Centrality dependent Levy HBT at PHENIX

SANDOR LOKOS (IFJ PAN & MATE KRC)

BIALASOWKA SEMINAR 2025

Centrality dependent Levy HBT at PHENIX

SANDOR LOKOS (IFJ PAN & MATE KRC)

BIALASOWKA SEMINAR 2025

MY PREVIOUS BIALASOWKA:
HTTPS://INDICO.FIS.AGH.EDU.PL/EVENT/115/

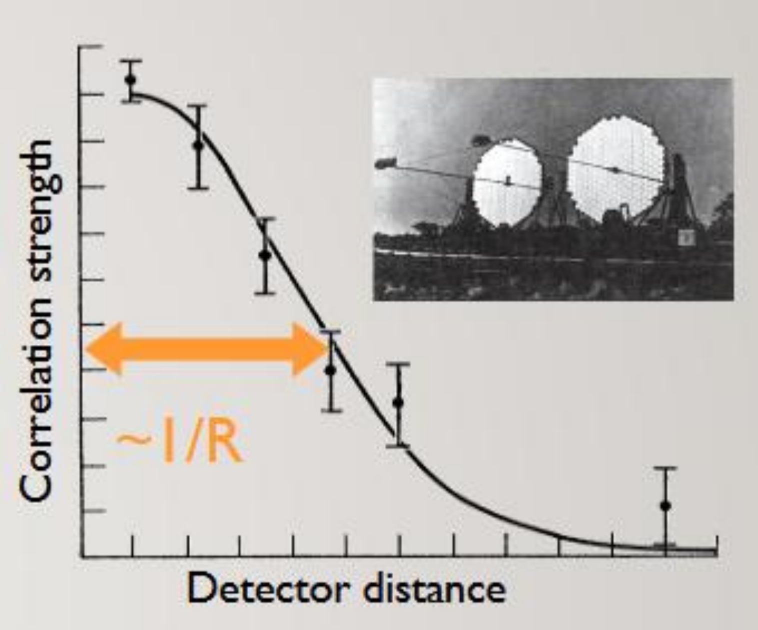
Improved, final results are on the way (Christmas plan to write the paper finally)

THIS IS THAT

HBT in high energy physics

R. Hanbury-Brown, R. Q. Twiss - observing Sirius with radio telescopes

- Intensity correlations vs detector distance ⇒ source size
- Measure the sizes of apparently point-like sources!



Goldhaber et al: applicable in high energy physics

Understanding: Glauber, Fano, Baym, …

- Momentum correlation $C(q)$ related to source $S(r)$ (under some assumptions):

$$C(q) \approx 1 + \left| \int S(r) e^{iqr} dr \right|^2$$

- Also with distance distribution $D(r)$:

$$C(q) \approx 1 + \left| \int D(r) e^{iqr} dr \right|^2$$

- Neglected: pair reconstruction, final state interactions, multi-particle correlations, coherence, …

What is the source shape? Can be explored via femtoscopy

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 – 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:

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

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

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

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

1D variable!

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

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

Final state interactions – about the $\Psi_2^{(\mathrm{Q})}(r)$

Like-charged pions $\rightarrow$ 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

Femtoscopy – two approaches

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

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:

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

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

Assume the **wave function**: free planewave

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

Not to realistic: Coulomb (and strong) FSI

What is the interacting wave function?

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

(more complicated with strong interaction)

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

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

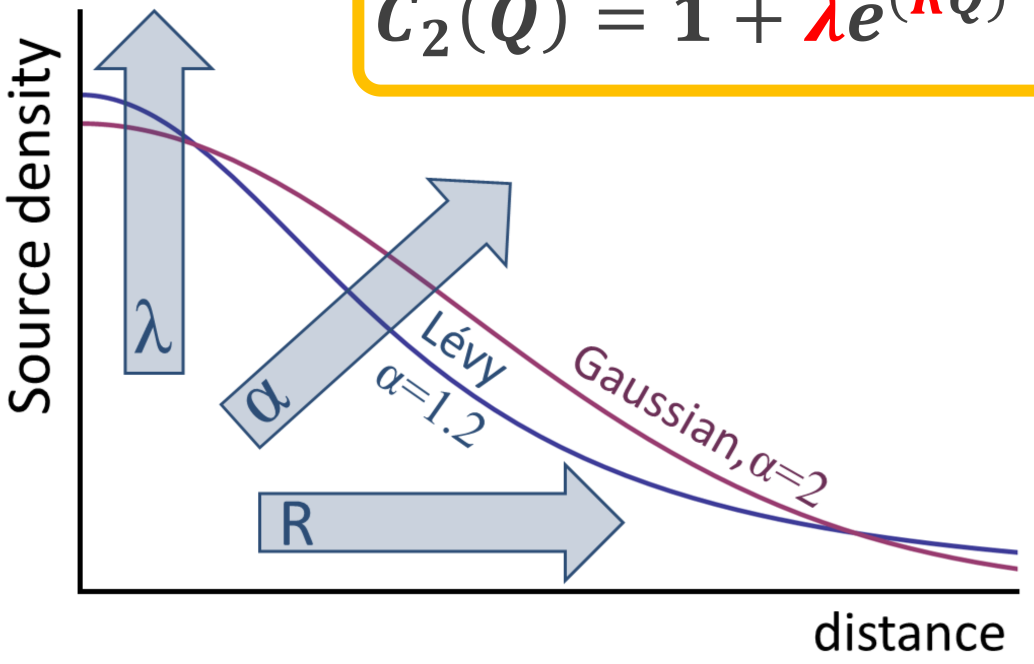
Assume the source to be Levy!

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

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

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

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



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

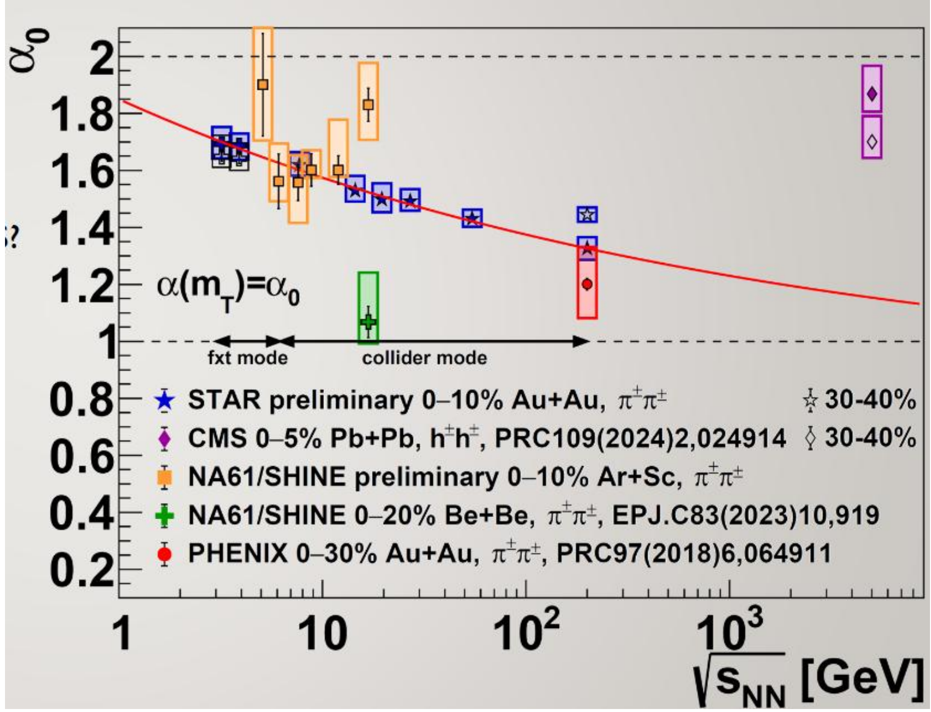
Physics in the parameters

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
- $\text{spatial corr.} \sim r^{-1-\eta}$ $\text{symm. Levy dist.} \sim r^{-1-\alpha}$
- Sudden change in α might be a sign for critical behavior
- Could be the sign of anomalous diffusion or jets



Physics in the parameters

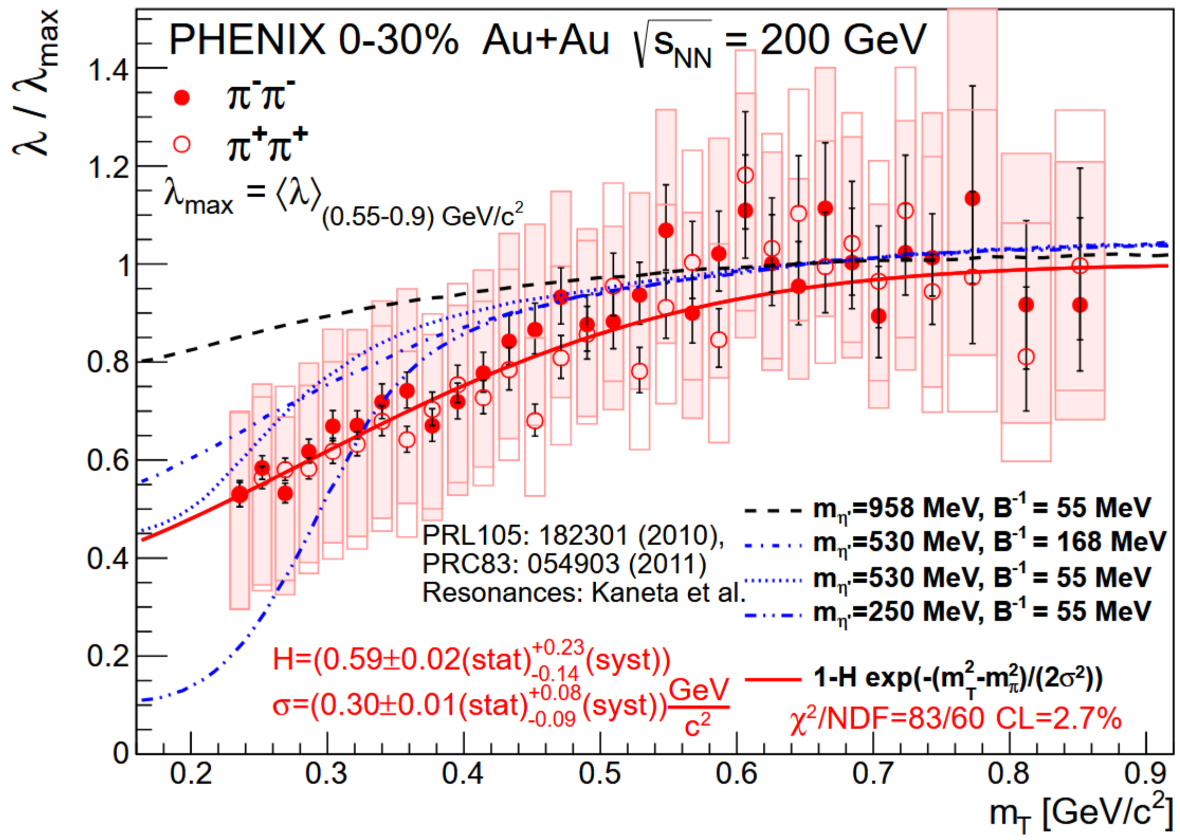
Possible interpretations of the λ:

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

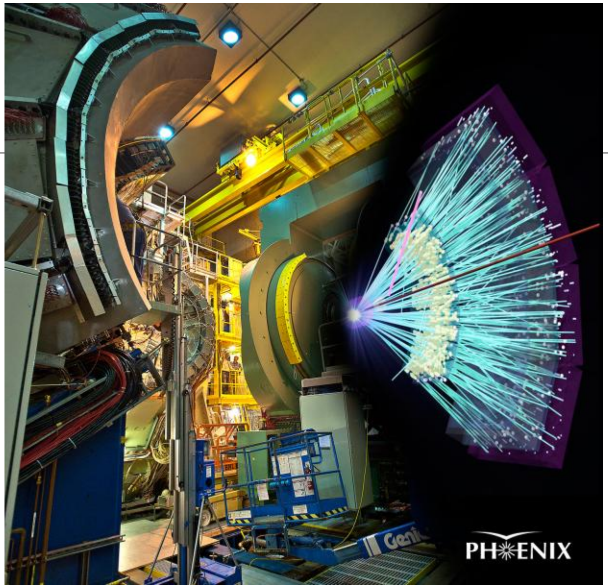
2. Measuring two- and three particle correlations could shed light on partially coherent particle production (see core-halo model)

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



MEASURE HBT WITH THE PROPER PARAMETRIZATION

The PHENIX and the BES

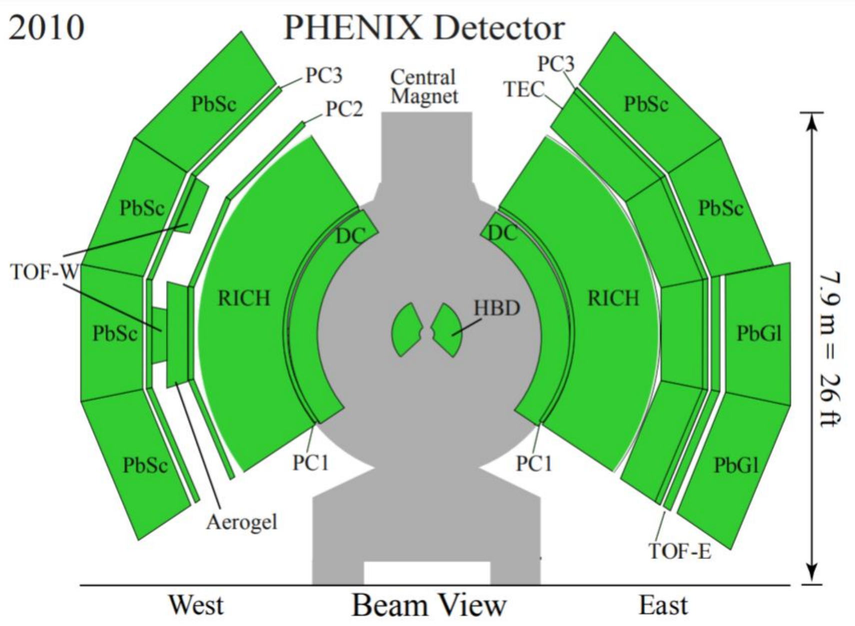


Collision energies: 7.7 to 200 GeV

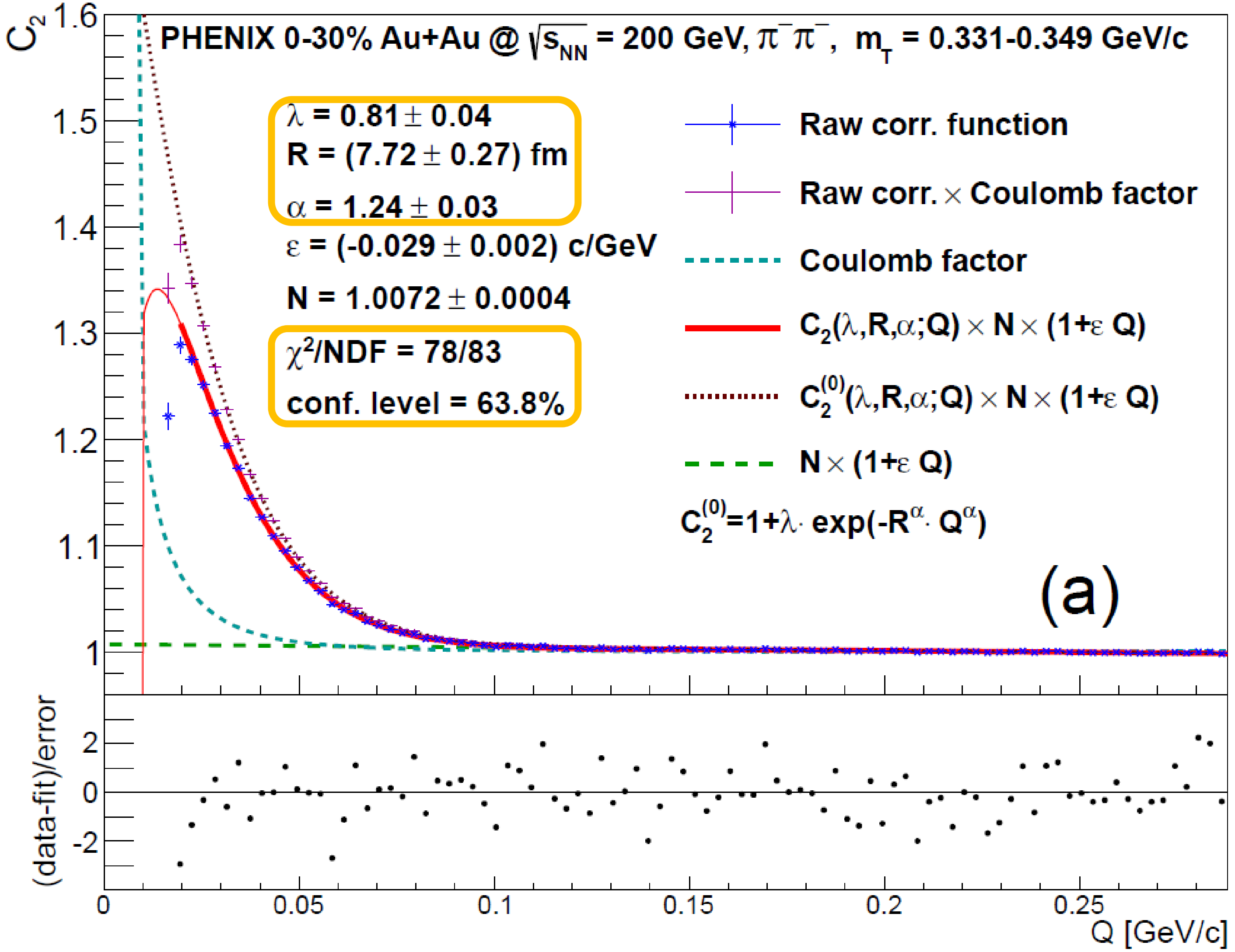
20-400 MeV in μ_B, 140-170 MeV in T

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								☑	



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

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

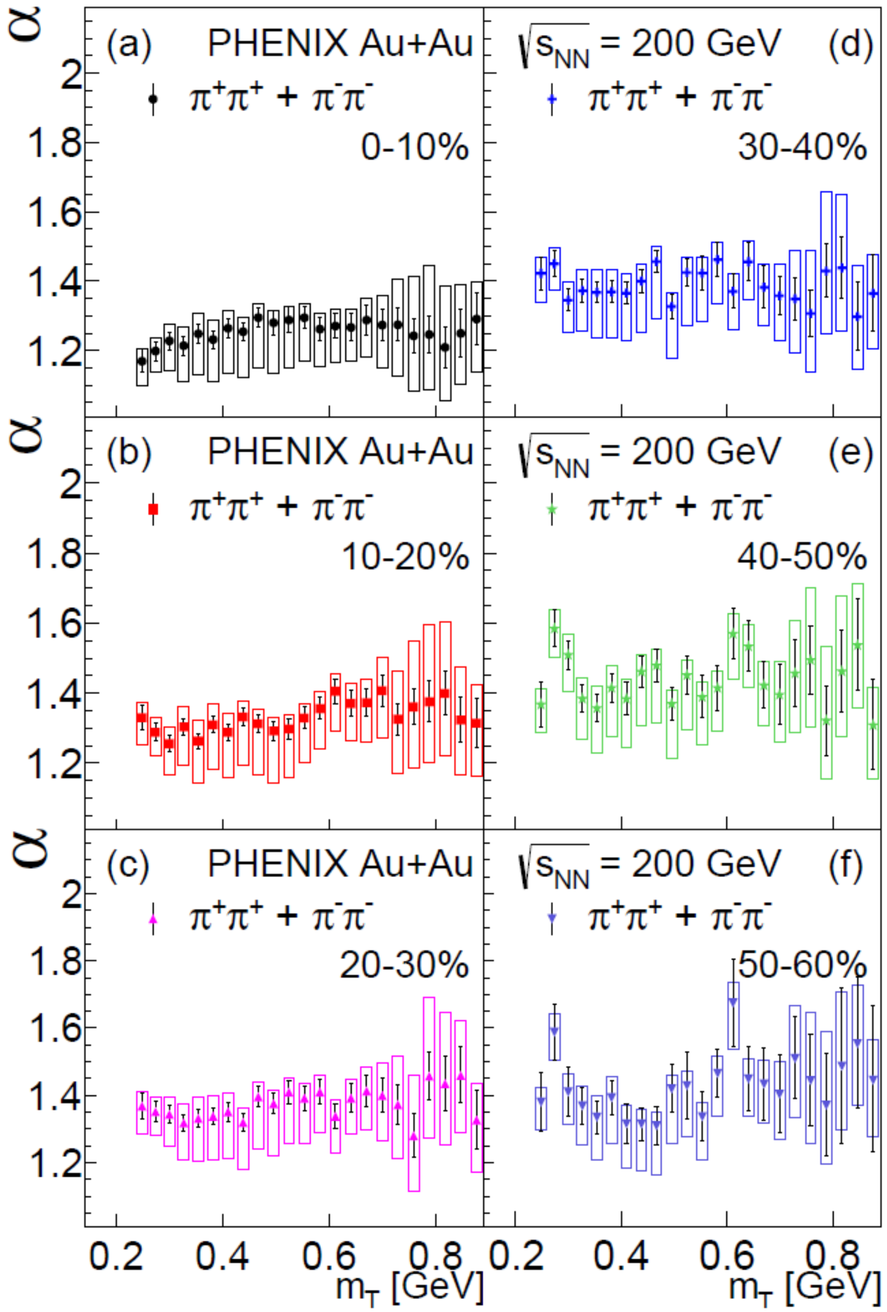
Fit function incorporates CC FSI (weighting for var. change)

Costume track and pair cuts to obtain clean sample

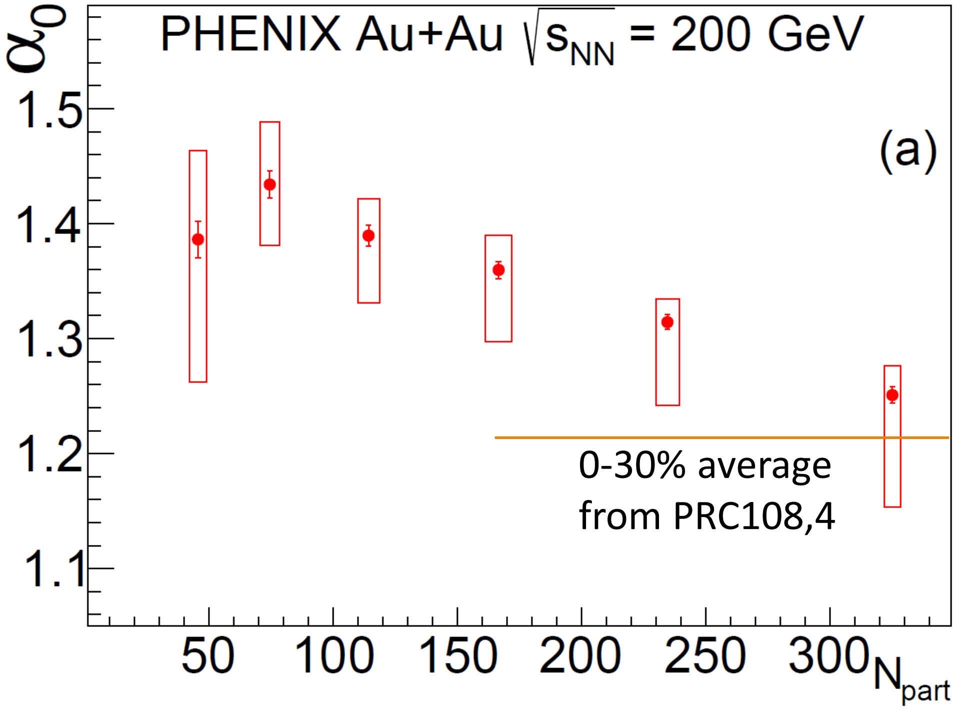
Check Levy shape validity: 1^{st} order corr. zero (*APP.Supp.* 9 (2016) 289)

PRC Highlight: [Phys. Rev. C 110, 064909]

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

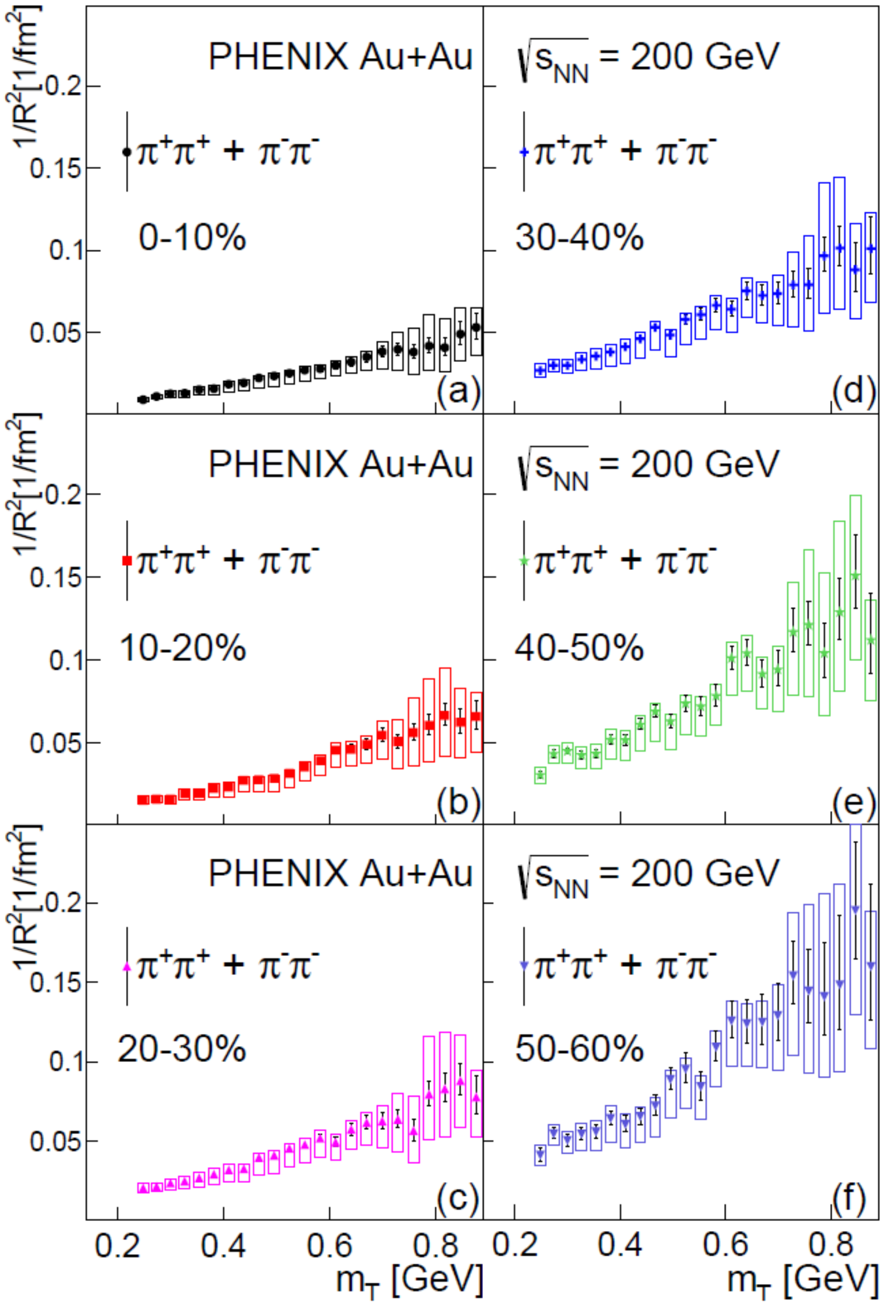


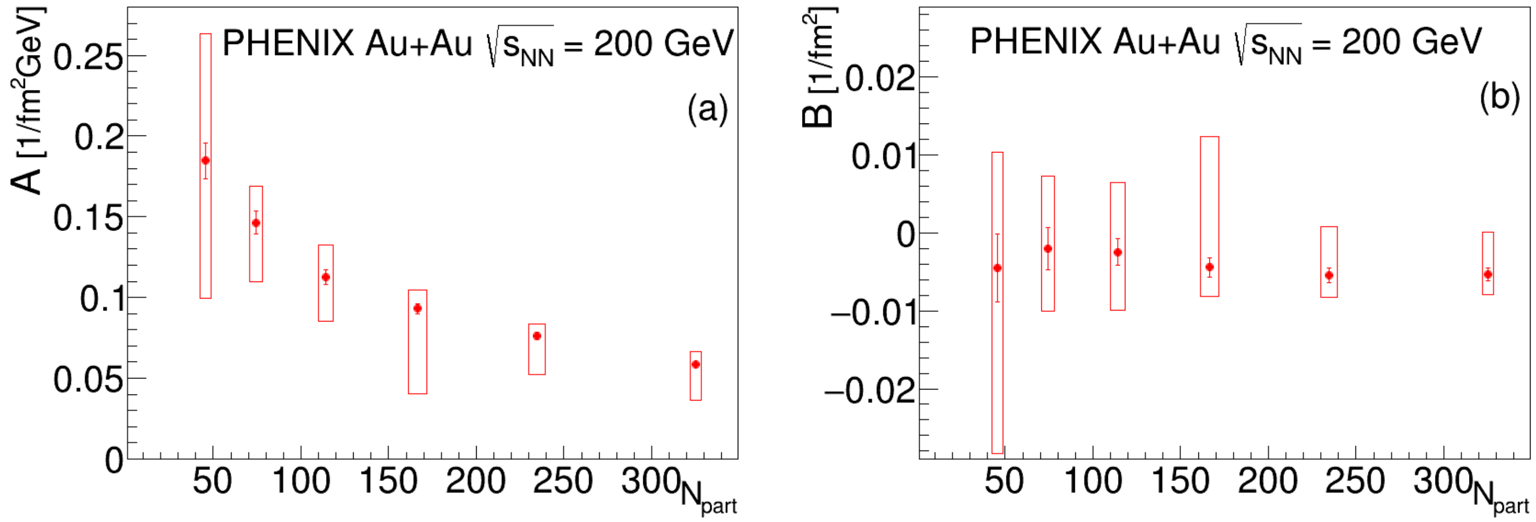
- Does not depend on m_T, does depend on N_{part}
- N_{part} dep. has model selection power
- Anomalous diffusion, QCD jets, resonances???



$R(m_T, N_{part})$

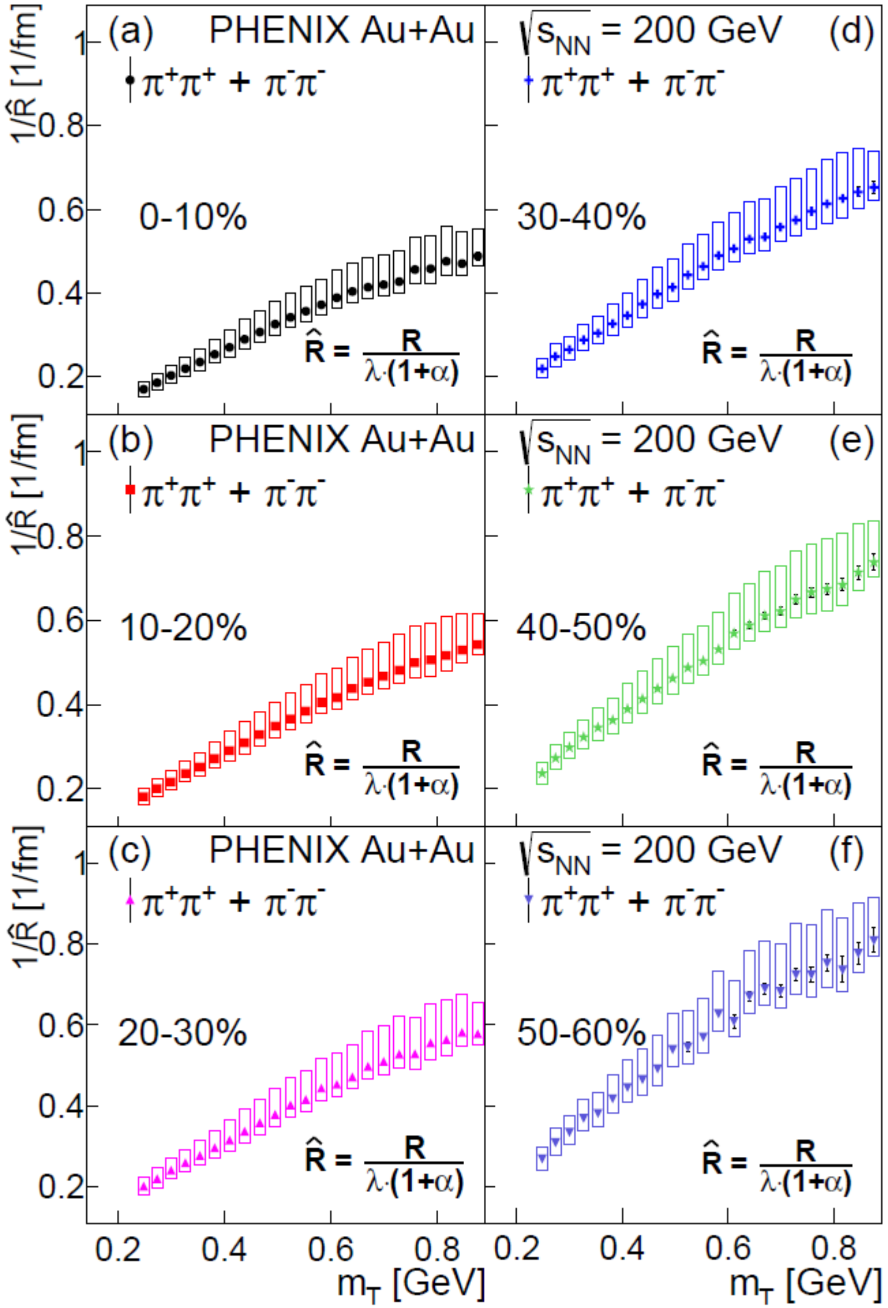
- Unexpected hydro scaling but not RMS
- Centrality ordering, monotonic behavior
- Related to the size?



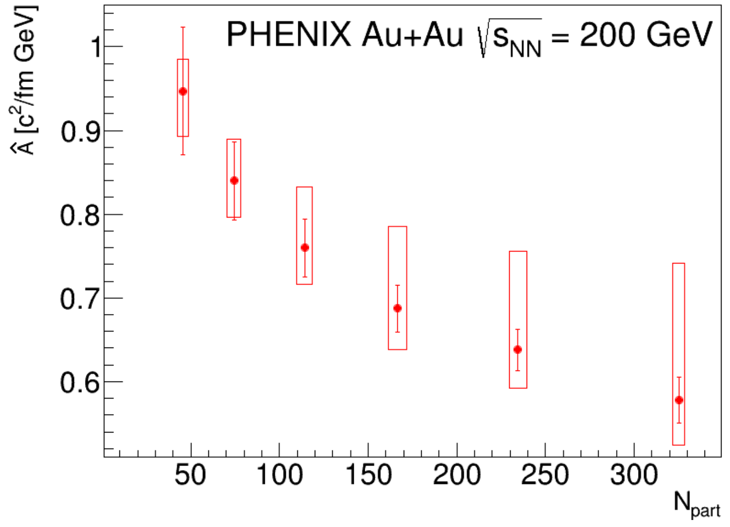


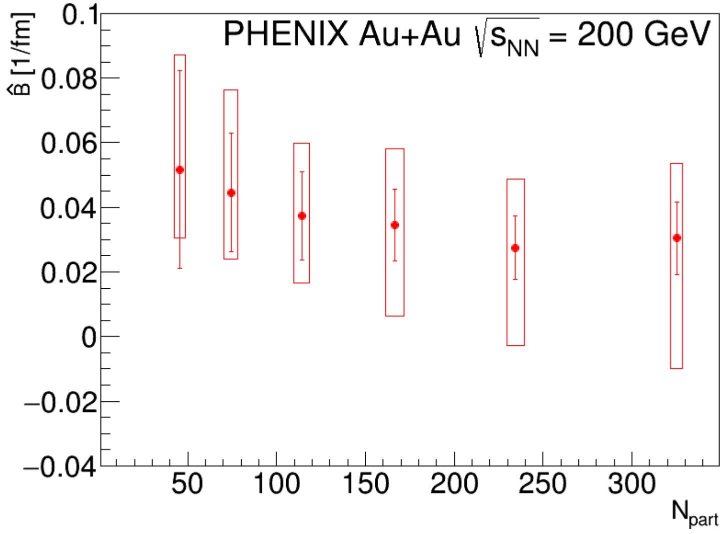
$$\frac{1}{R^2} = Am_T + B$$

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



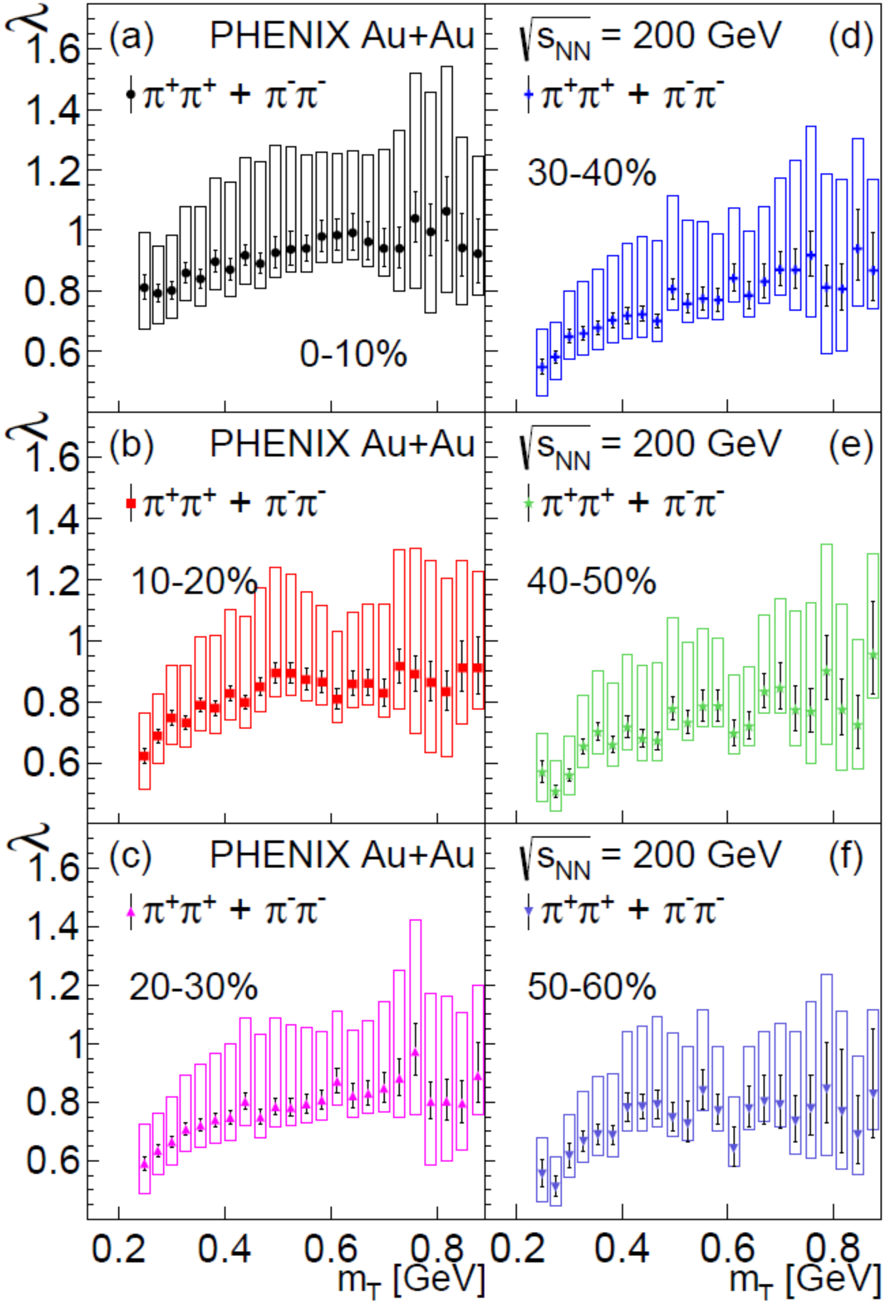
- Empirical parameter, surprisingly linear
- Centrality ordering, monotonic behavior
- Related to the size?





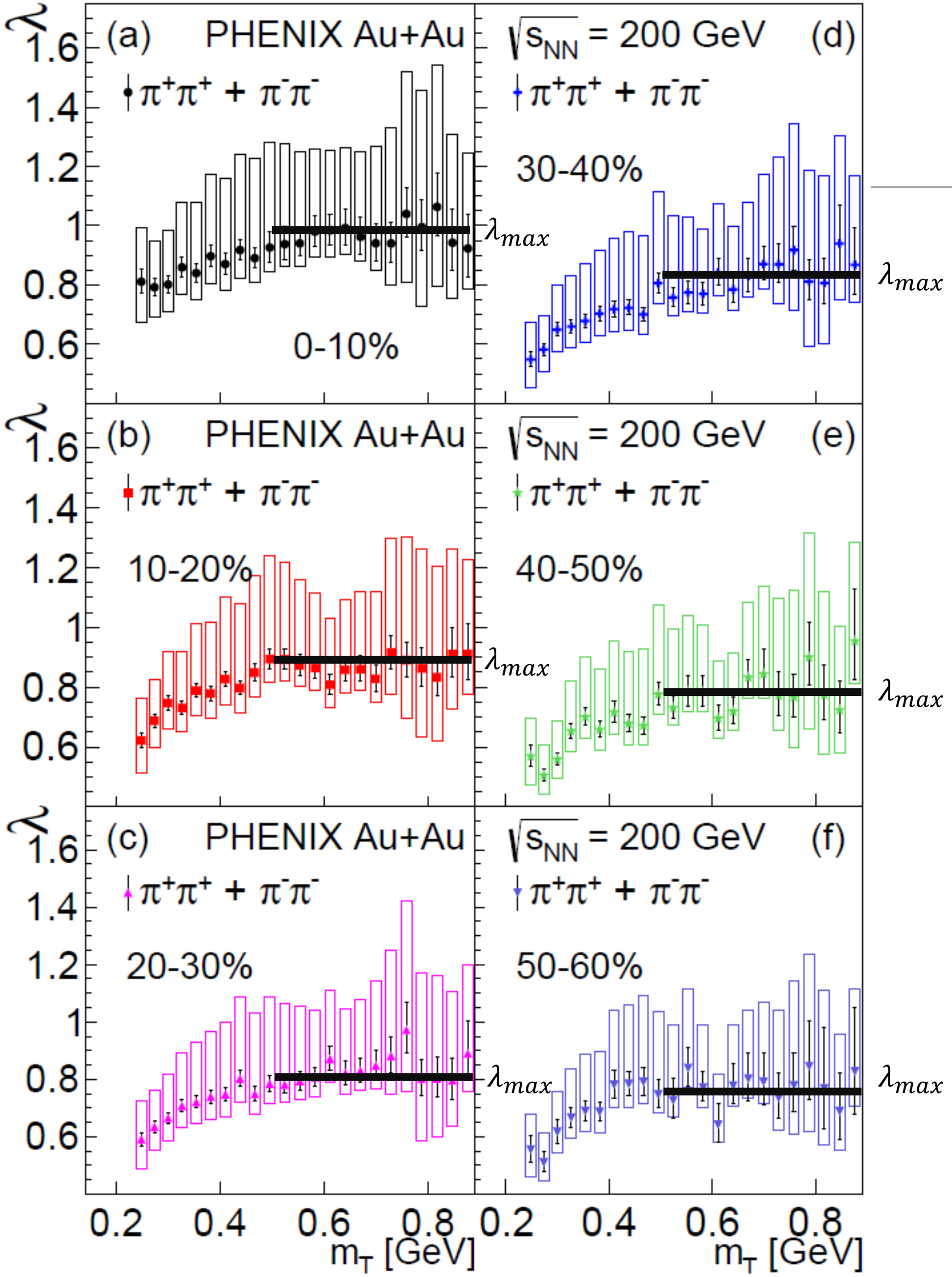
$$\frac{1}{\hat{R}} = \hat{A} m_T + \hat{B}$$

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

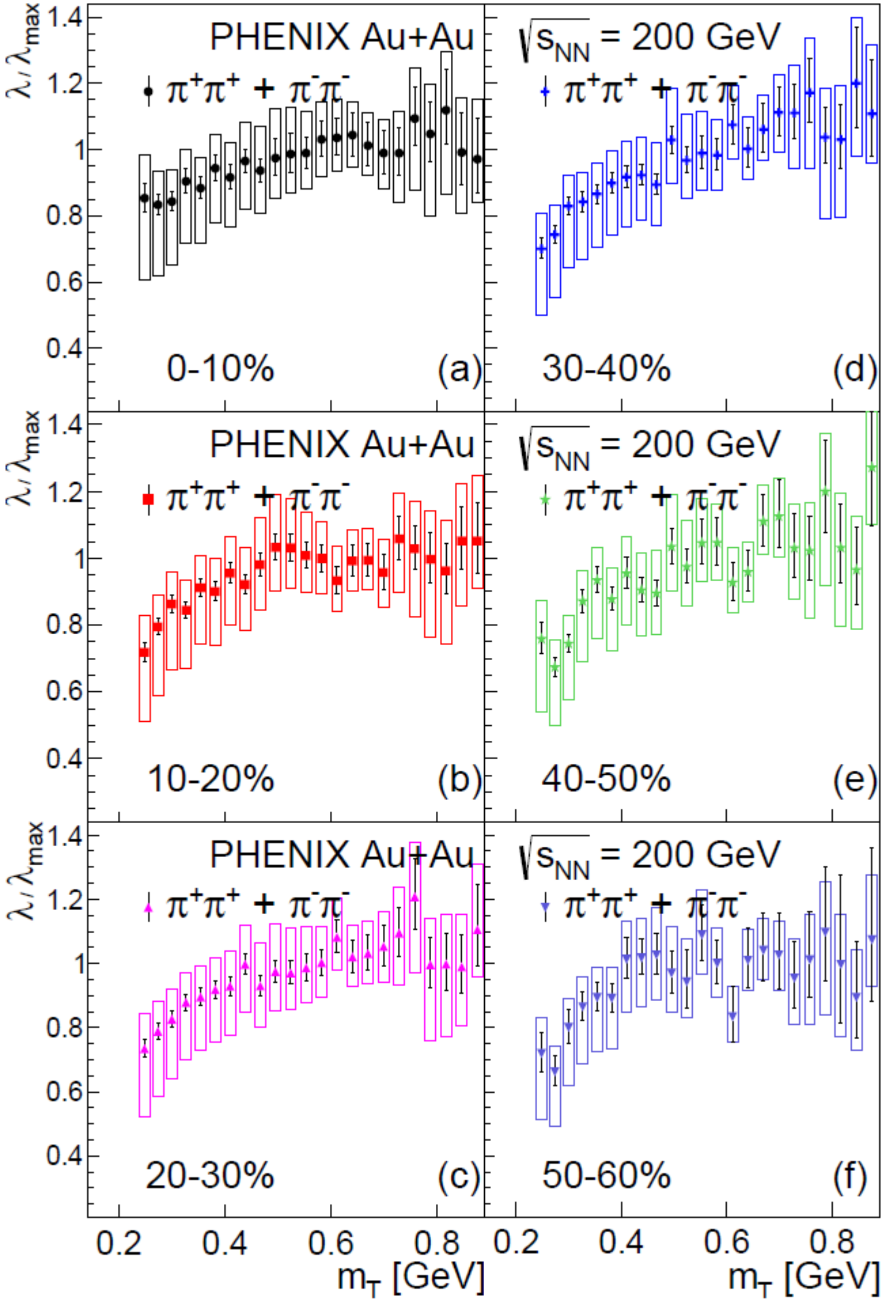


- Suppression and saturation in every centrality class

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



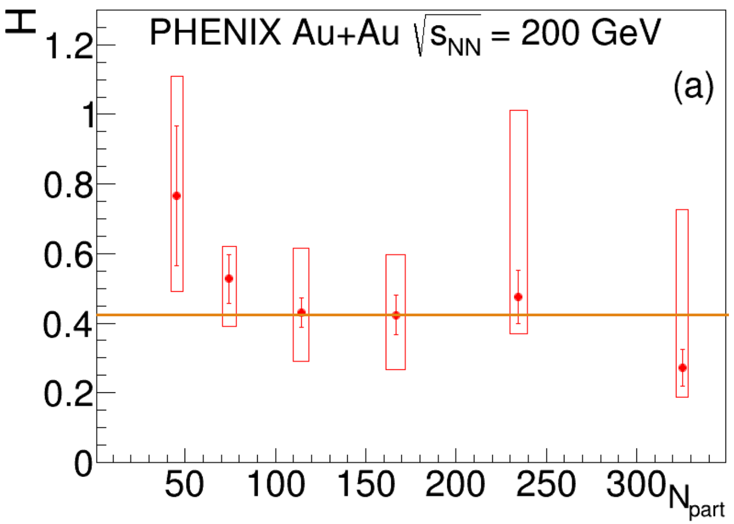
- Suppression and saturation in every centrality class
- Normalized to $\mathrm{m_T} > 0.45$

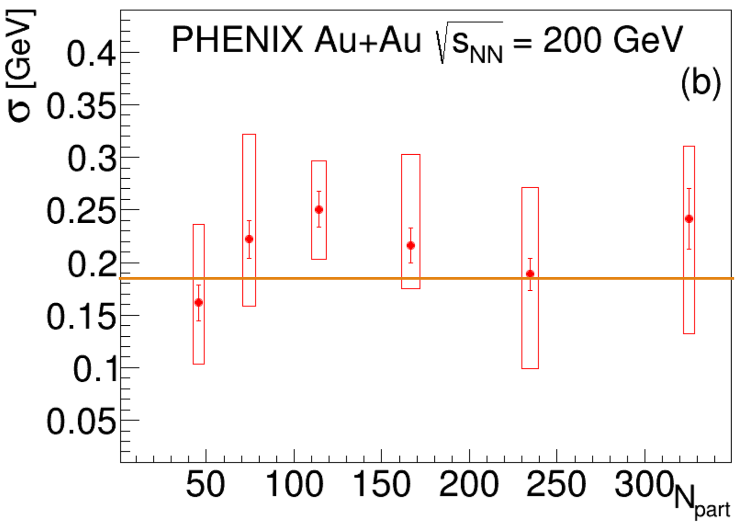


$\lambda/\lambda_{max}(m_T, N_{part})$

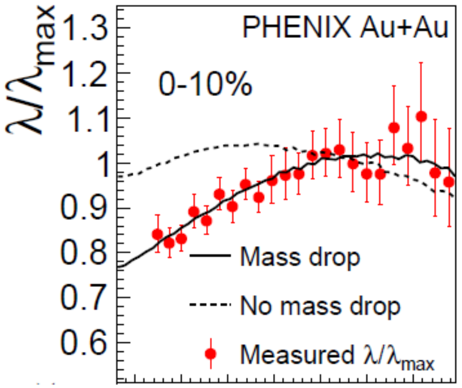
- Suppression and saturation in every centrality class
- Normalized to $\mathrm{m_T} > 0.45 \;\Rightarrow$ centrality independent!
- Sign of the η' in medium mass modification?
- Let's compare the results to Monte Carlo simulations

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



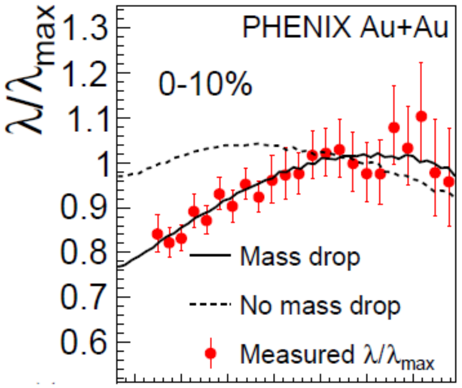


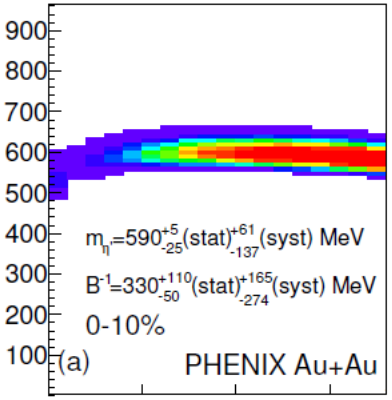
η' mass modification and $U_A(1)$ restoration ?



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

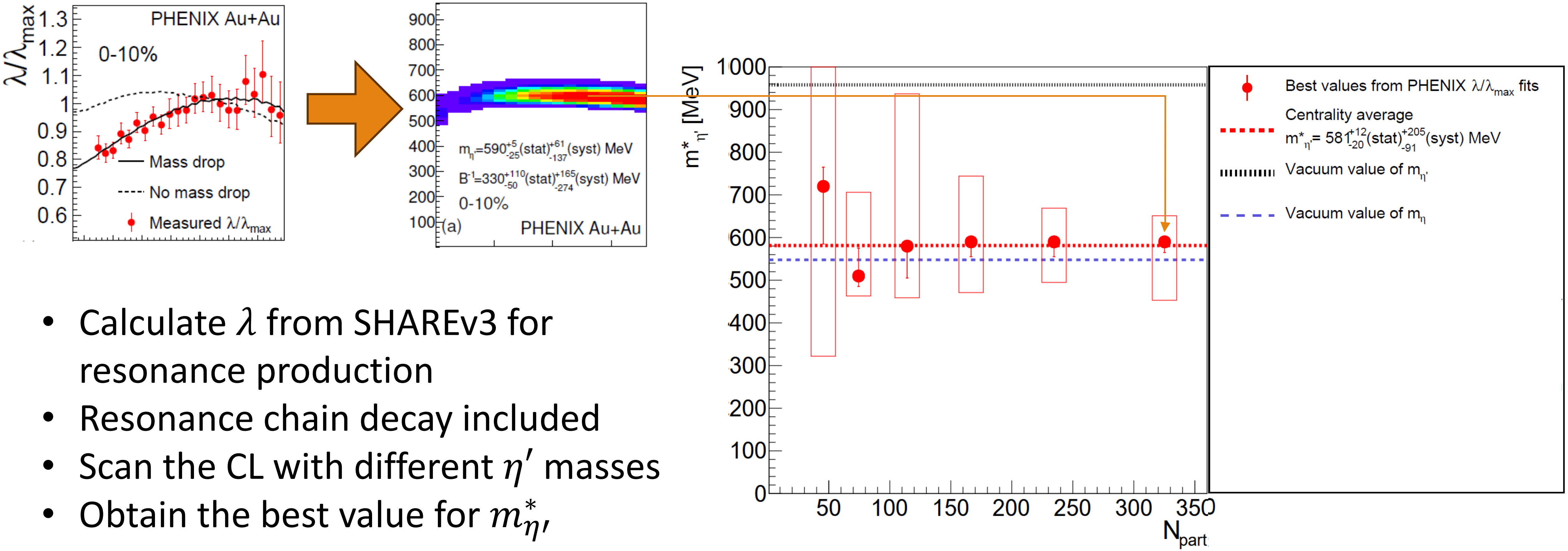
η' mass modification and $U_A(1)$ restoration ?





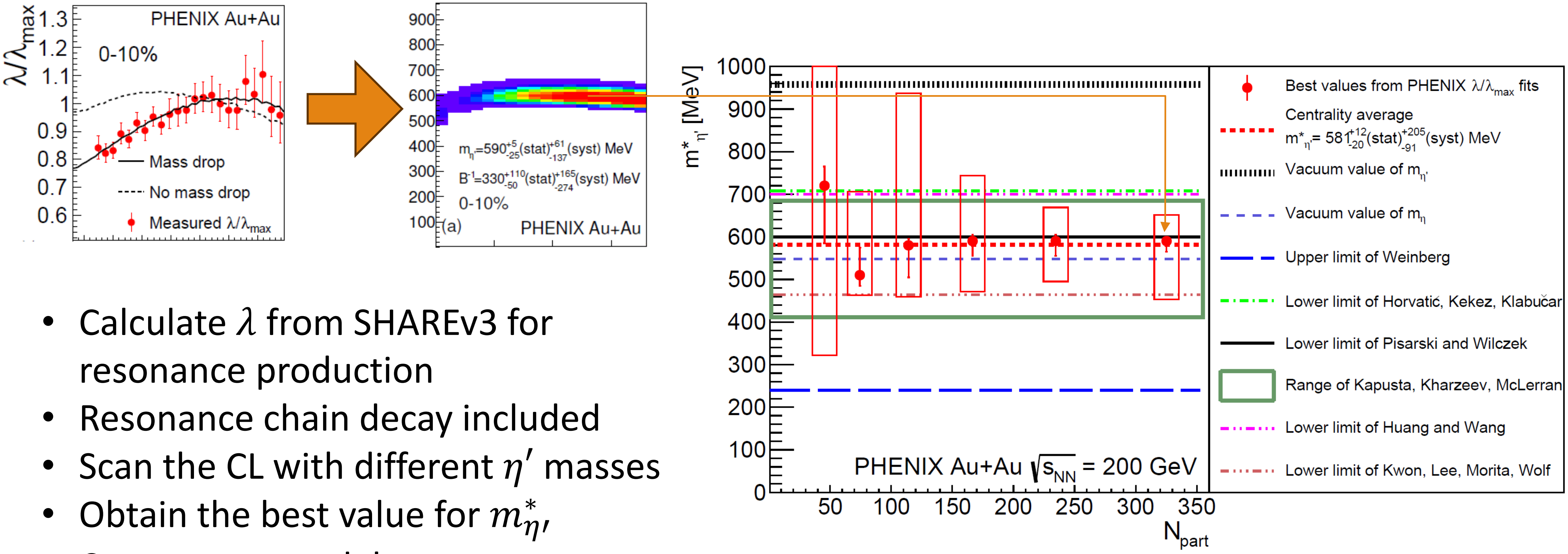
- Calculate λ from SHAREv3 for resonance production
- Resonance chain decay included
- Scan the CL with different η' masses

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

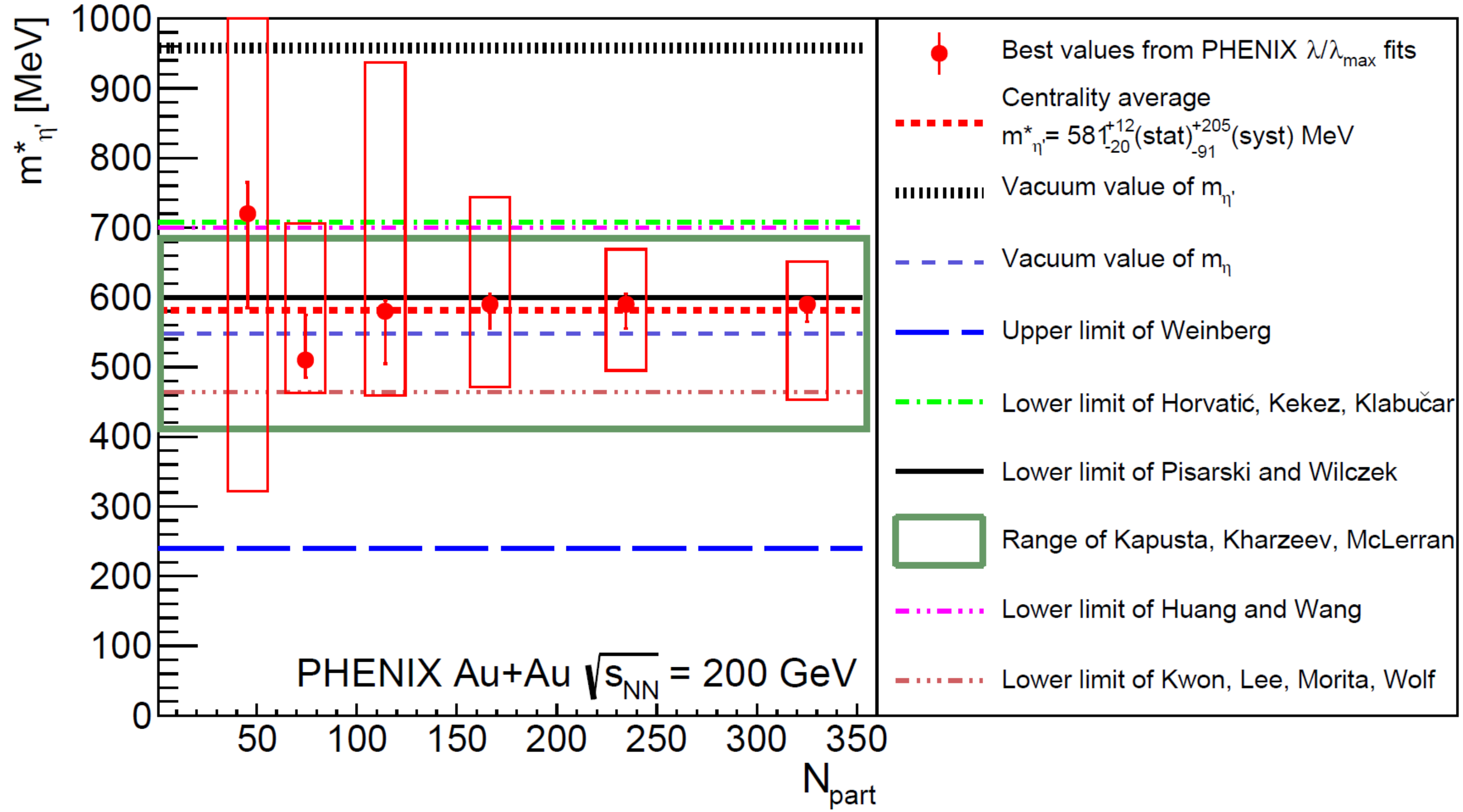


- Calculate λ from SHAREv3 for resonance production
- Resonance chain decay included
- Scan the CL with different η' masses
- Obtain the best value for $m^*_{\eta'}$

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

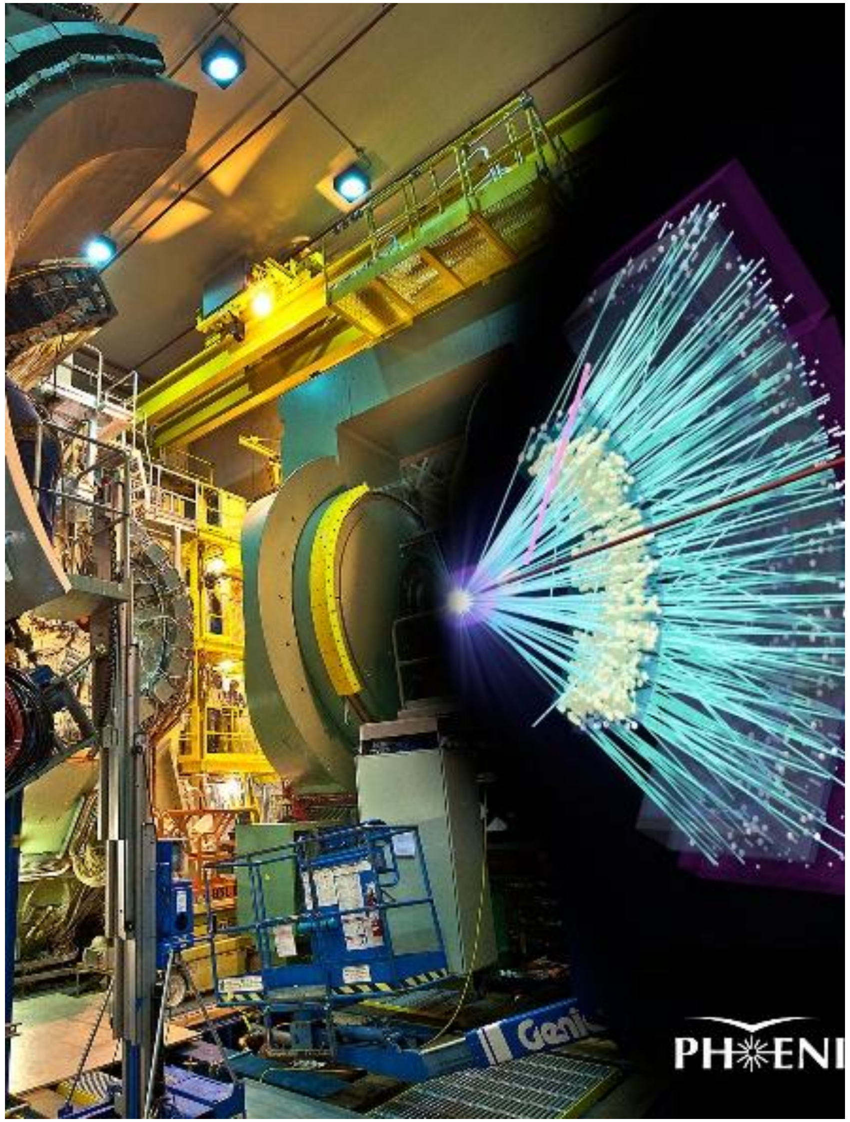


- Calculate λ from SHAREv3 for resonance production
- Resonance chain decay included
- Scan the CL with different η' masses
- Obtain the best value for $m^*_{\eta'}$
- Compare to model



Results suggest in-medium partial $U_A(1)$ 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

Indirect sign calls for dedicated dilepton spectrum measurements

PRC Highlight Phys. Rev. C 110, 064909

THANK YOU FOR YOUR ATTENTION!

ZIMÁNYI SCHOOL 2025

I. Csók: Lightning over Balaton

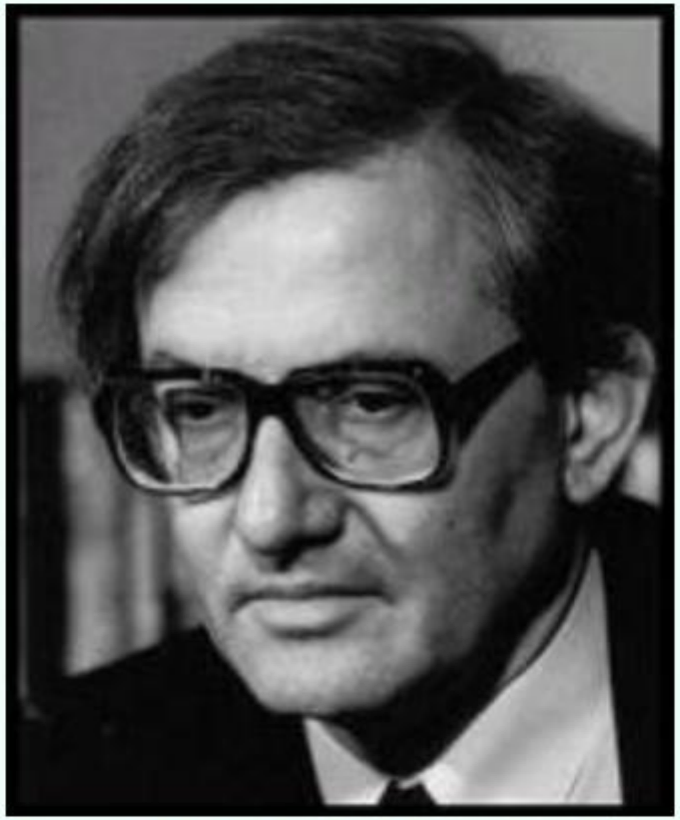
25th ZIMÁNYI SCHOOL

WINTER WORKSHOP

ON HEAVY ION PHYSICS

December 1-5, 2025

Budapest, Hungary



József Zimányi (1931 - 2006)

References

R. H. Brown and R. Q. Twiss, Nature 177, 27 (1956)

Goldhaber et al. Phys. Rev. 120, 300 (1960)

Csörgő et al., AIP Conf.Proc. 828

Metzler et. al, Phys.Rep.339 (2000) 1-77

Csanád et al. Braz.J.Phys. 37 (2007) 1002

Csörgő et al. Acta Phys.Polon. B36

Universe 2019, 5(6), 133

Phys. Part. Nuclei 51, 238-242 (2020)

Gribov-90 Memorial Volume, pp. 261-273 (2021)

Acta Phys.Hung.A 15 (2002) 1-80

Phys.Part.Nucl. 51 (2020) 3, 263-266

Acta Phys. Pol. B Proc. Suppl. vol. 12 (2), pp. 477 - 482 (2019)

Phys.Part.Nucl. 51 (2020) 3, 267-269

Acta Phys.Polon.Supp. 12 (2019) 445

Universe 5 (2019) 6, 154

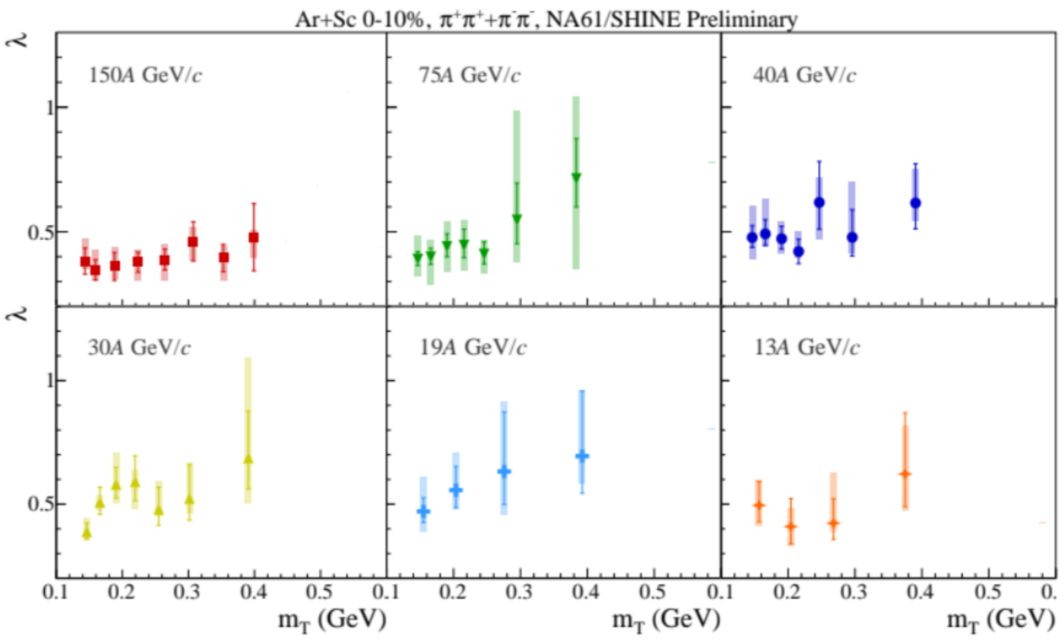
EPJ Web Conf. 206 (2019) 03004

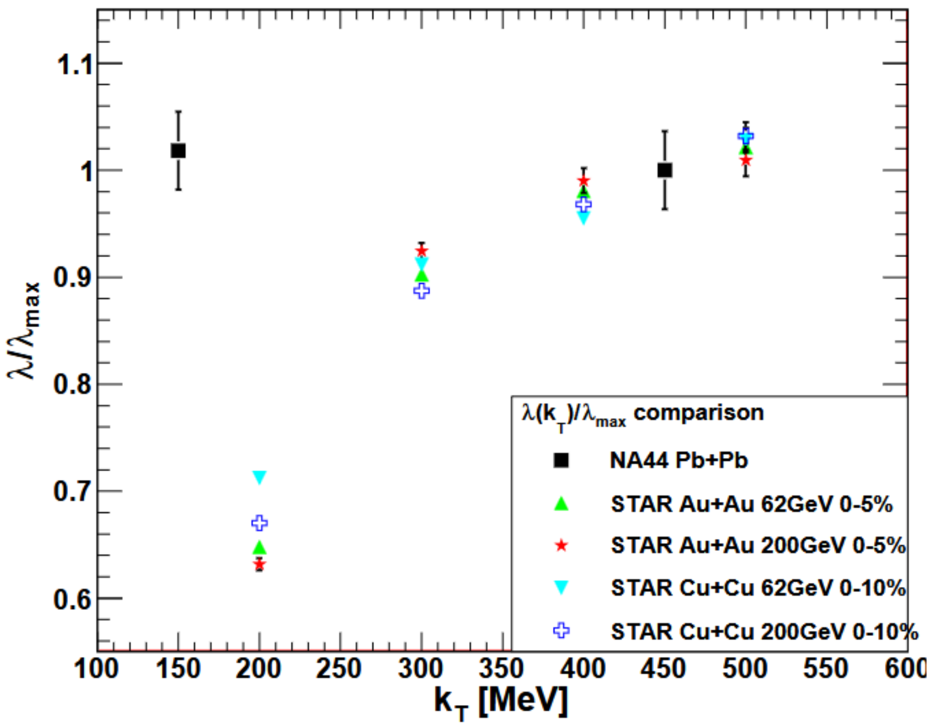
Universe 4 (2018) 2, 31

Phys.Rev.C 97 (2018) 6, 064911

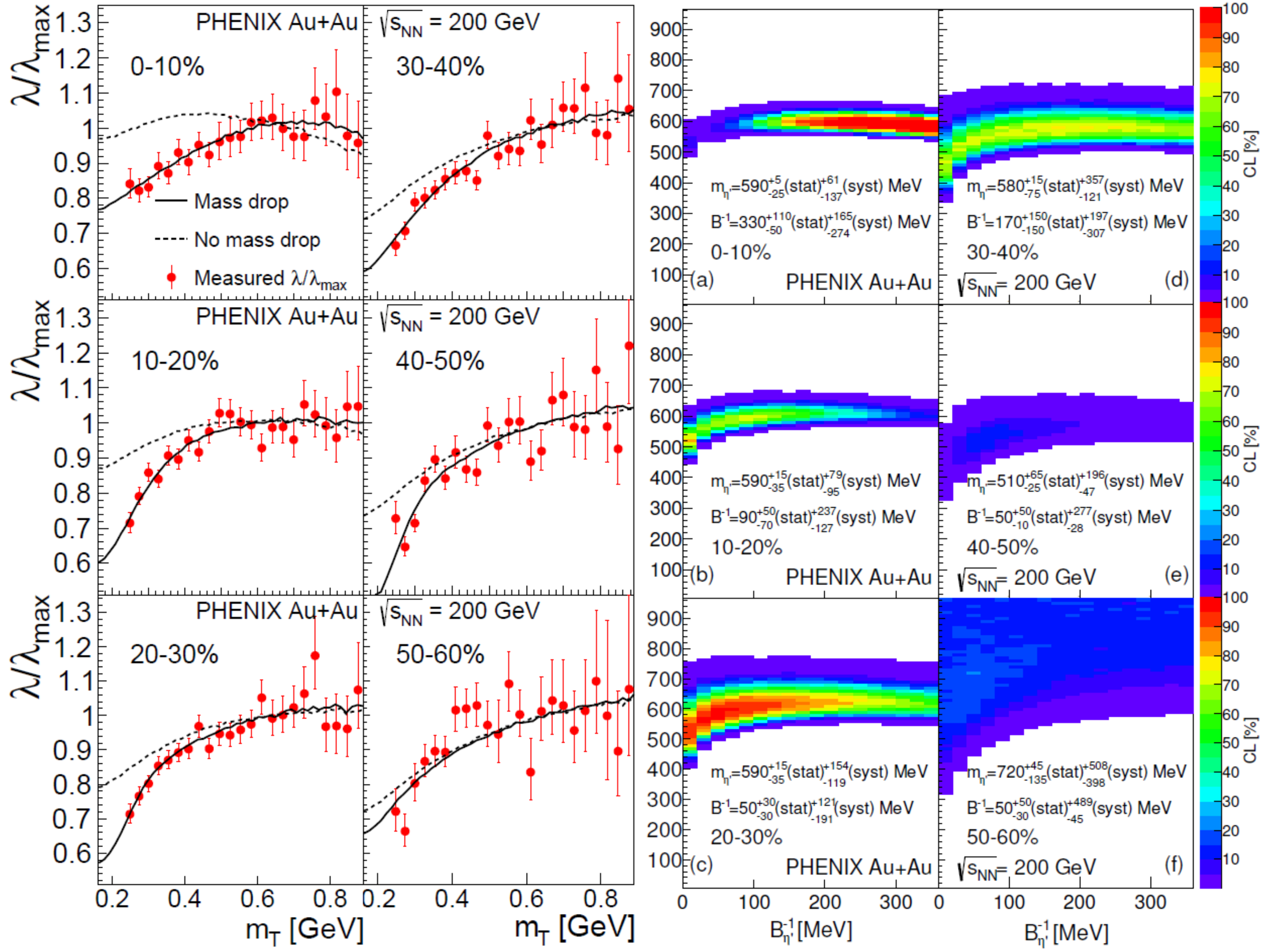
AIP Conf.Proc. 828 (2006) 1, 539-544

https://arxiv.org/abs/2407.08586





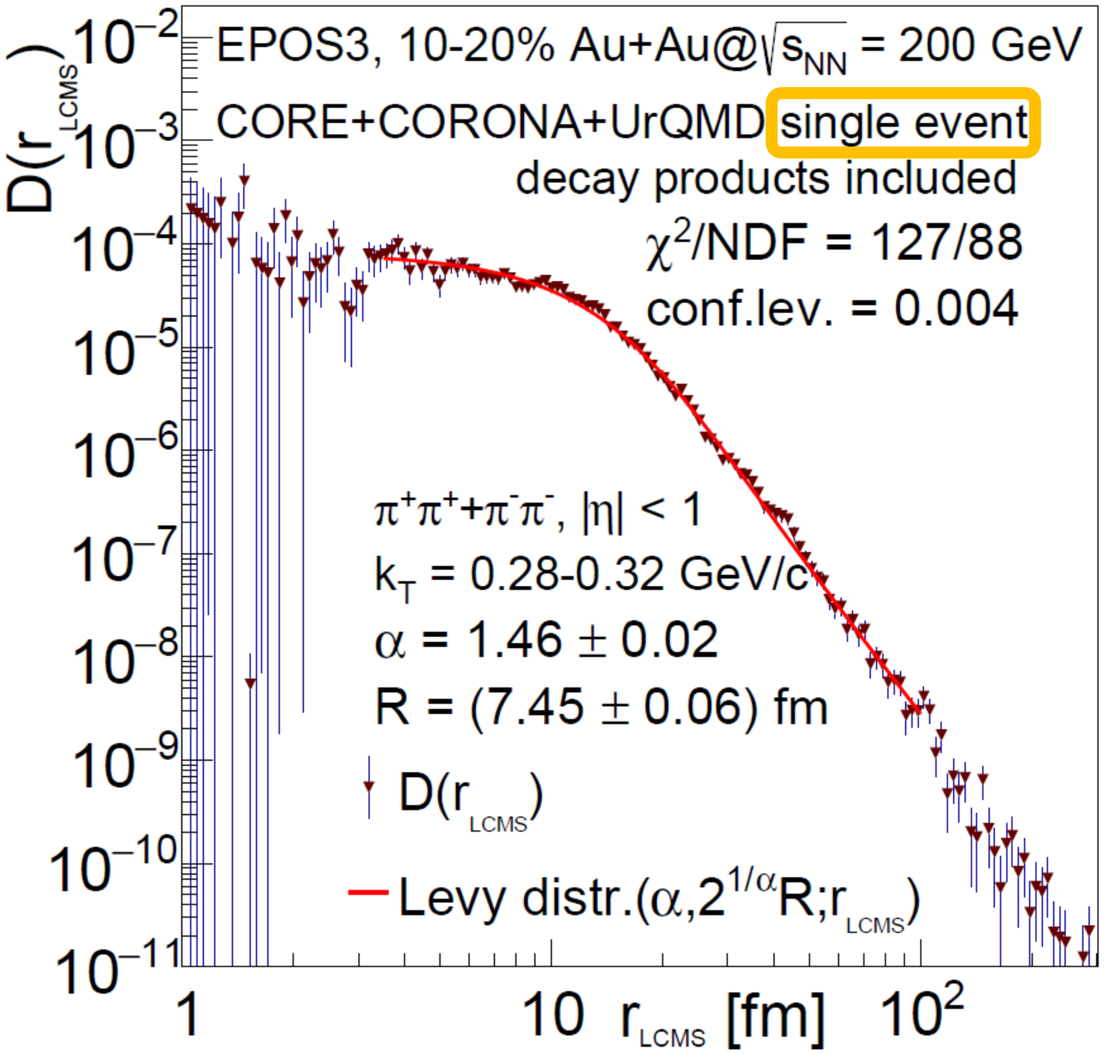
The effect can be turned off



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



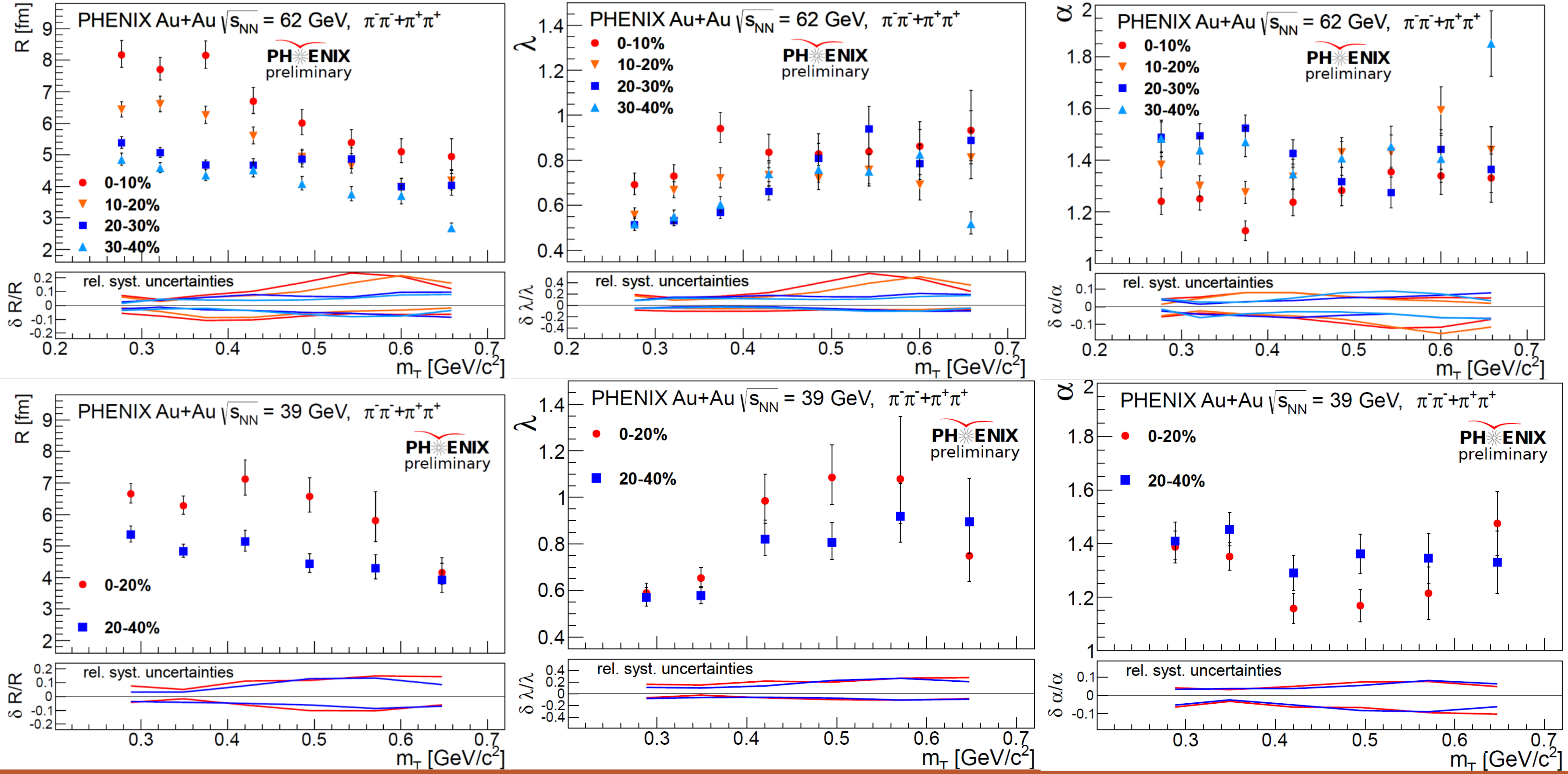
- Core-halo picture is included
- UrQMD for the hadronic cascade

- Levy gives the good description

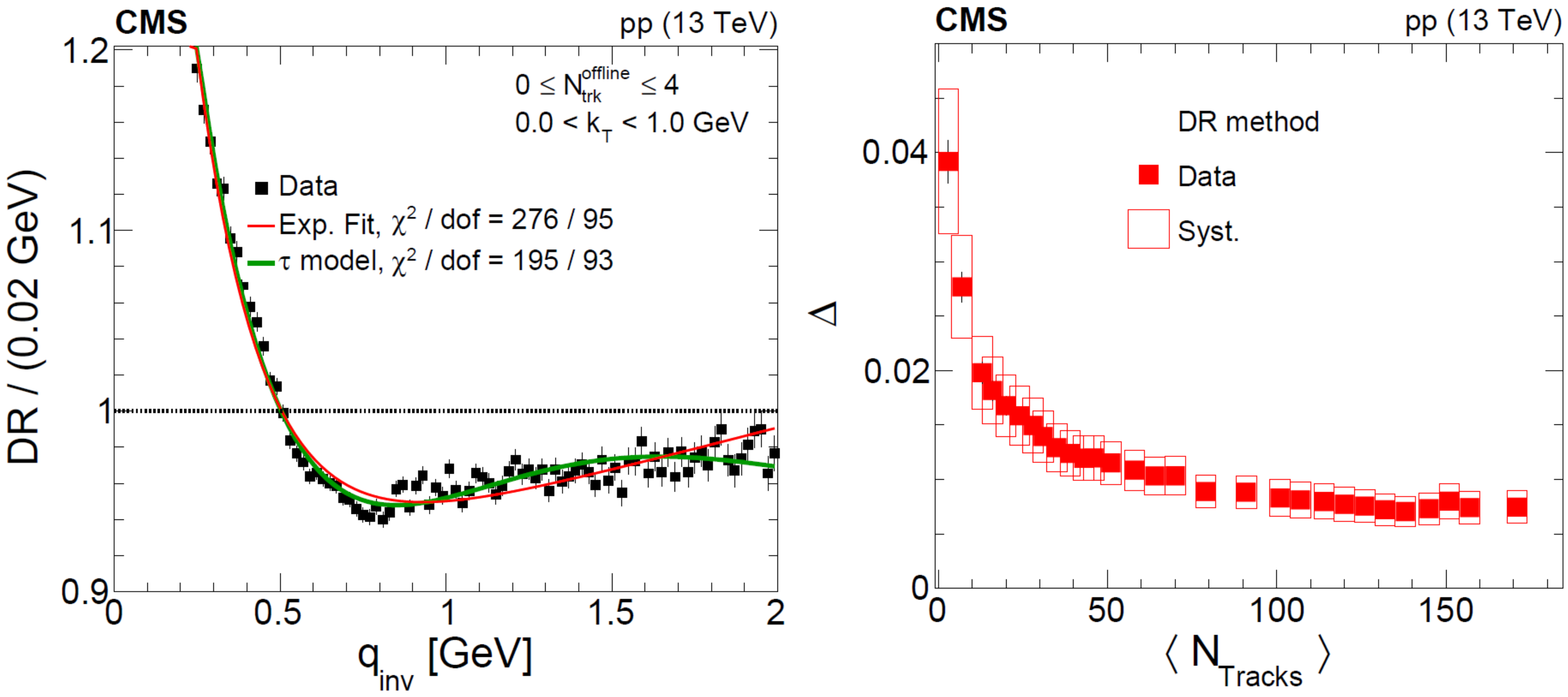
- It is a single event!
- This analysis support that the origin of the Levy shape could be explained only with the experimental averaging
- This analysis also support the role of the resonances, i.e., the anomalous diffusion

- With this confidence let's look at other experiments

Backup slides



Backup slides

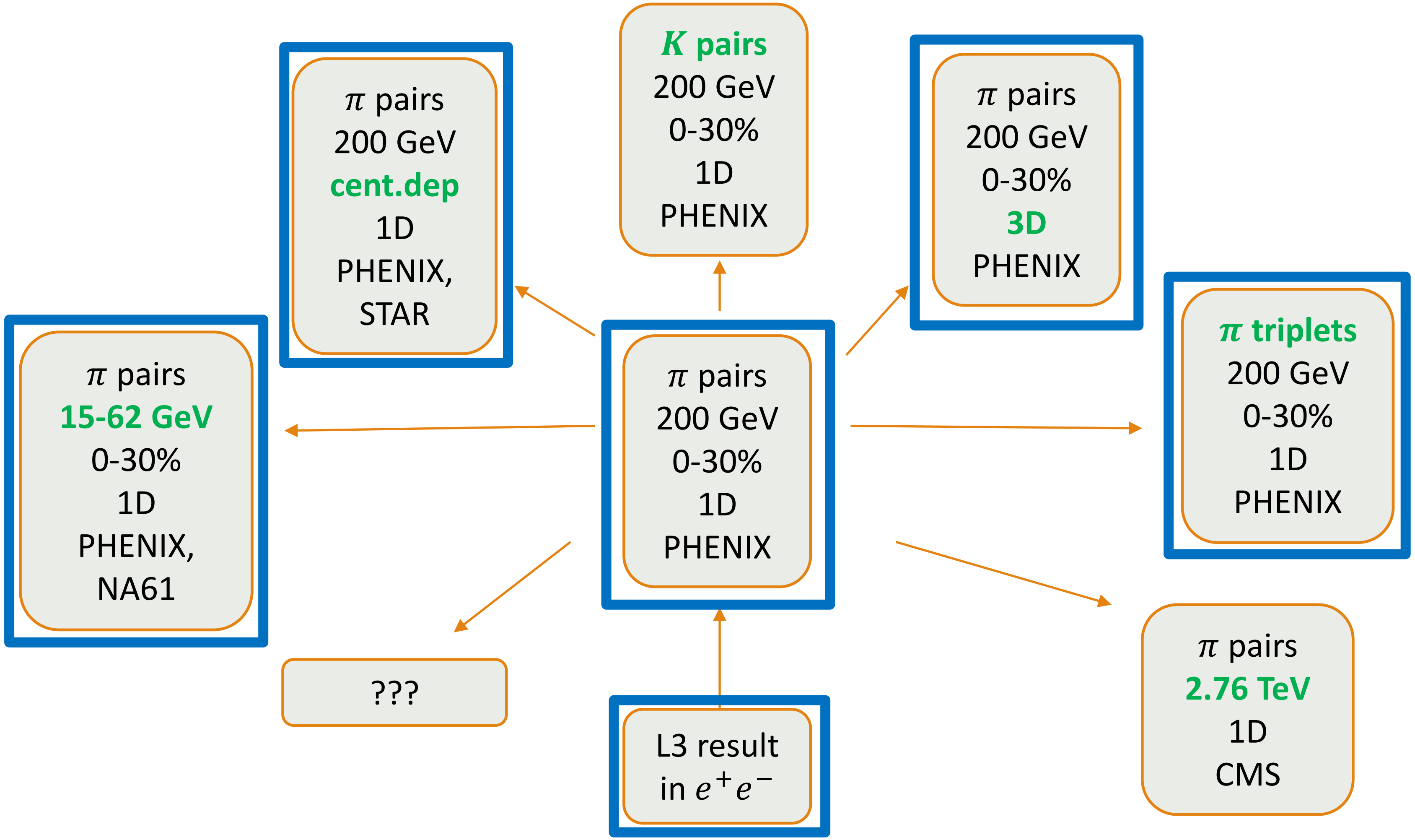


Backup slides

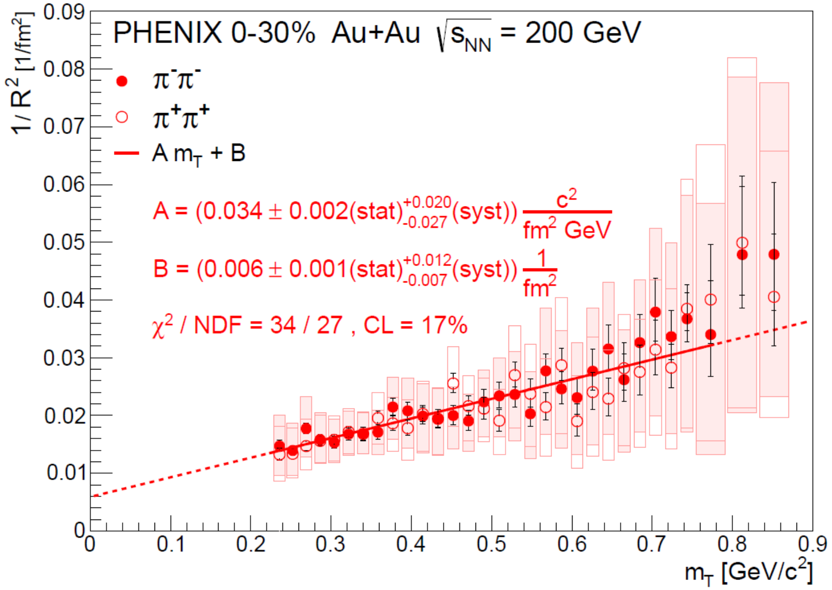
$$Q = \sqrt{(p_{1x} - p_{2x})^2 + (p_{1y} - p_{2y})^2 + q^2_{\mathrm{long,LCMS}}},$$

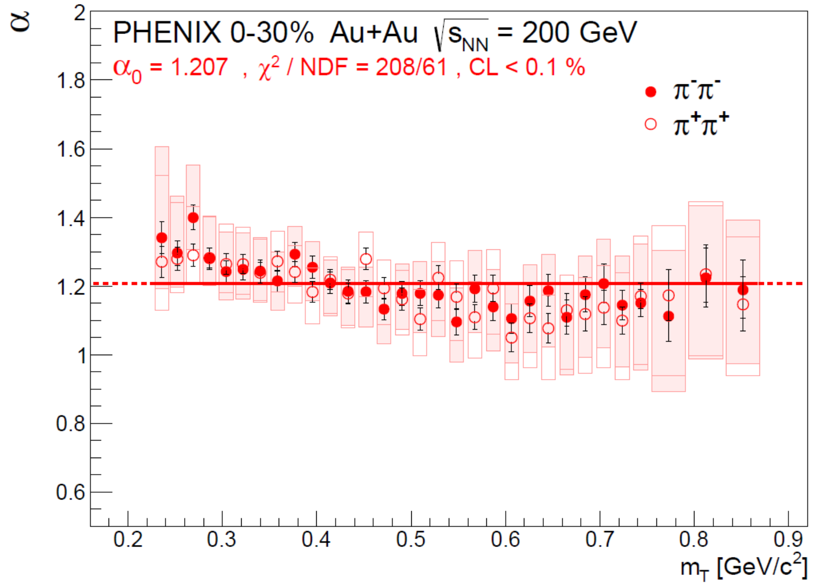
$$\text{where} \quad q^2_{\mathrm{long,LCMS}} = \frac{4(p_{1z}E_2 - p_{2z}E_1)^2}{(E_1 + E_2)^2 - (p_{1z} + p_{2z})^2}$$

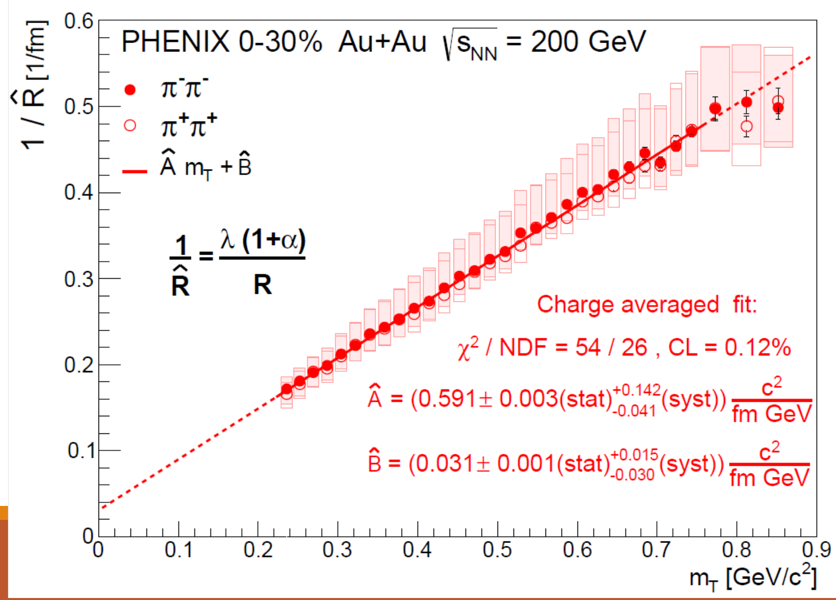
The tree of the Levy analyses

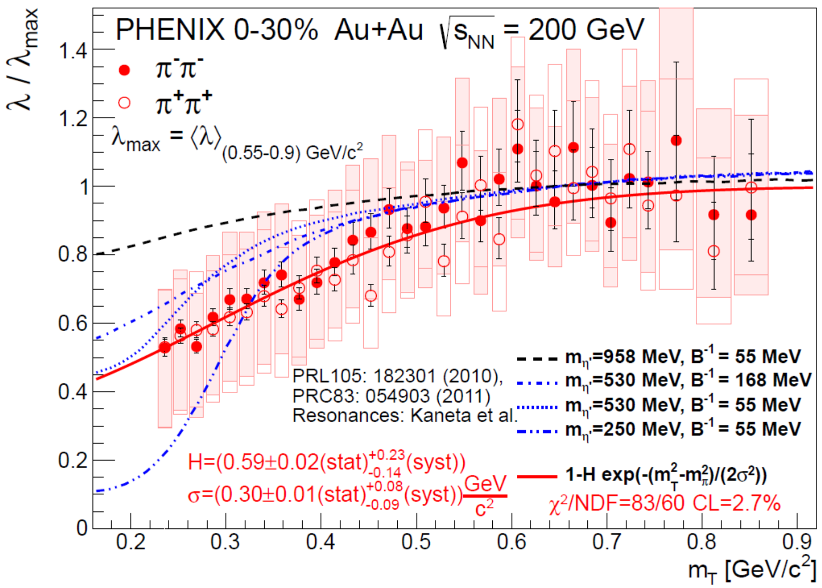


The first results – PHENIX 0-30%, Au+Au







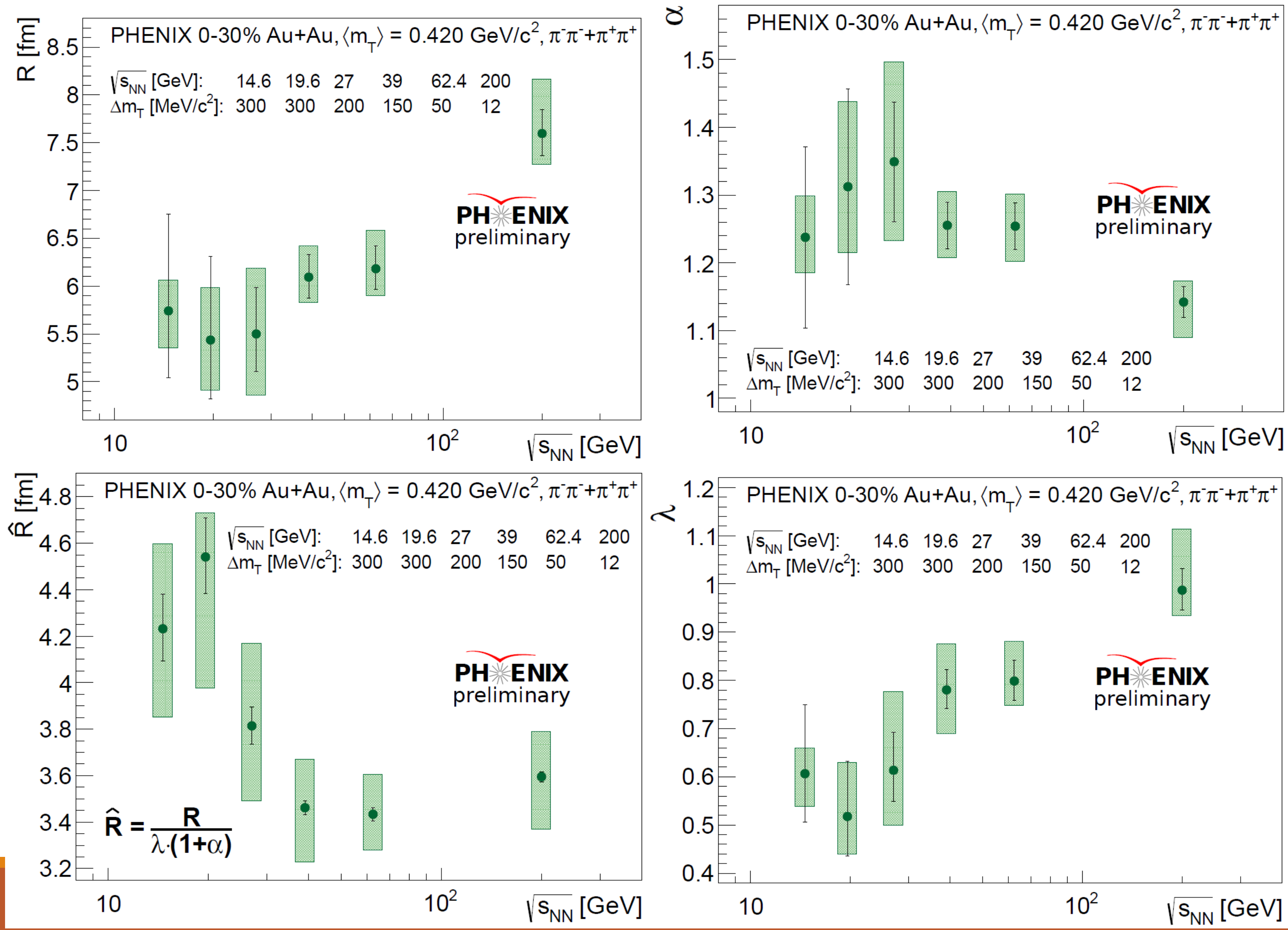


- R exhibits hydro scaling
- $1 < \alpha < 2$, $\langle\alpha\rangle \approx 1.2$
- $\lambda(m_T)$ suppressed which compatible with modified η' mass in the medium (compared with a resonance model)

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

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

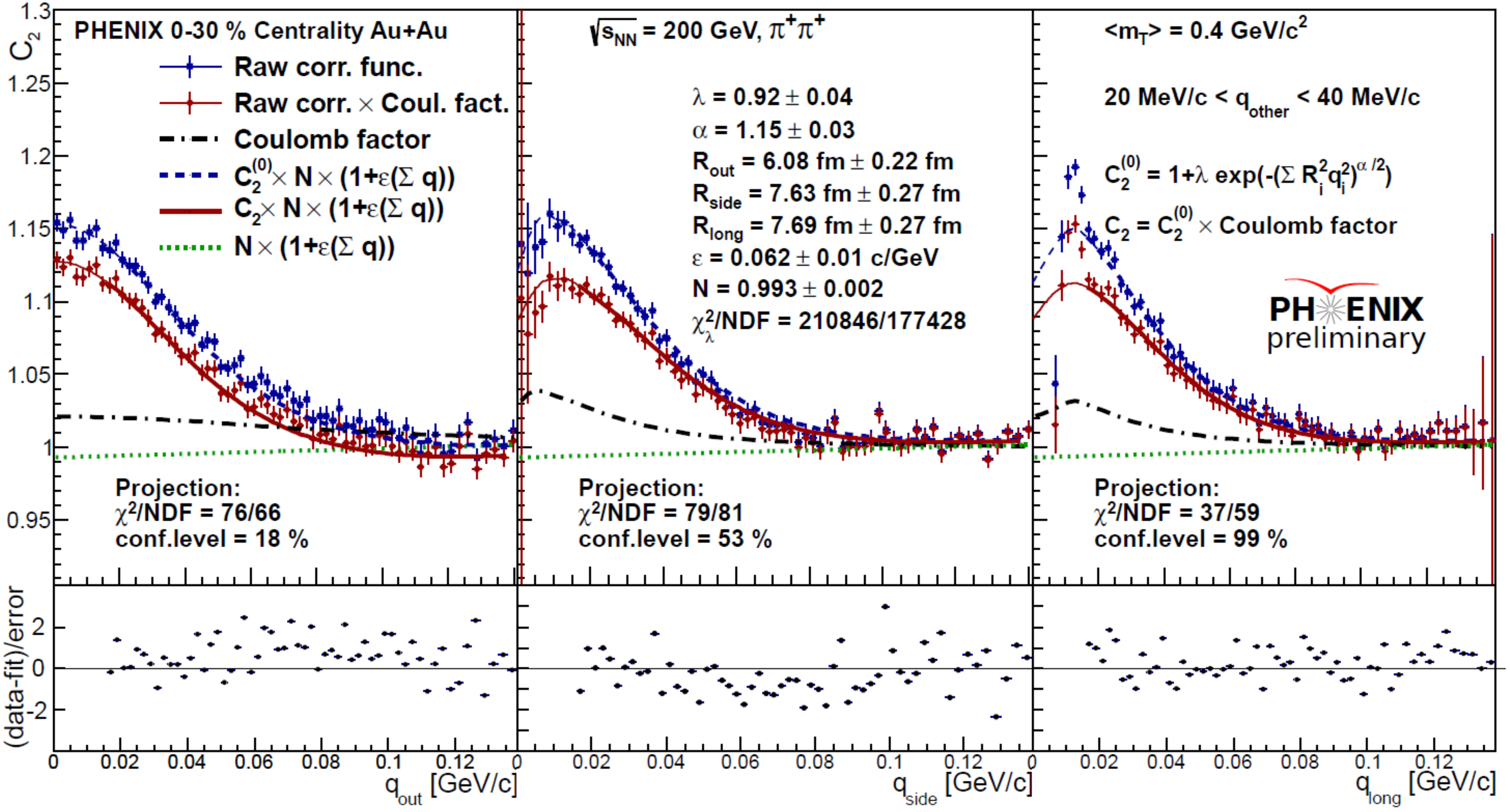
$\sqrt{s_{NN}}$ dependence – PHENIX Au+Au



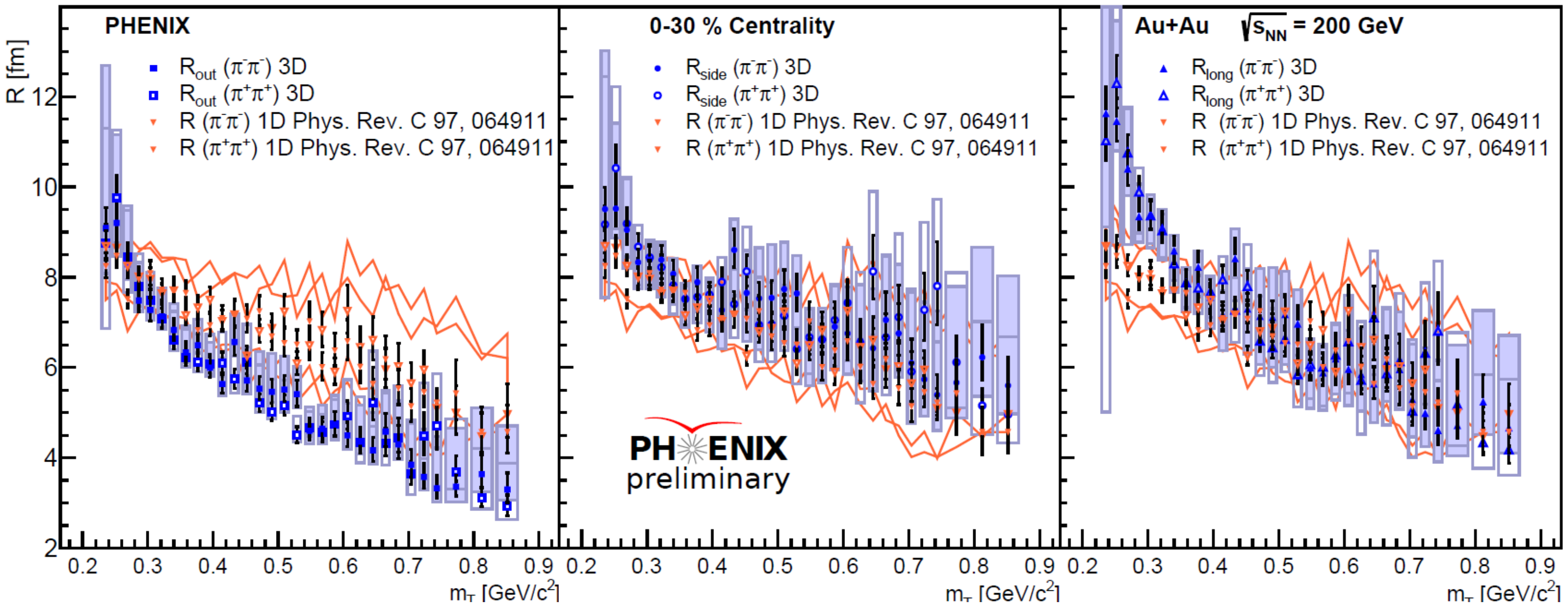
- Integrated in m_T due to the lack of statistics
- α does not really depend on $\sqrt{s_{NN}}$
- Non-monotonic behavior of $\hat{R}$ observed
  - Interpretation?

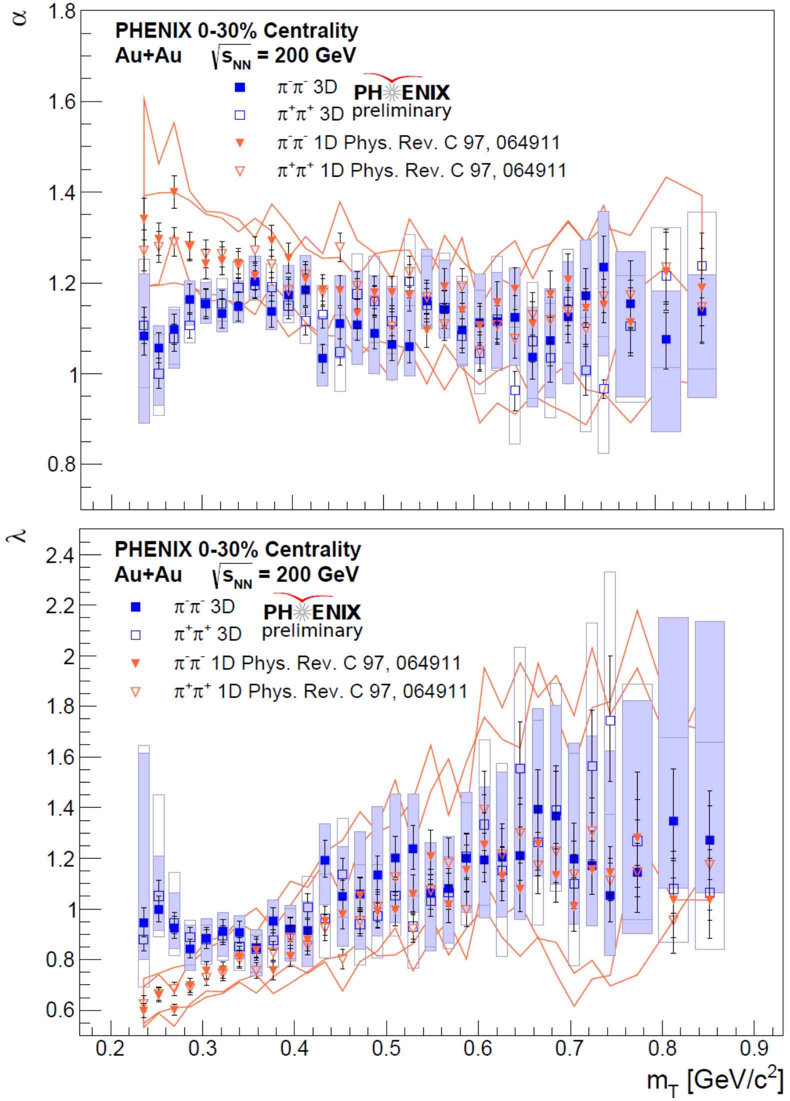
- For $\sqrt{s_{NN}} \geq 39$ GeV there are m_T dependent analysis but the trends are not clear

Backup slides



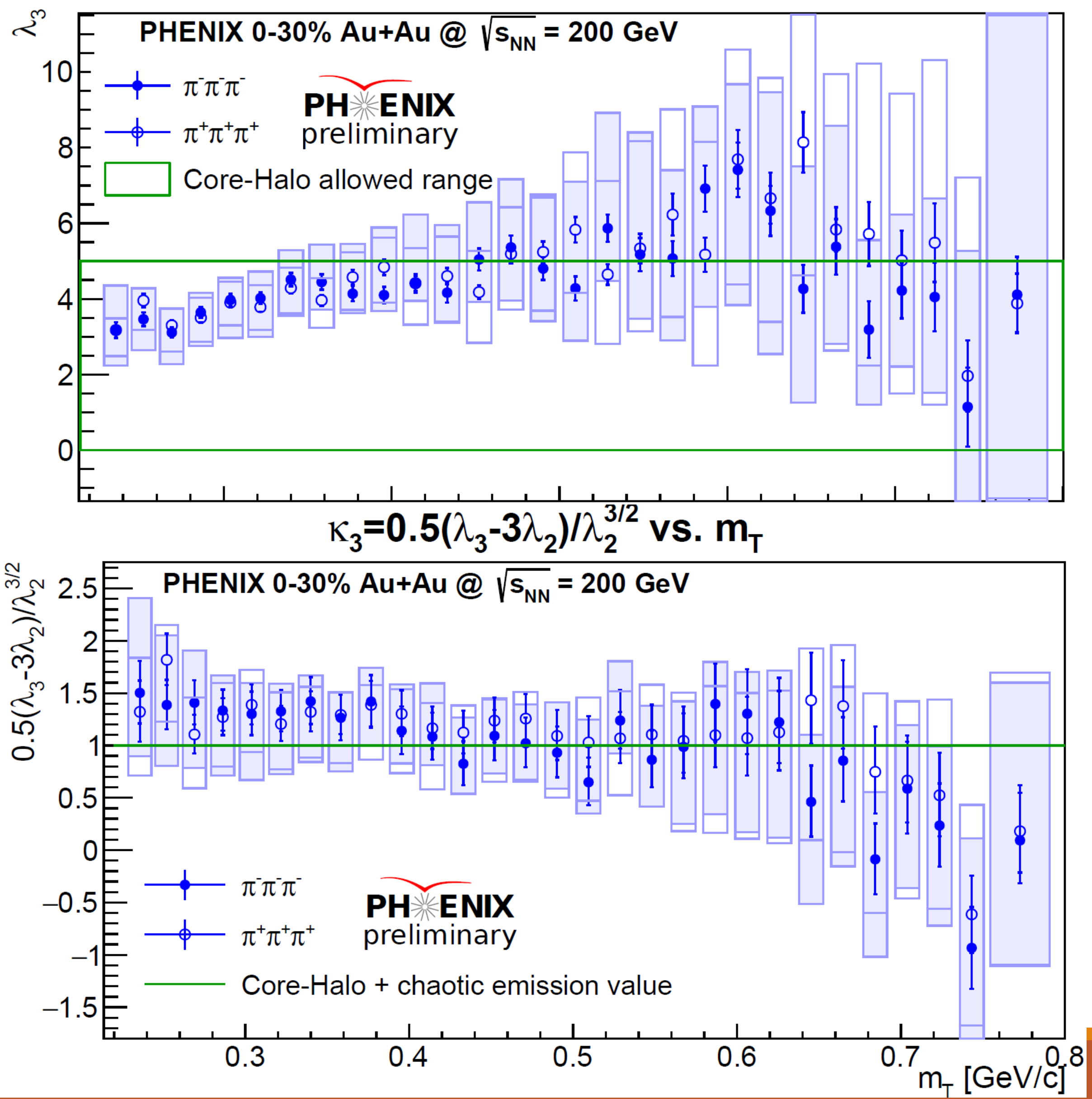
3D correlation – PHENIX 0-30% Au+Au





- 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

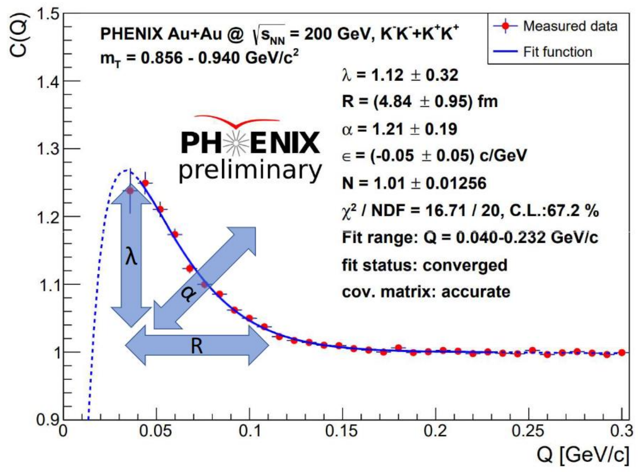


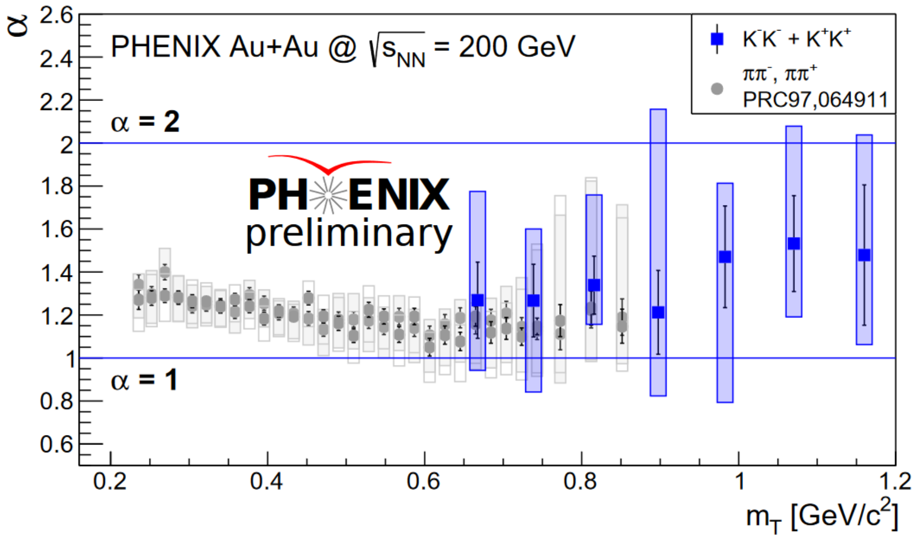
$$\kappa_3 = \frac{(\lambda_3 - 3\lambda_2)}{2\sqrt{\lambda_2^3}}$$

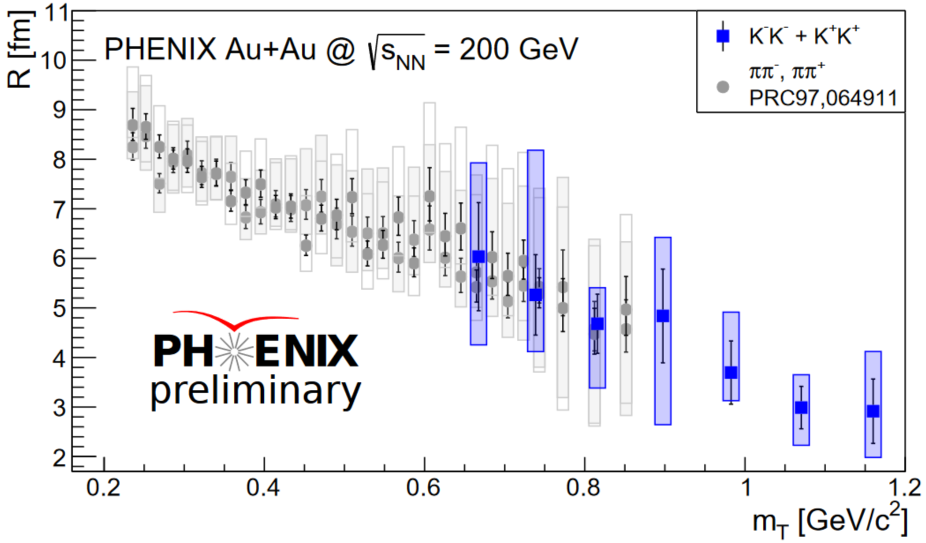
- From the definition:
  - No coherence: $p_c = 0 \Rightarrow \kappa = 1$
  - Coherence: $p_c > 0 \Rightarrow \kappa < 1$

- 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