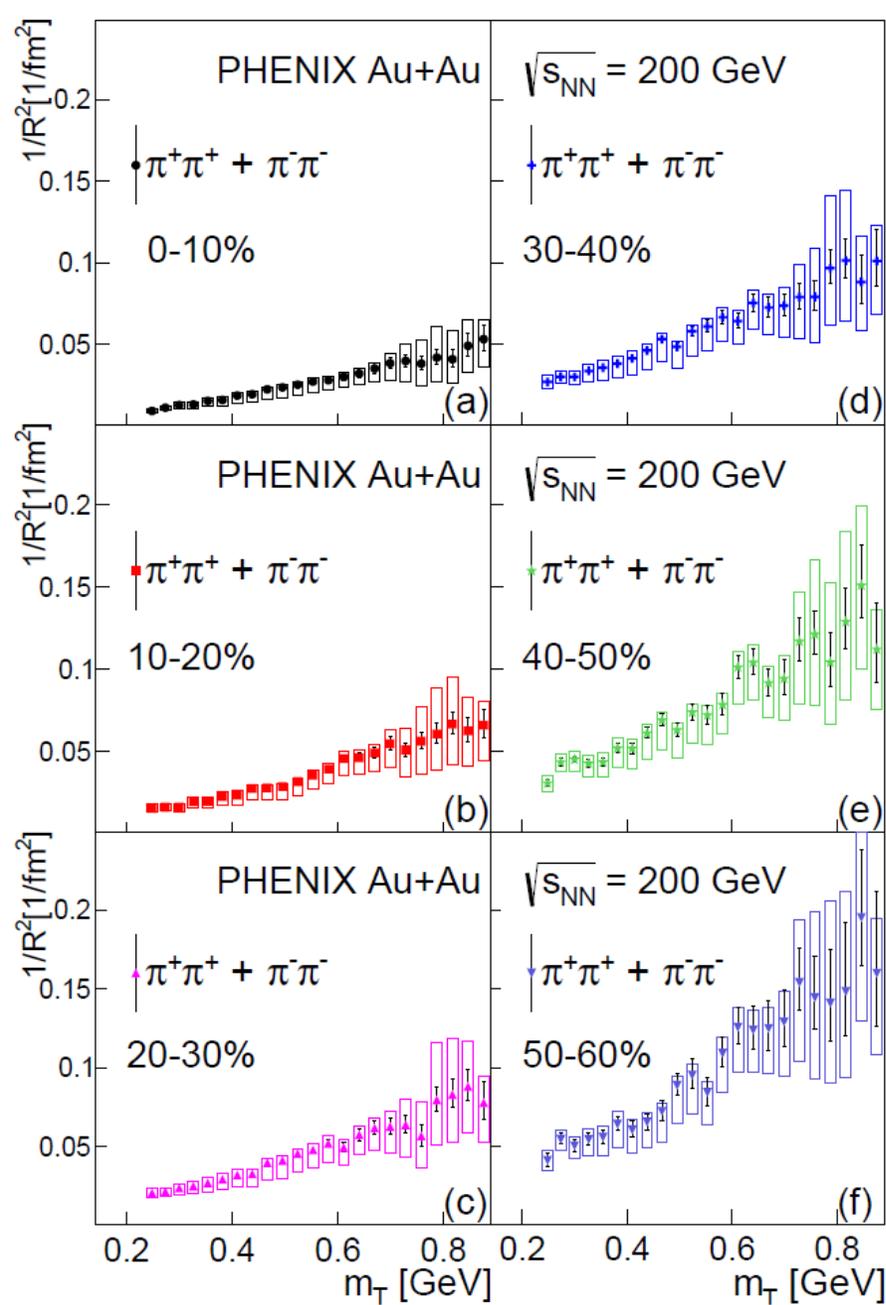
$$\alpha(m_T, N_{part})$$



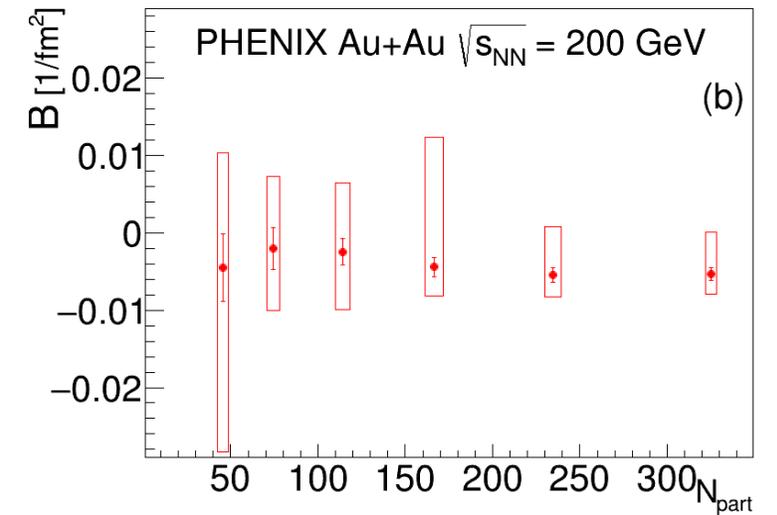
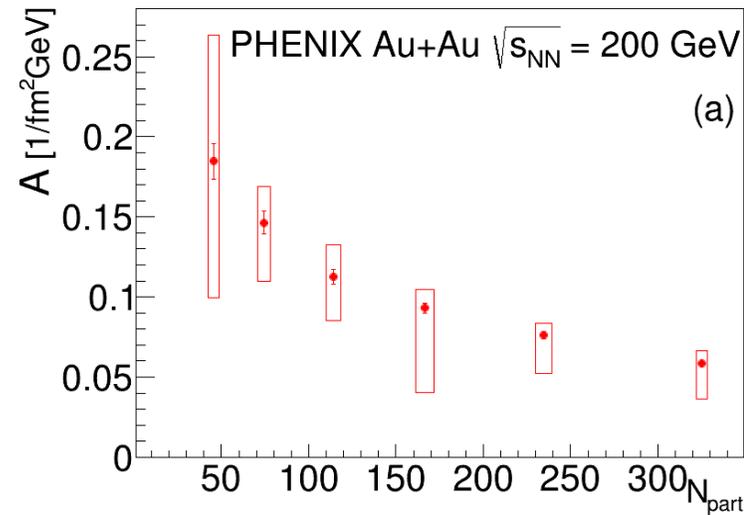
- Does not depend on m_T , does depend on N_{part}
- N_{part} dep. has model selection power
- Anomalous diffusion, QCD jets, resonances???



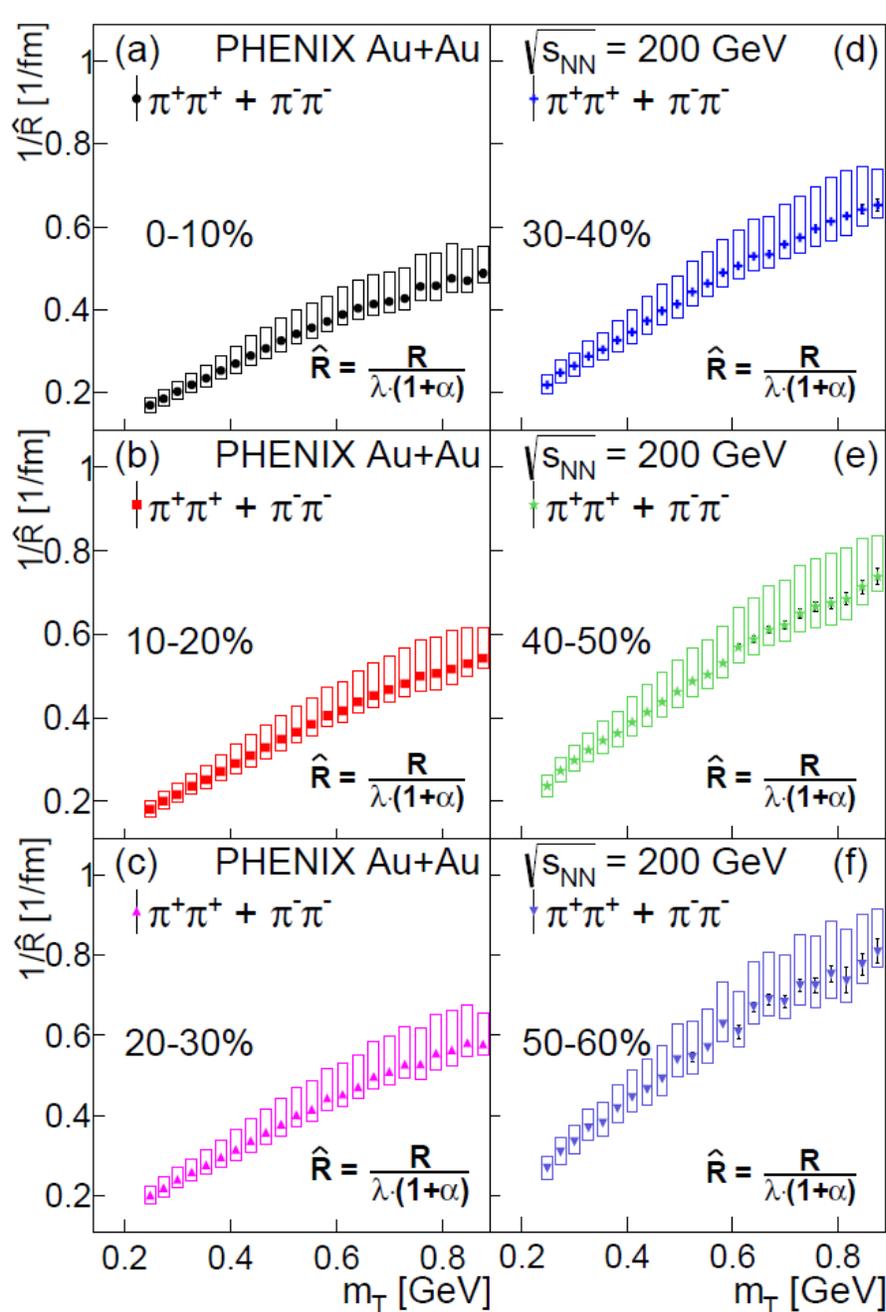
$R(m_T, N_{part})$



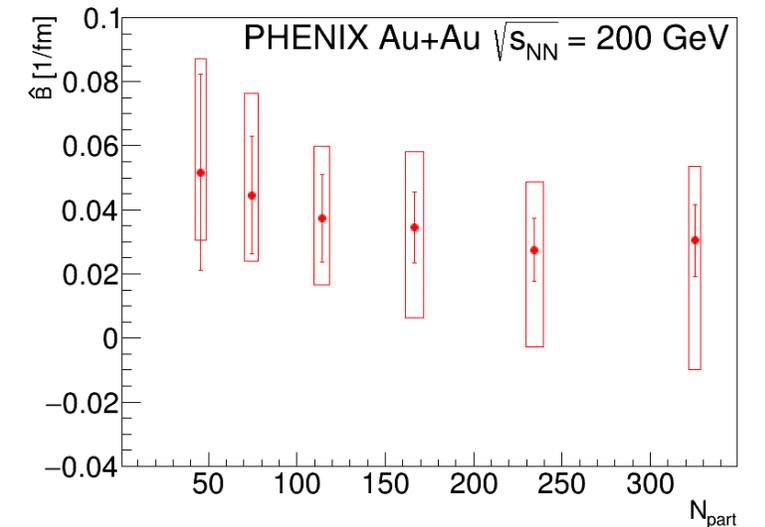
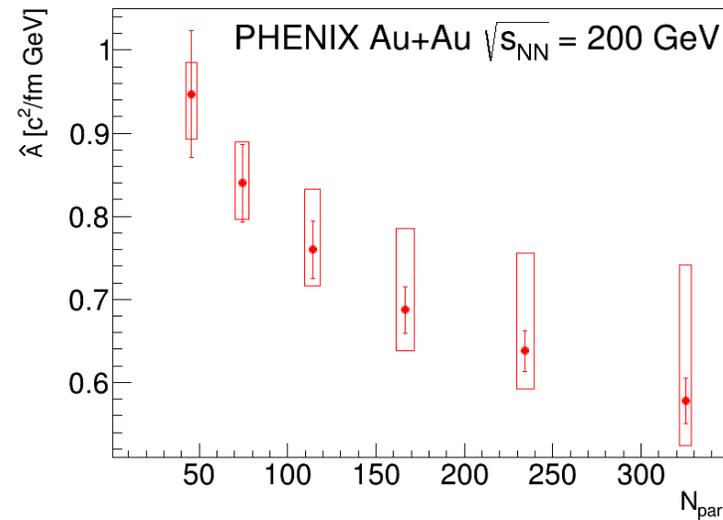
- Unexpected hydro scaling but not RMS
- Centrality ordering, monotonic behavior
- Related to the size?



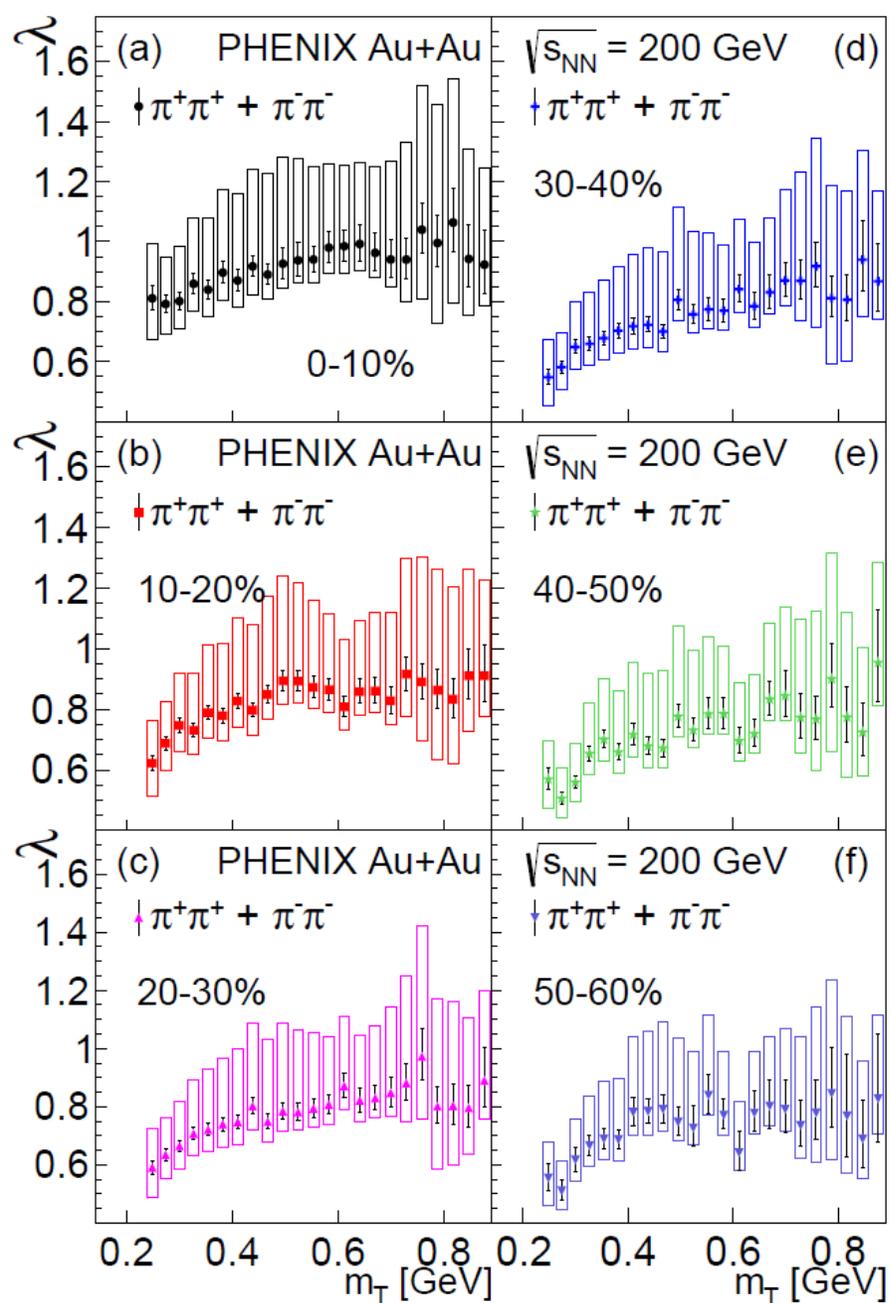
$\hat{R}(m_T, N_{part})$



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

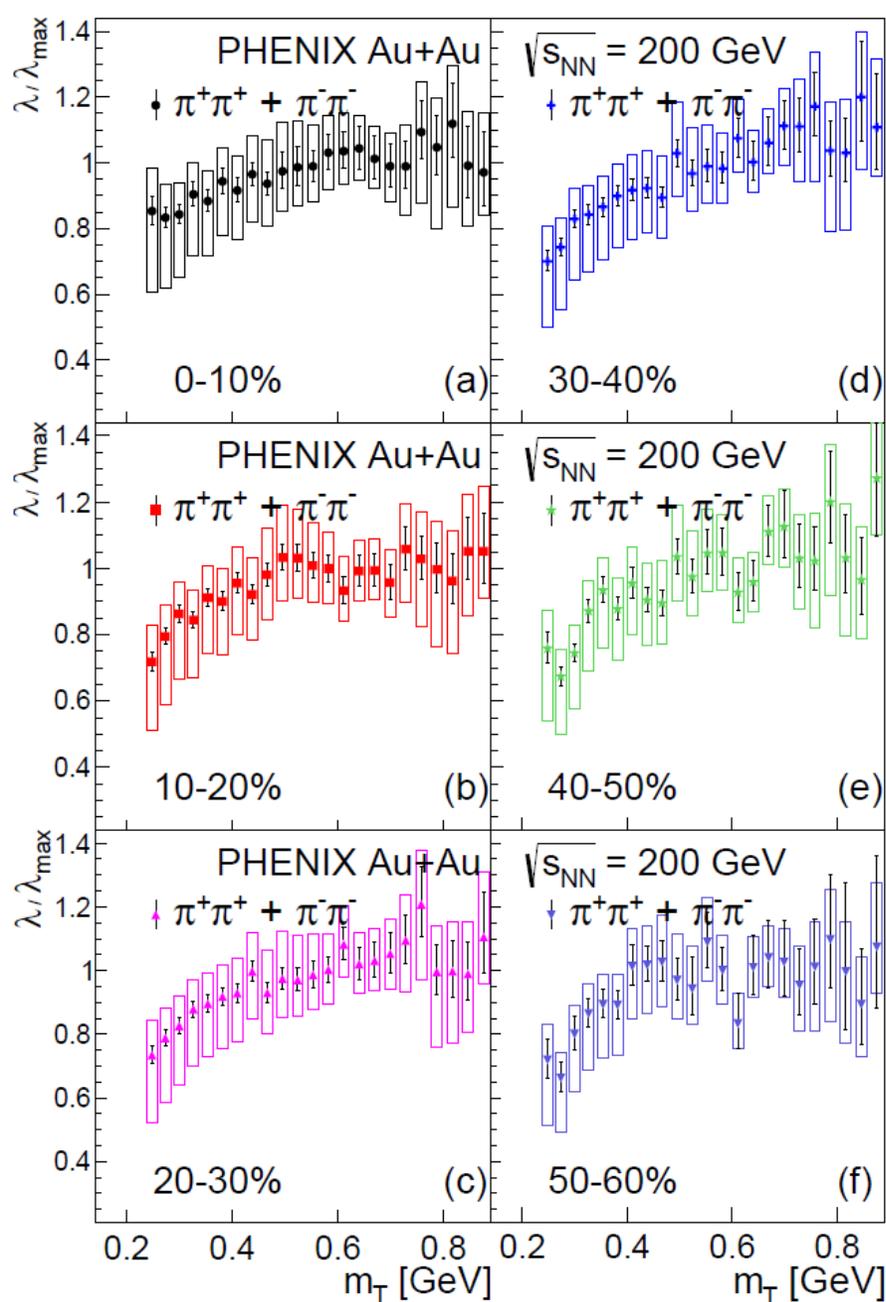


$$\lambda(m_T, N_{part})$$

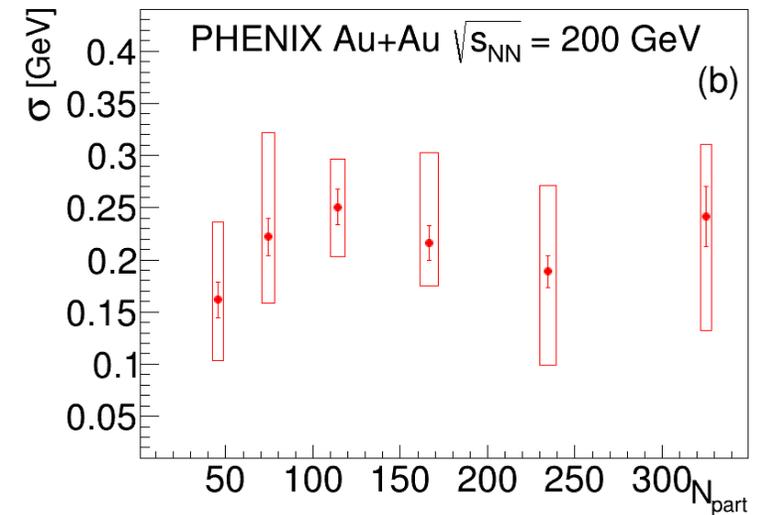
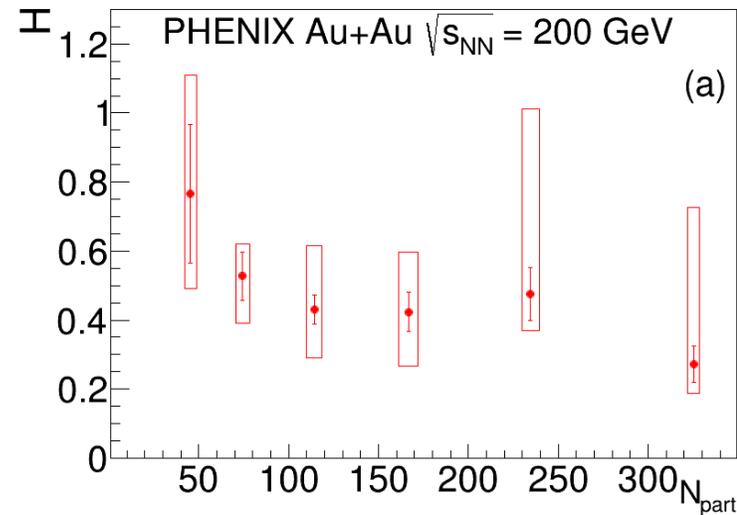


- Suppression on every centrality
- Centrality independent!
- Sign of the η' in medium mass modification?
- Let's compare the results to Monte Carlo simulations

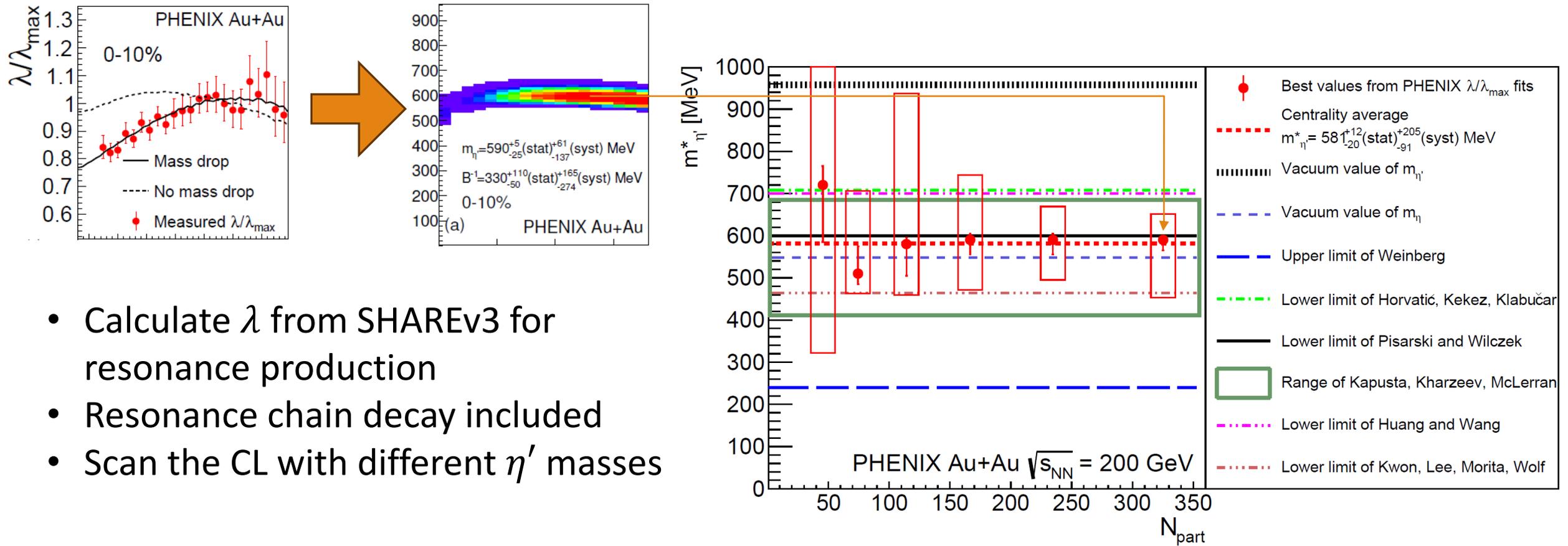
$$\lambda/\lambda_{max}(m_T, N_{part})$$



- Suppression on every centrality
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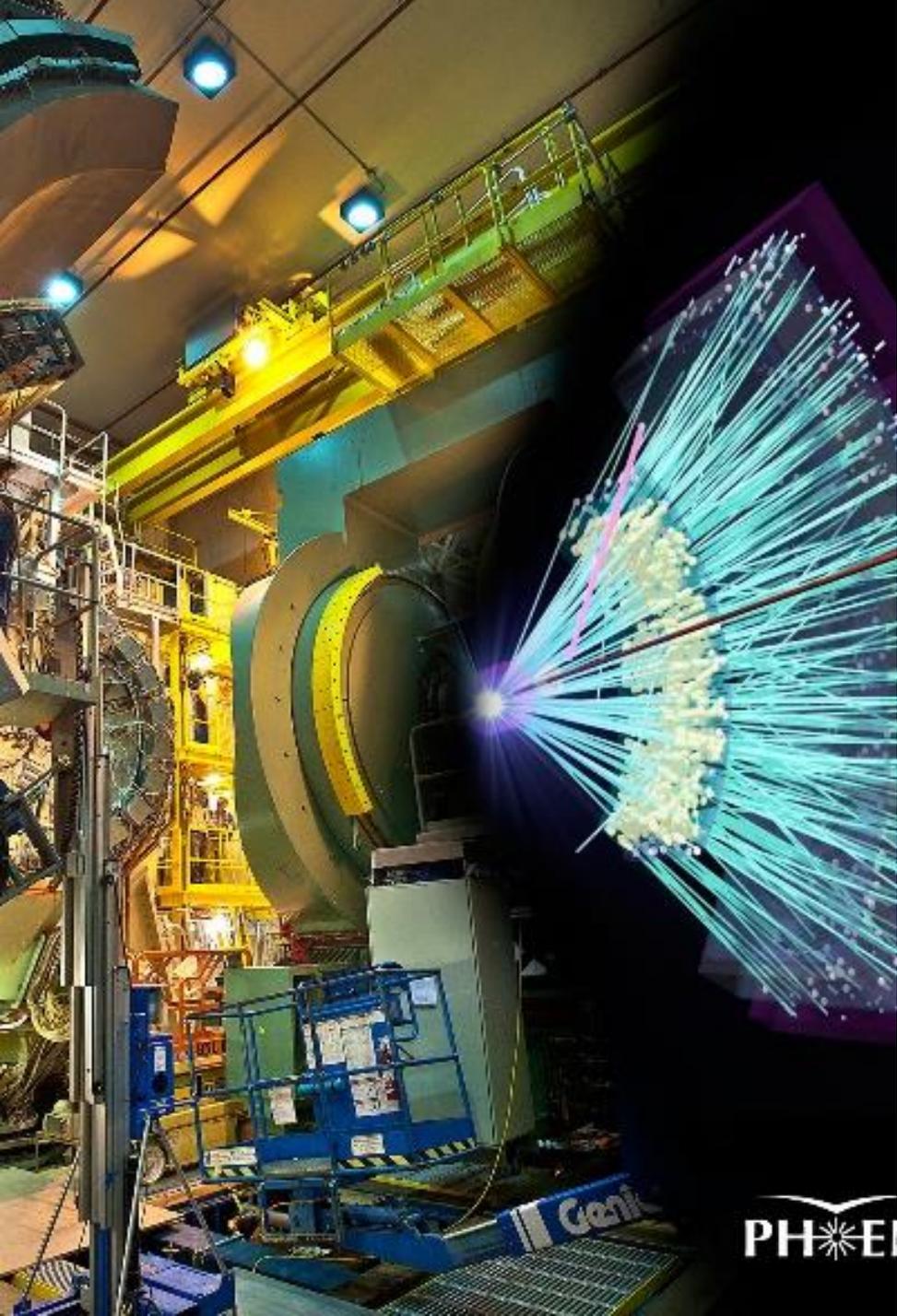


η' mass modification and $U_A(1)$ restoration ?



- 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: $m_{\eta} \approx m_{\eta'}$



Summary and outlook

Precise measurement of BEC requires Levy-exponent

$$1 < \alpha < 2$$

Levy scale R exhibits hydro scaling \rightarrow size?

Levy scale \hat{R} linear scaling \rightarrow size?

Strength parameter λ indicates in medium mass modification of η' meson

Accepted to PRC : [arXiv:2407.08586](https://arxiv.org/abs/2407.08586)

THANK YOU FOR YOUR ATTENTION!¹⁶

References

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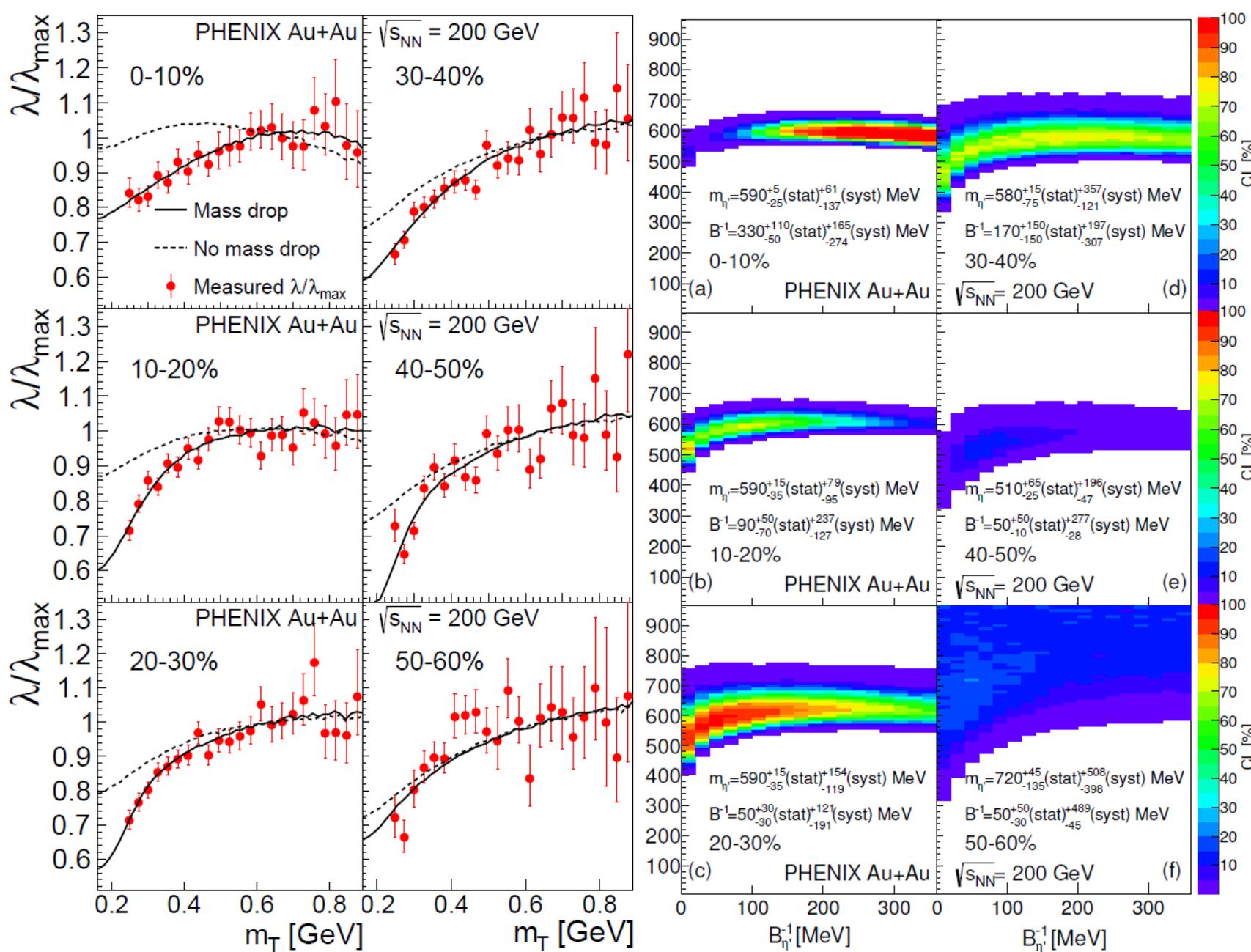
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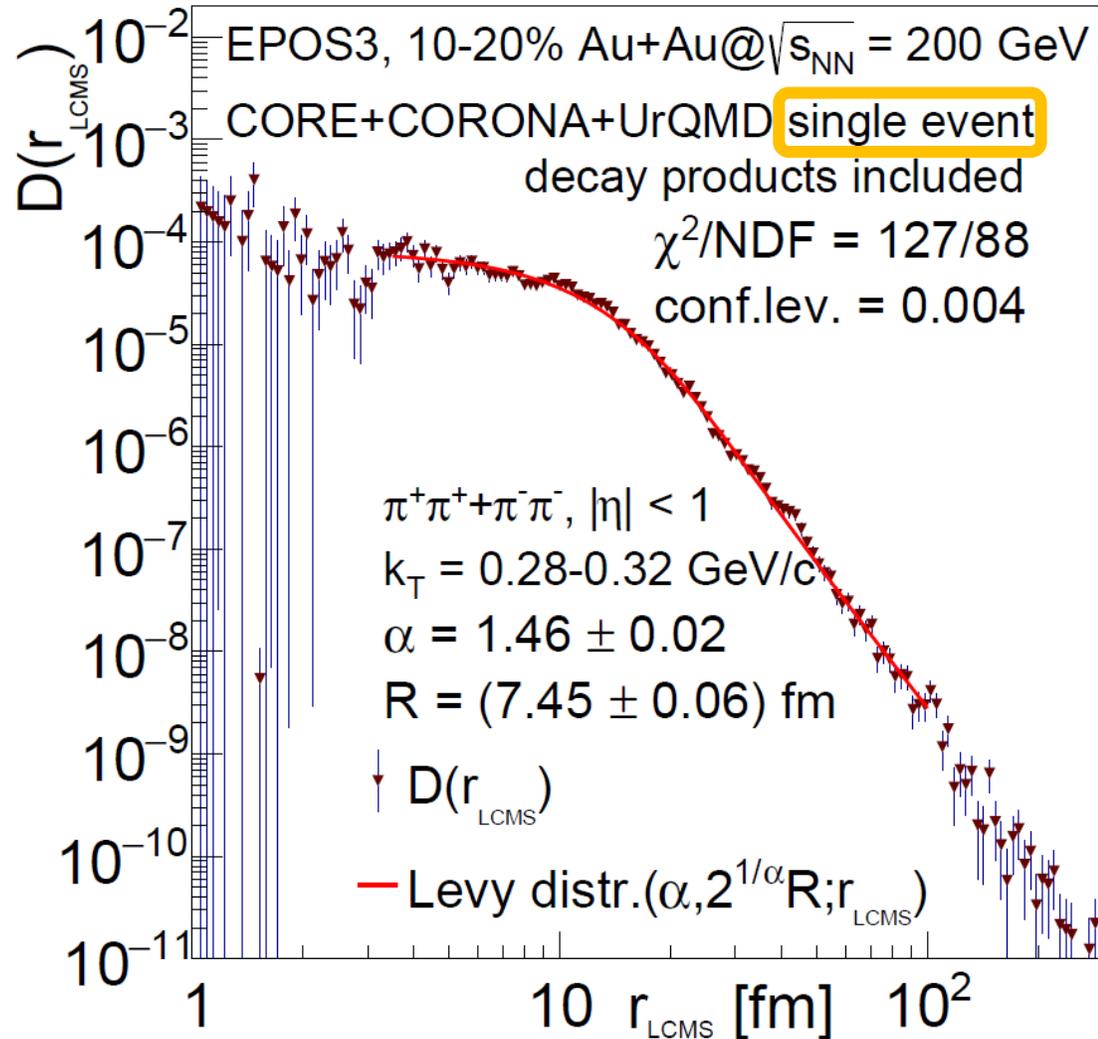
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Comparison to MC



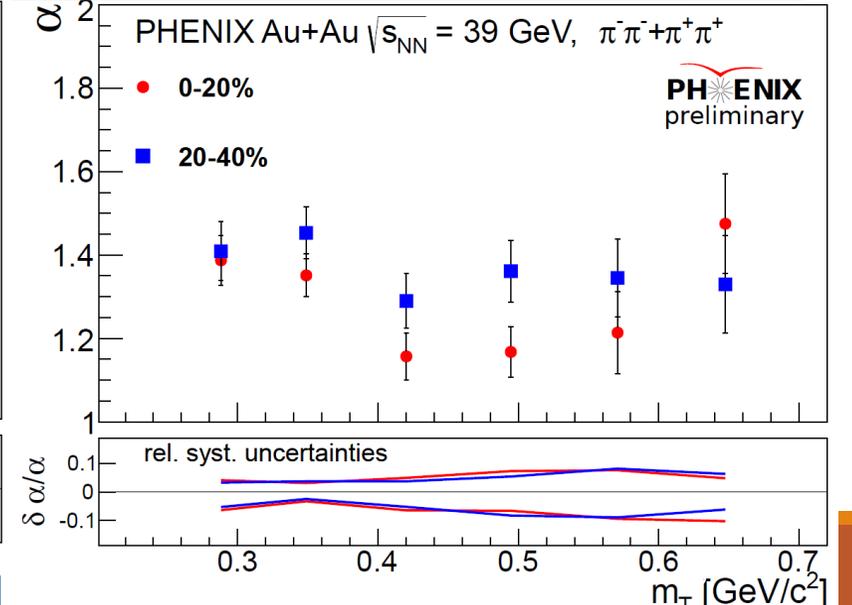
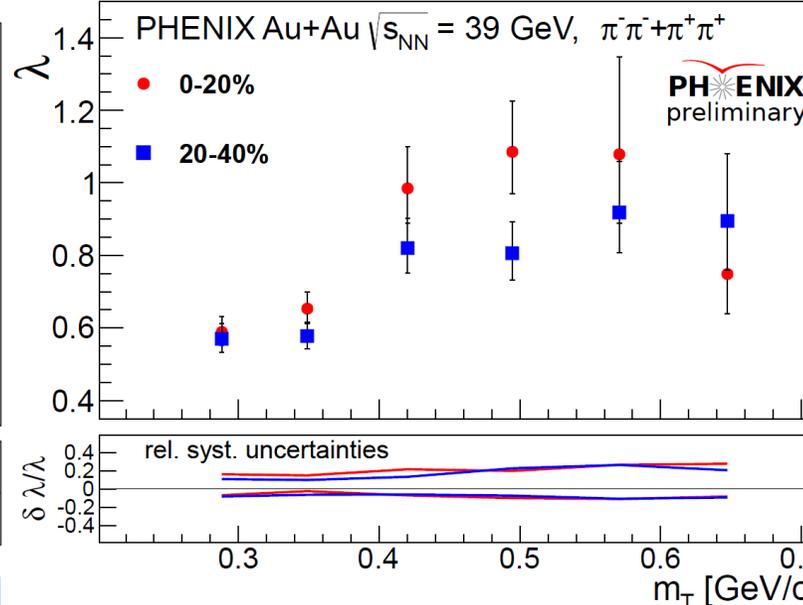
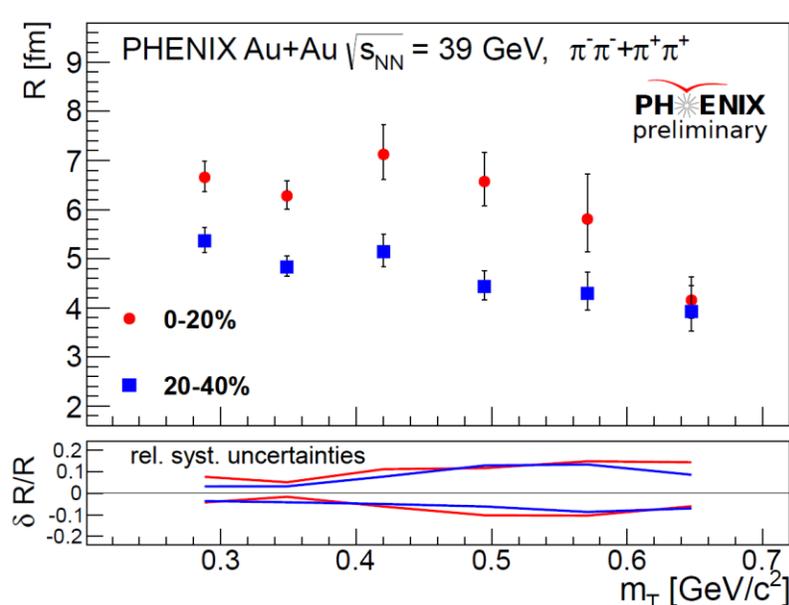
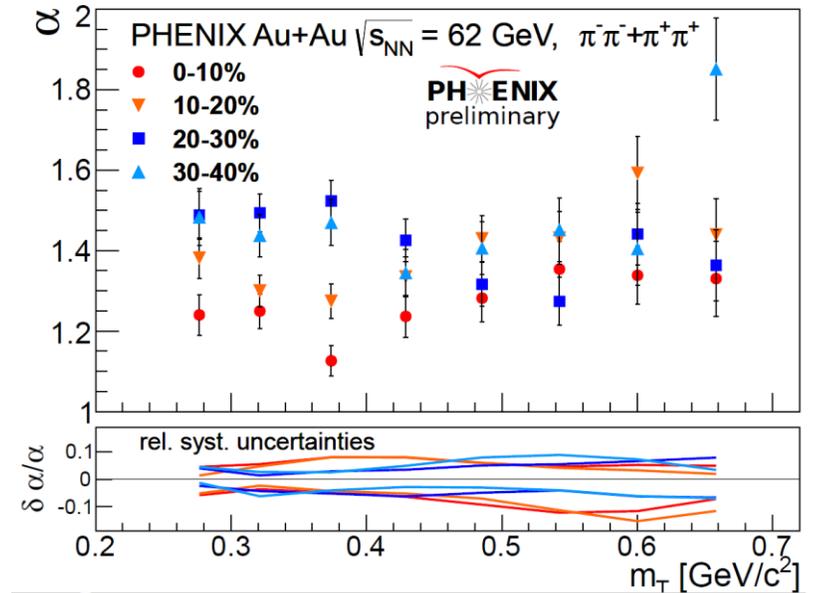
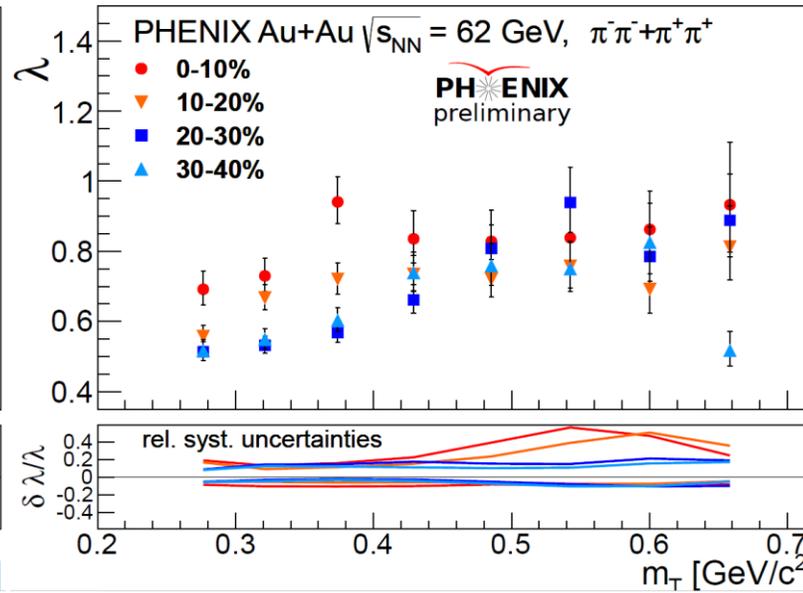
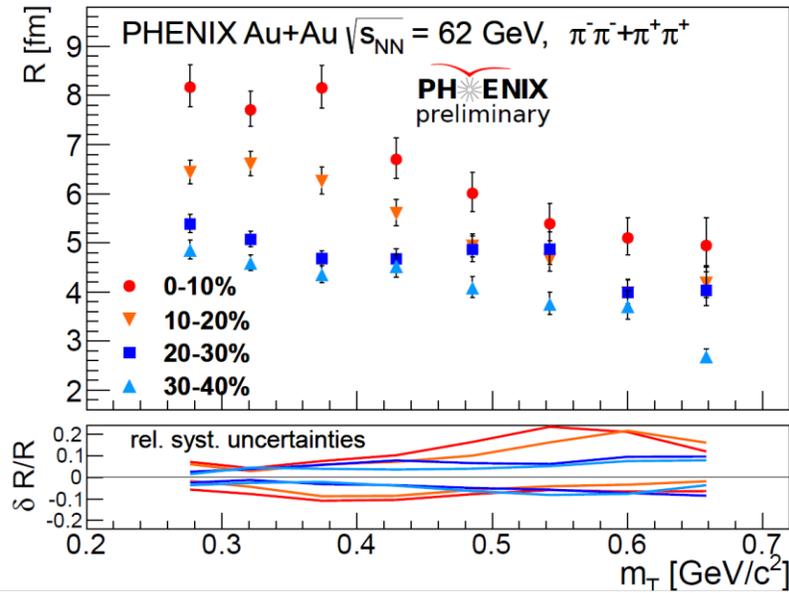
- Calculate λ from SHAREv3 for resonance production
- Resonance chain decay included
- Scan the CL with different η' masses

EPOS simulation – event-by-event correlation

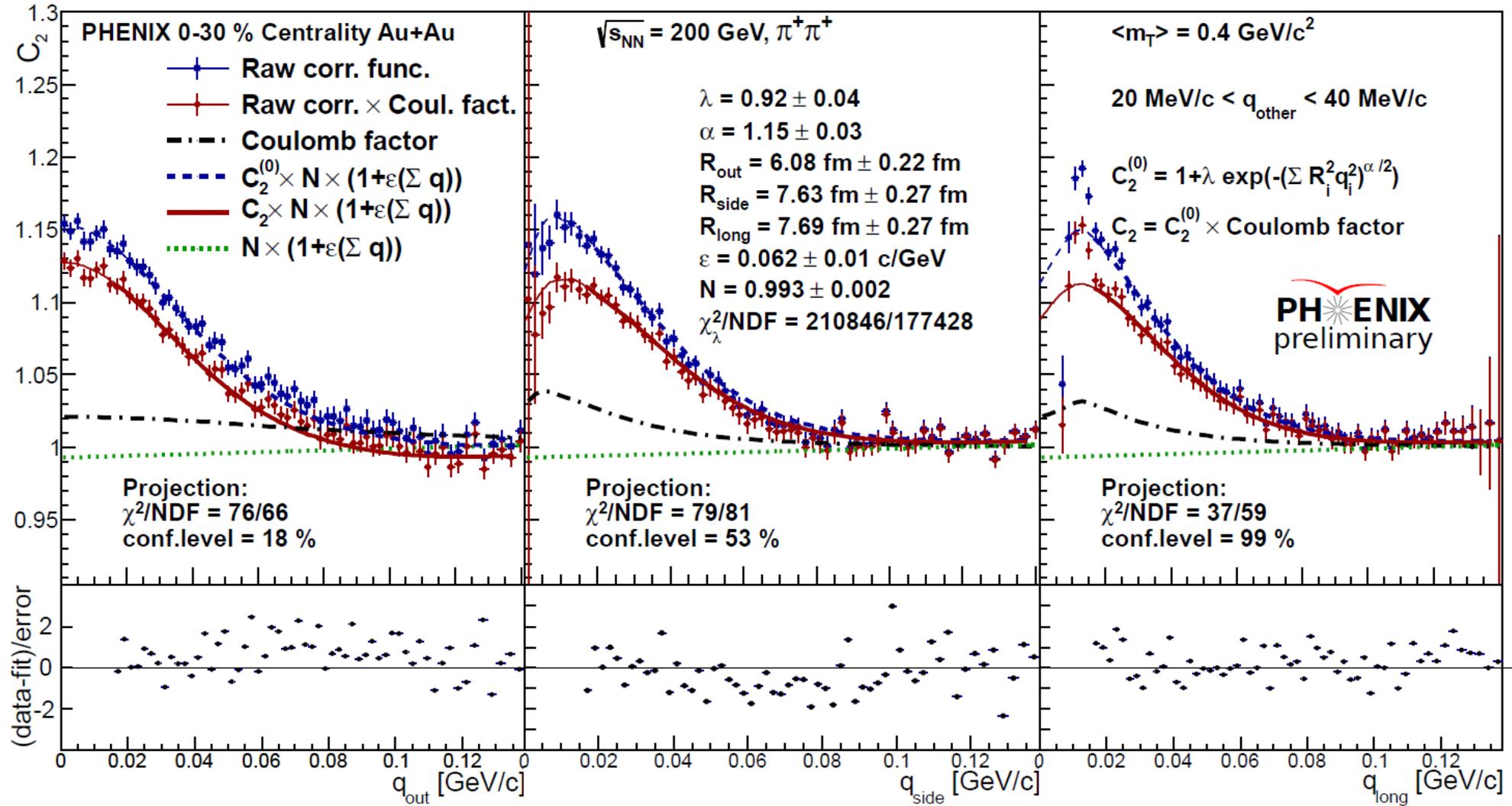


- Core-halo picture is included
- UrQMD for the hadronic cascade
- Levy gives the good description
- It is a single event!
- This analysis support that the origin of the Levy shape could be explained only with the experimental averaging
- This analysis also support the role of the resonances, i.e., the anomalous diffusion
- With this confidence let's look at other experiments

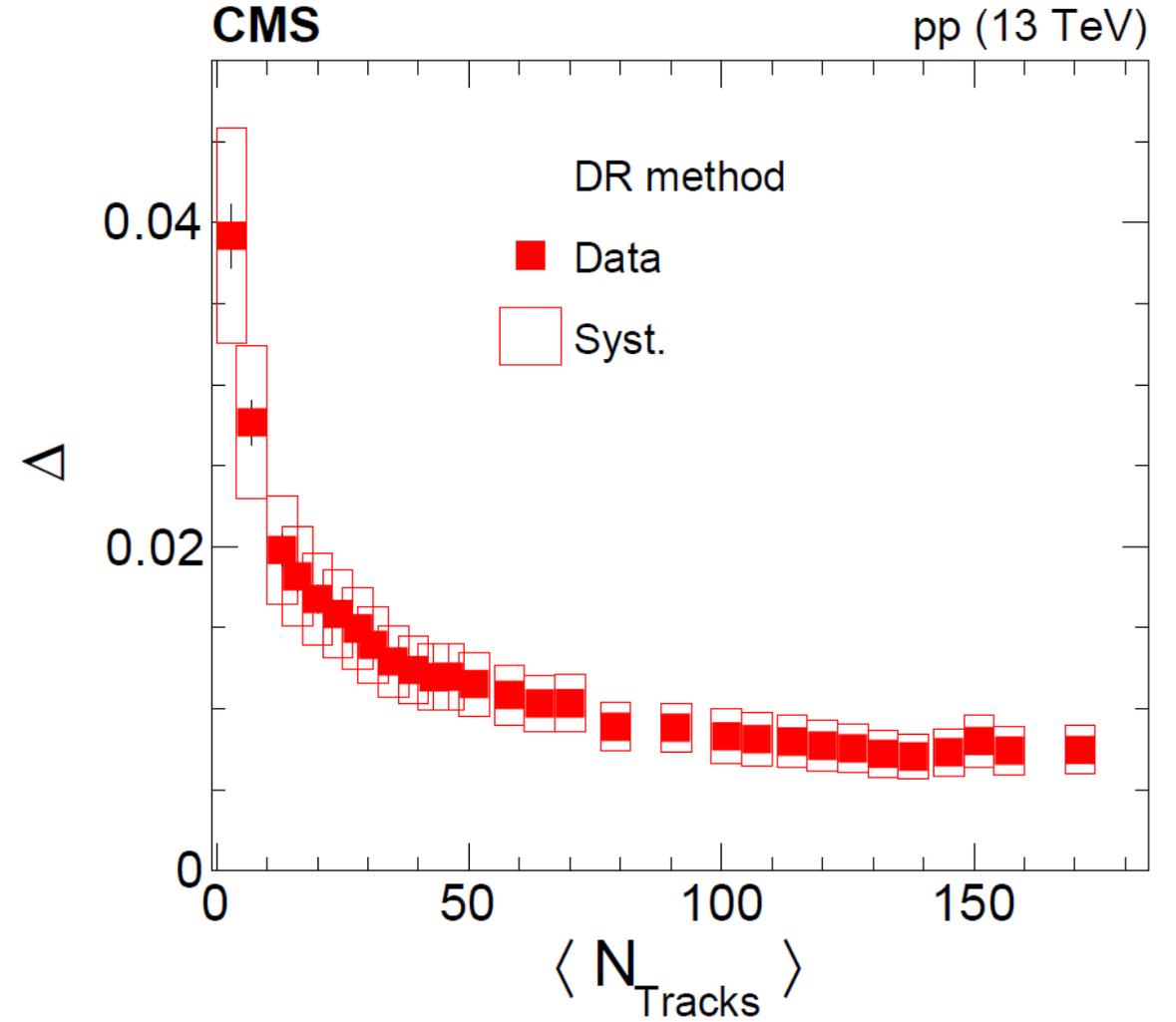
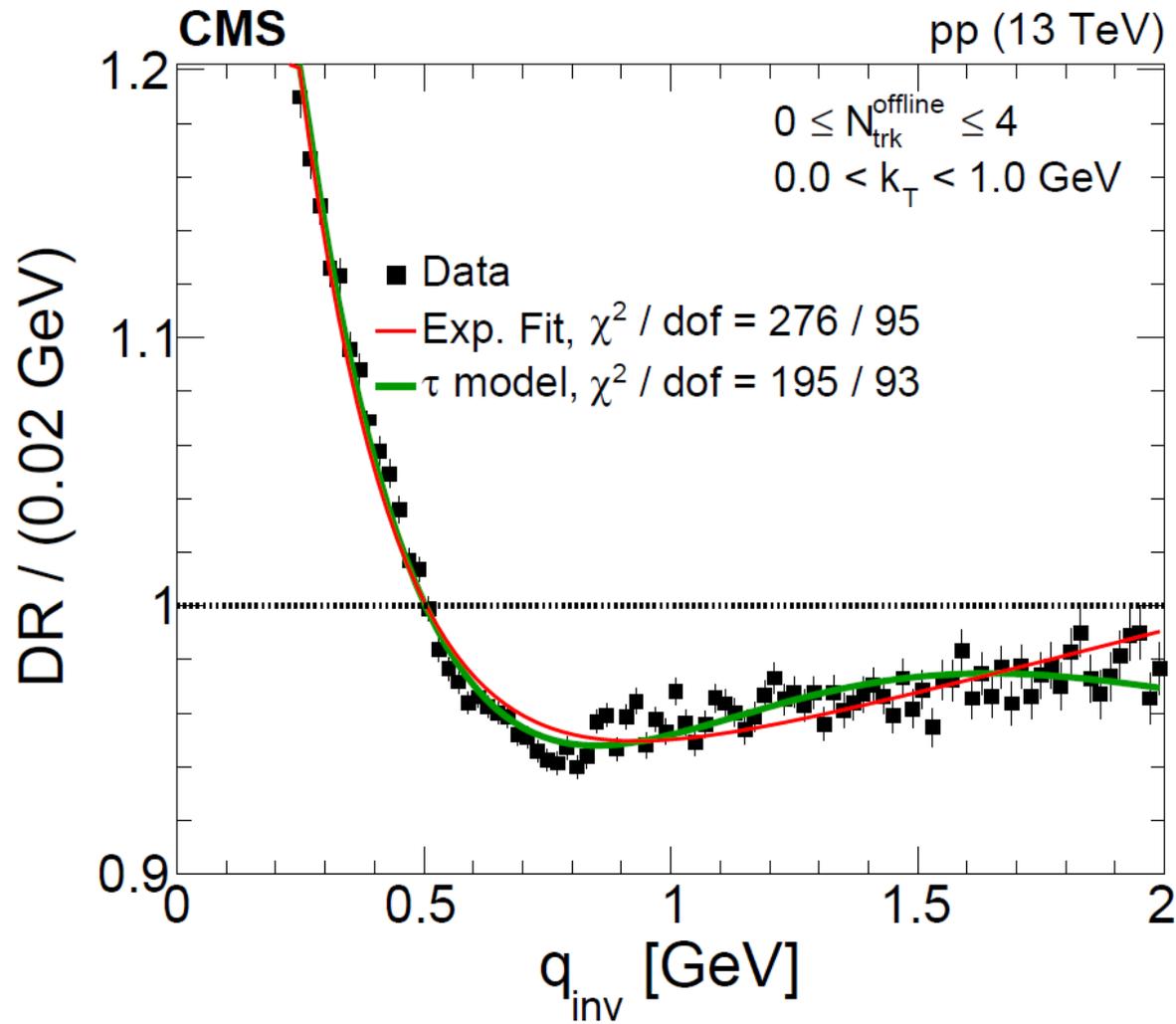
Backup slides



Backup slides



Backup slides



Backup slides

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

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

Femtoscscopy – the core-halo model

Usually pions, kaons, protons are measured

Resonance contributions are considerable: core-halo model

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

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:

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

Femtoscscopy – 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 $R_h \rightarrow \infty$ 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):

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

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 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 $\vec{Q} = (Q_{out}, Q_{side}, Q_{long})$

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 $Q_{out}^2 \approx Q_{side}^2 \approx Q_{long}^2 \neq 0$

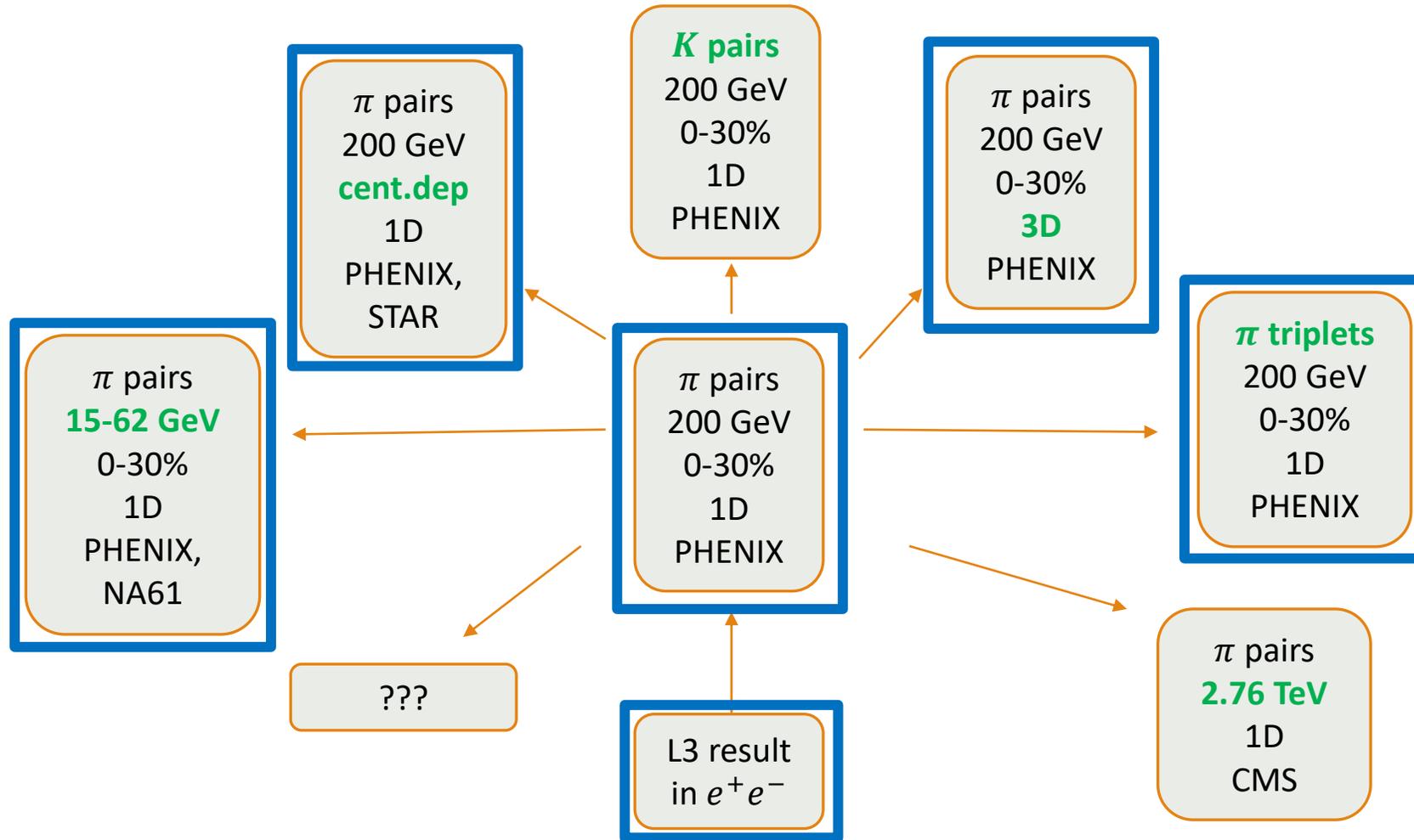
It is also known that the source approximately spherical at RHIC

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

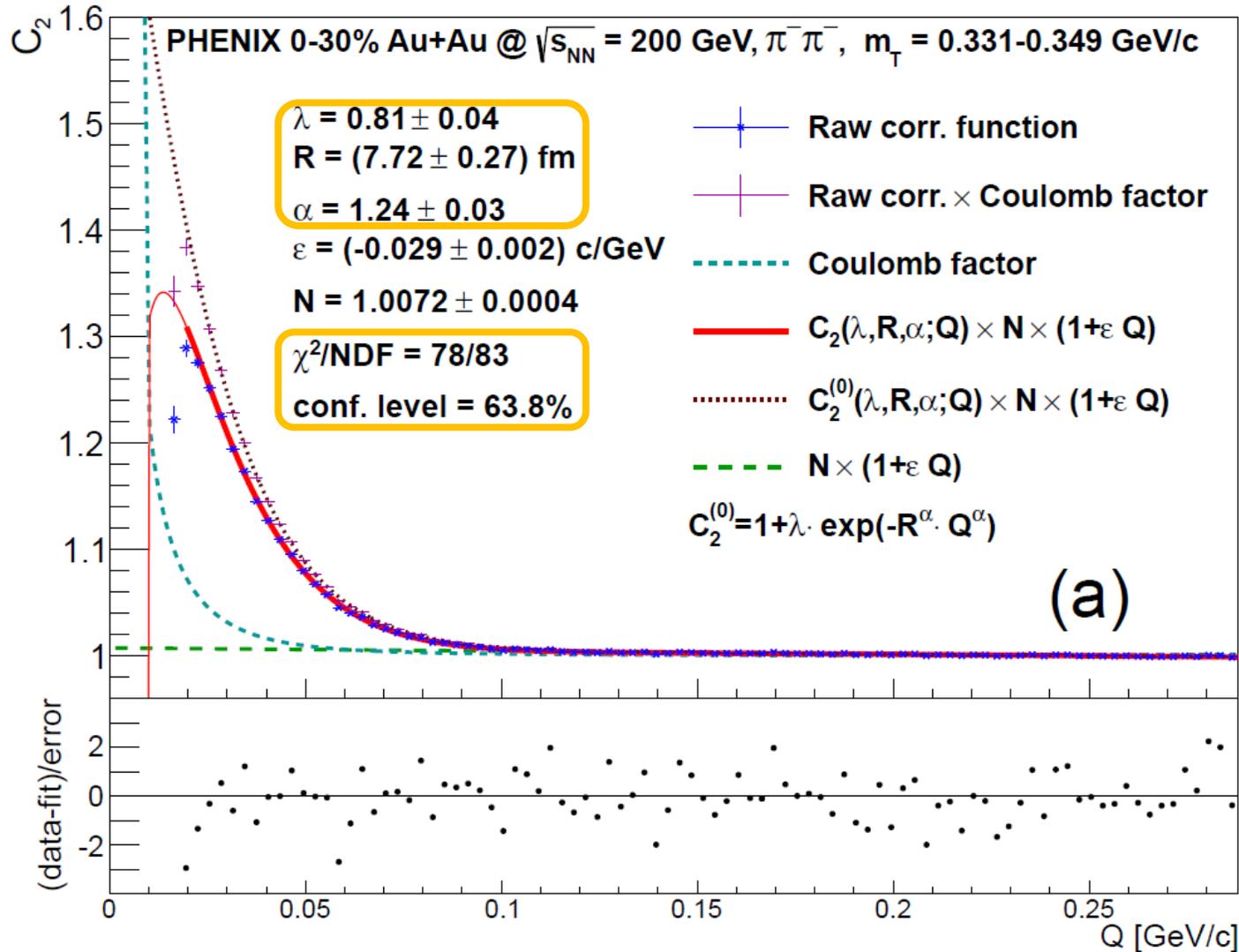
1D variable!

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

The tree of the Levy analyses

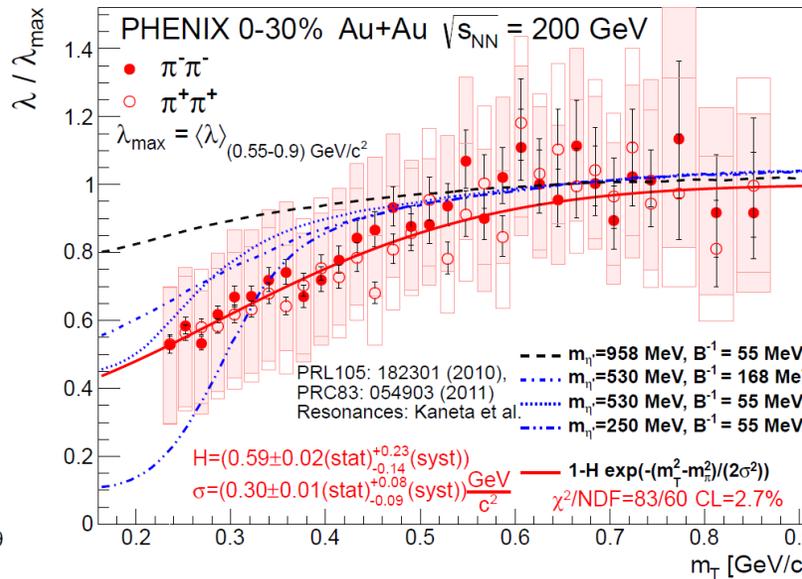
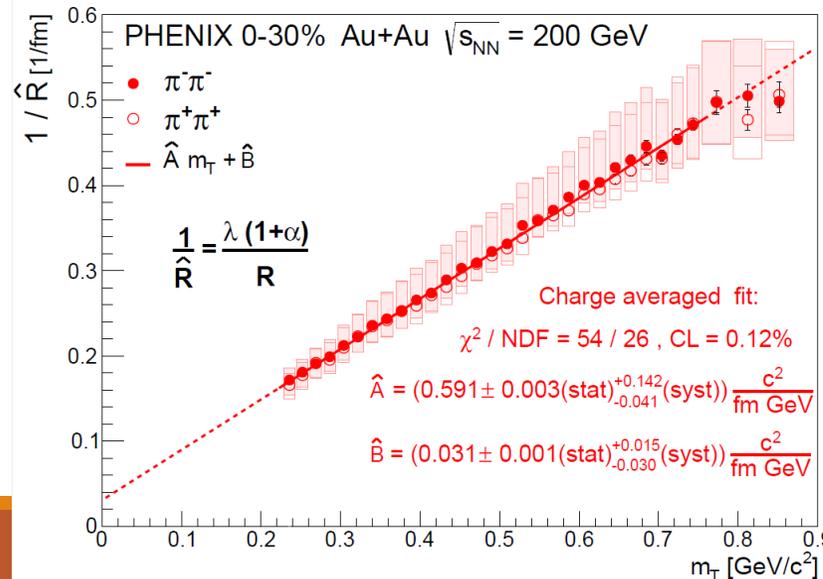
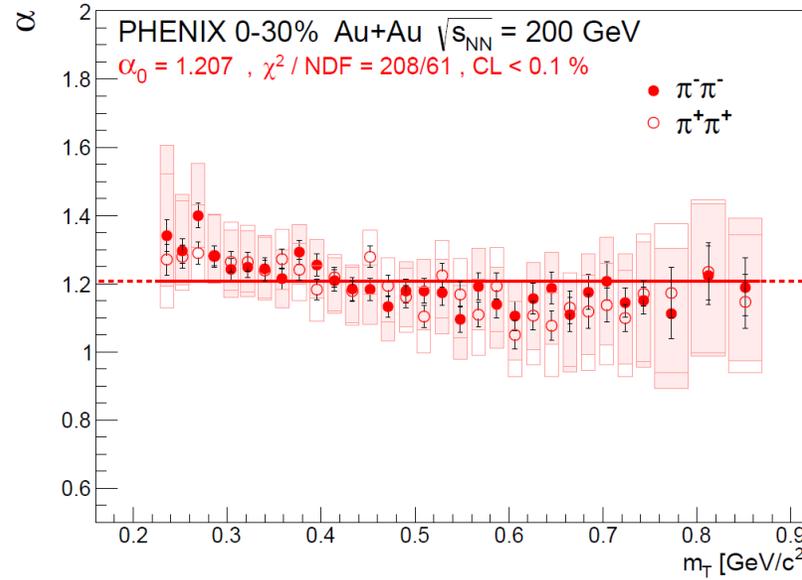
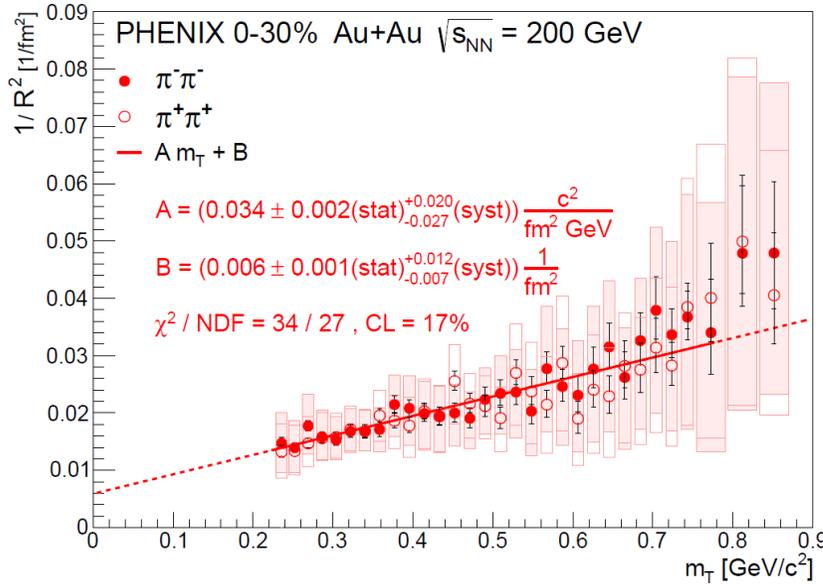


The first results – PHENIX 0-30% Au+Au



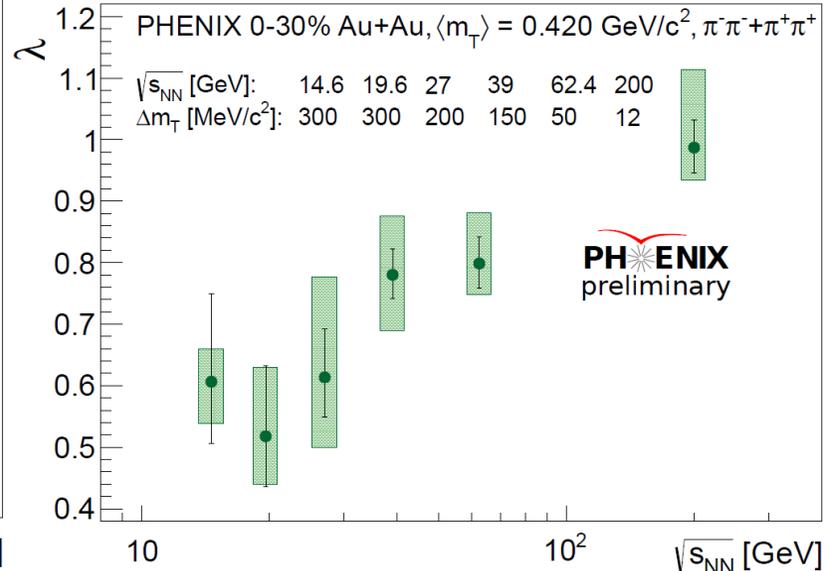
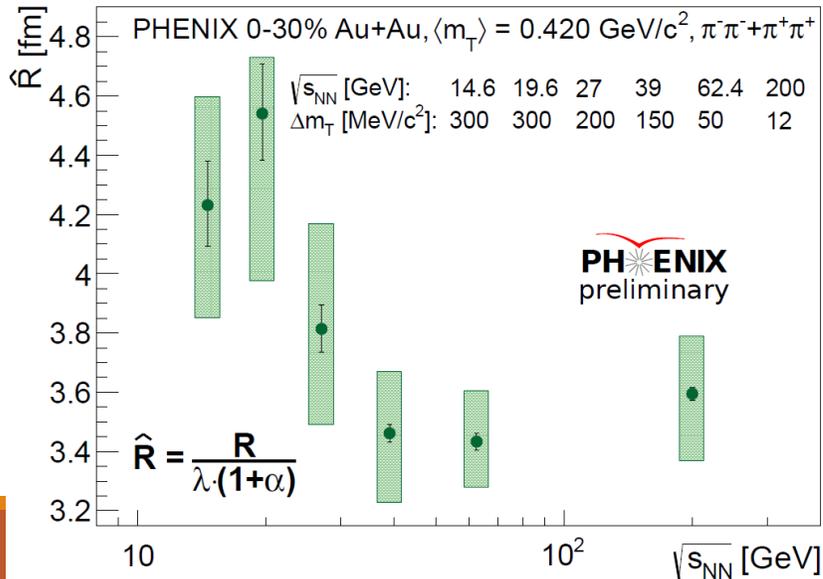
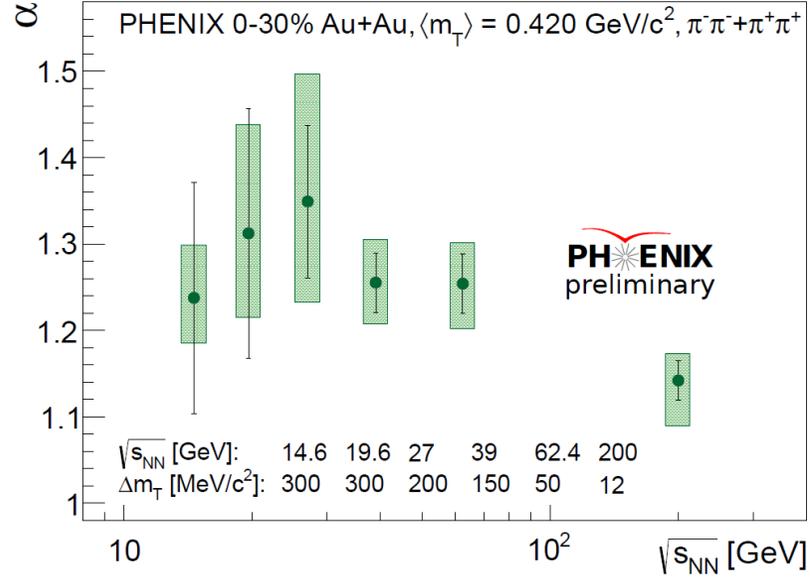
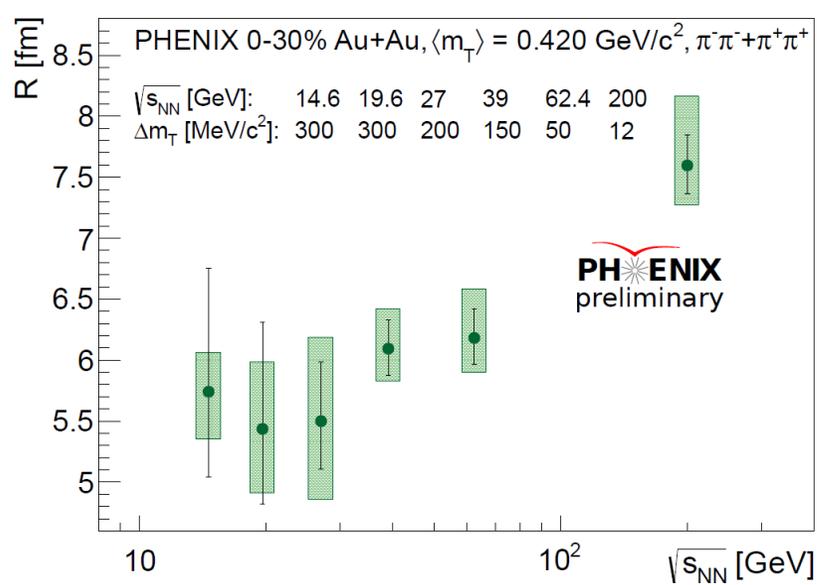
- Measured correlation function in 31 m_T bin with 0-30% cent.
- Coulomb correction incorporated into the fit function
- $\alpha \neq 2$ nor $\alpha \neq 1$
- The fits are acceptable in terms of confidence level and χ^2/NDF
- Gaussian parametrization cannot describe the data

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



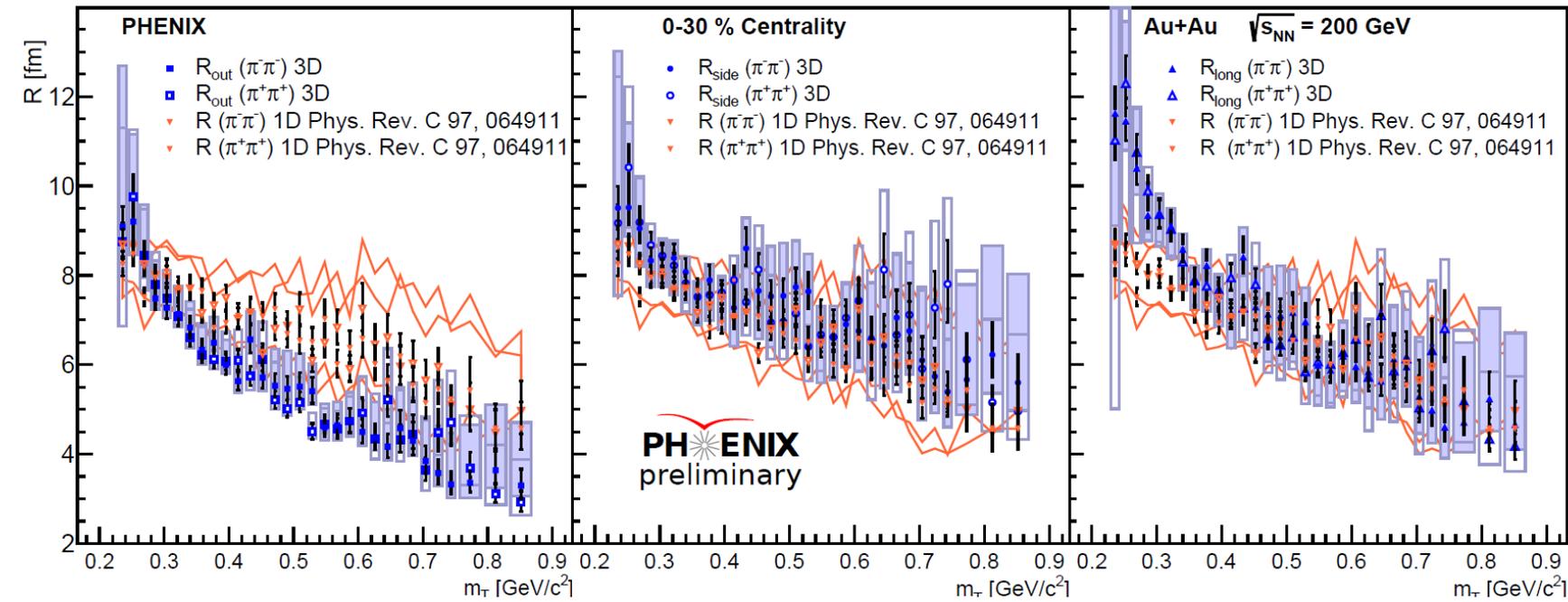
- R exhibits hydro scaling
- $1 < \alpha < 2, \langle \alpha \rangle \approx 1.2$
- $\lambda(m_T)$ suppressed which compatible with modified η' mass in the medium (compared with a resonance model)
- New scaling parameter
 - Interpretation?
- Interpretation of α ?
- Let's see the N_{part} and $\sqrt{s_{NN}}$ dependence

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

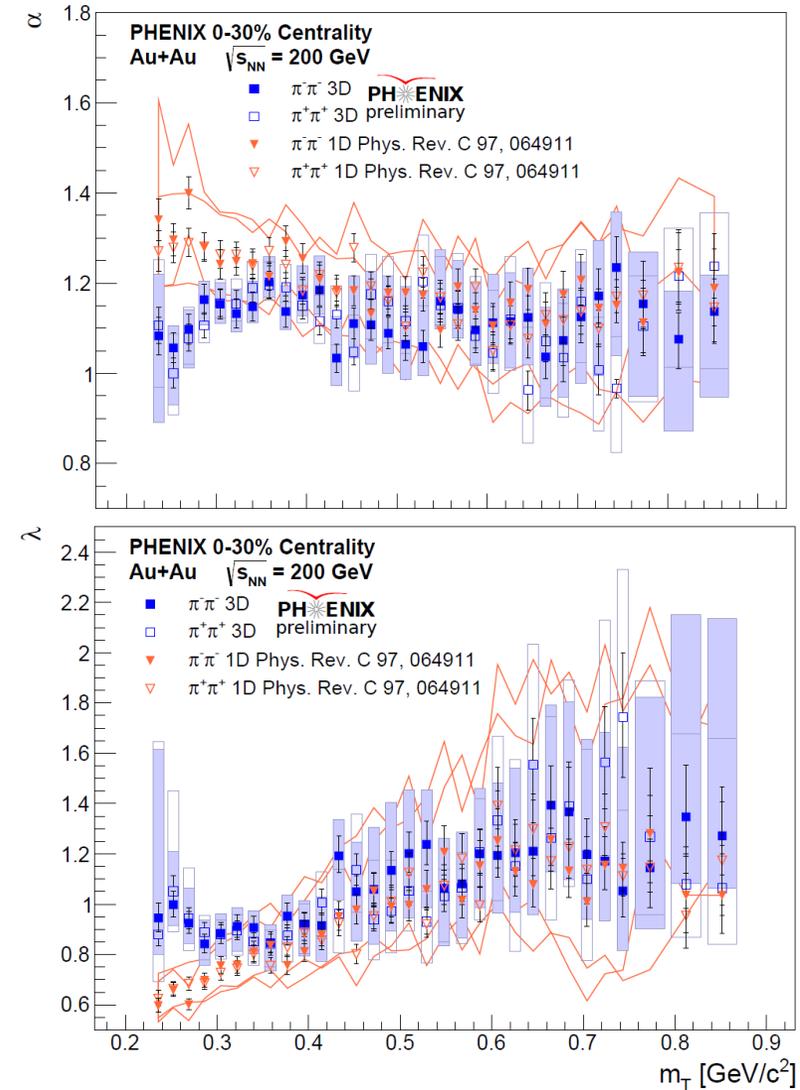


- Integrated in m_T due to the lack of statistics
- α does not really depend on $\sqrt{s_{NN}}$
- Non-monotonic behavior of \hat{R} observed
 - Interpretation?
- For $\sqrt{s_{NN}} \geq 39 \text{ GeV}$ there are m_T dependent analysis but the trends are not clear

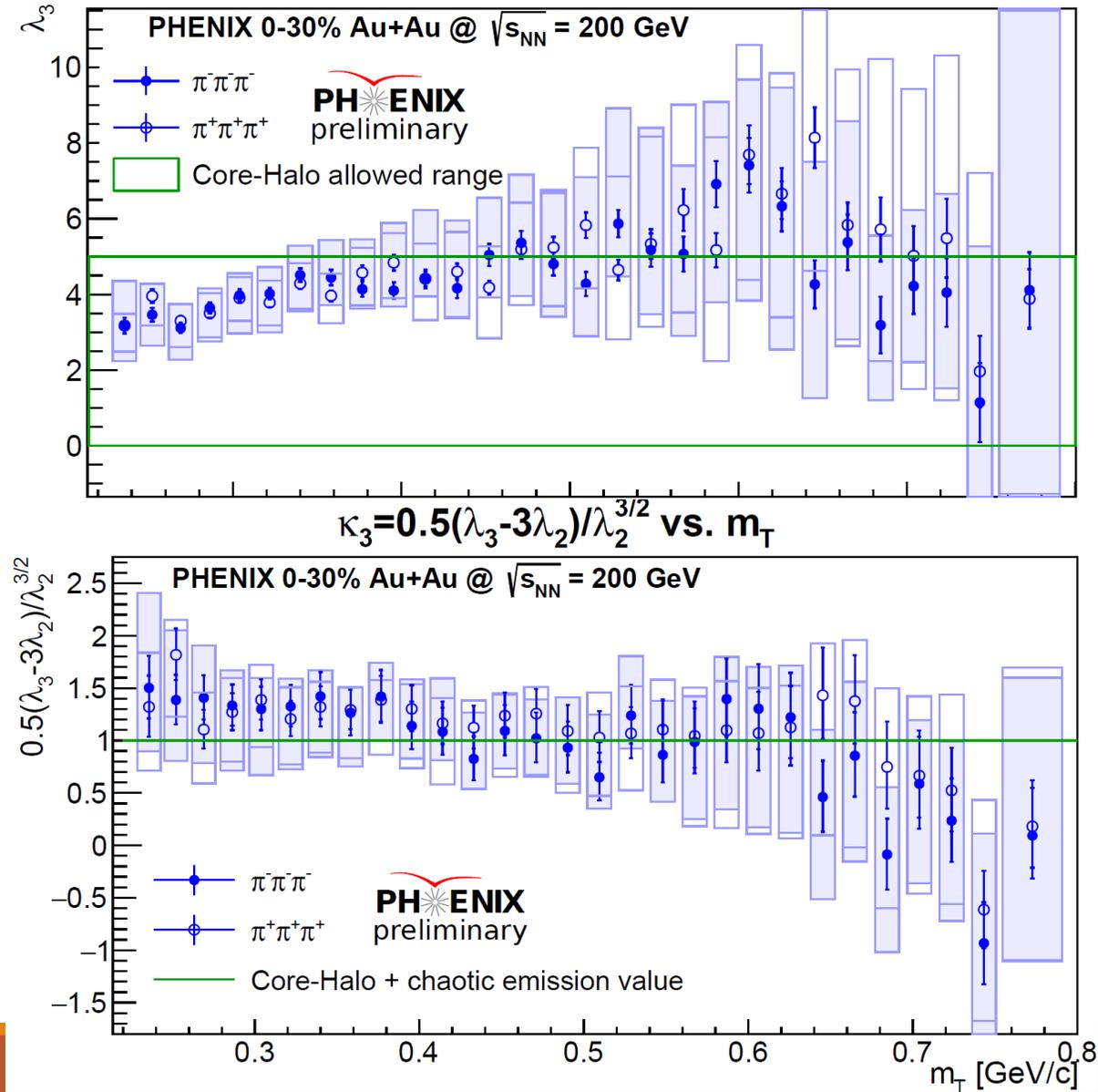
3D correlation – PHENIX 0-30% Au+Au



- 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!



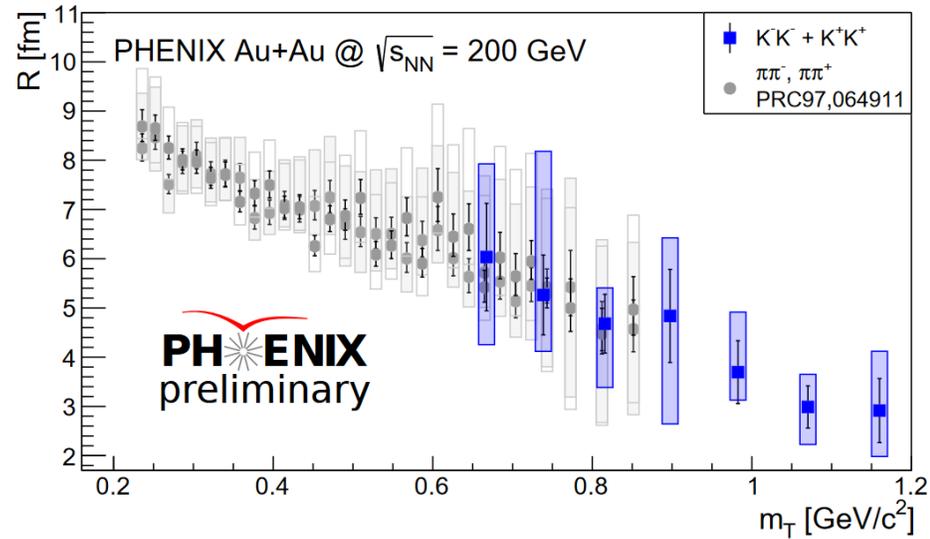
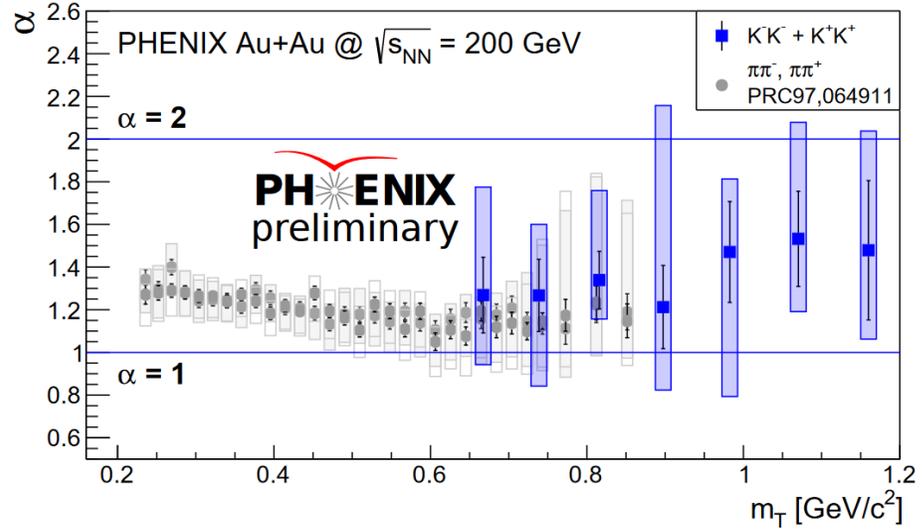
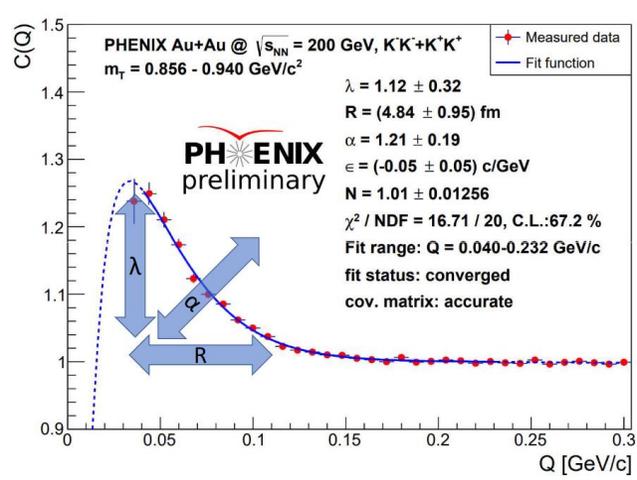
3 particle correlation – PHENIX 0-30% Au+Au



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

- 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

