

# Levy analysis of three particle correlation functions at PHENIX

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# The PHENIX experiment

- Different collision energies

7.7-200 GeV in  $\sqrt{s_{NN}}$   
20-400 MeV in  $\mu_B$

- Different collision systems

p+p, p+A, A+A

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

# Levy-type source assumption

Correlation function:  $C_2(q) \cong 1 + |\int S(r)e^{iqr}|^2$

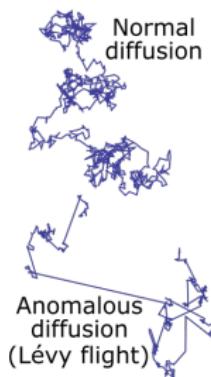
Assumption for source function  $\rightarrow$  Levy-type source

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

- Generalized centr. lim. theorem
- Levy-exponent:  $\alpha$  (Gaussian  $\alpha = 2$ , Cauchy  $\alpha = 1$ )
- Levy-scale parameter:  $R$

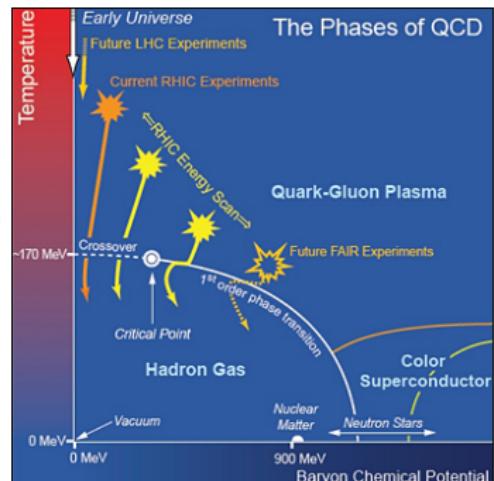
Probable reasons:

- Anomalous diffusion
- QCD jets
- Critical phenomena
- ...

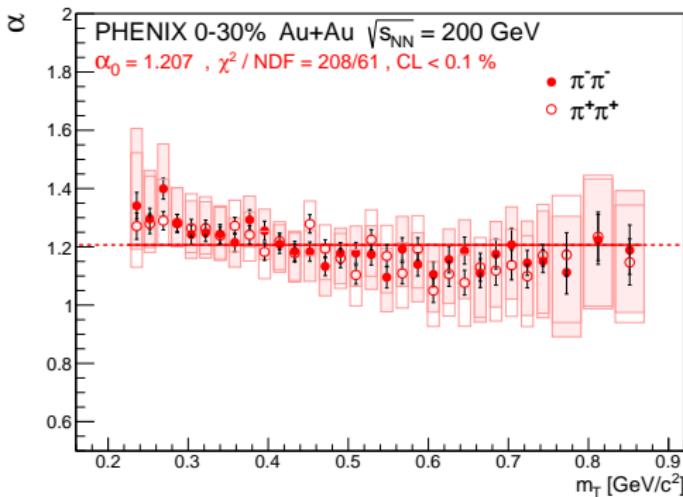


# The connection of Lévy-index and the critical point

- Looking for critical behavior with critical exponents
- Critical spatial correlation:  $\sim r^{-(d-2+\eta)}$
- Lévy source:  $\sim r^{-(d-2+\alpha)} \rightarrow \eta \iff \alpha ?$   
Csörgő et al. Eur. Phys. J. **C36** 67 (2004)
- QCD universality class  $\iff$  3D Ising  
Halasz et al., Phys. Rev. **D58** 096007 (1998)  
Stephanov et al., Phys. Rev. Lett. **81** 4816 (1998)
- Critical point:
  - Random field 3D Ising:  $\eta = 0.50 \pm 0.05$   
Rieger, Phys. Rev. **B52** 6659 (1995)
  - 3D Ising:  $\eta = 0.03631(3)$   
El-Showk et al., J. Stat. Phys. **157** (4-5):869
- Motivation for precise Lévy HBT!
- Finite size, non-equilibrium effects
  - What does the power-law tail mean?

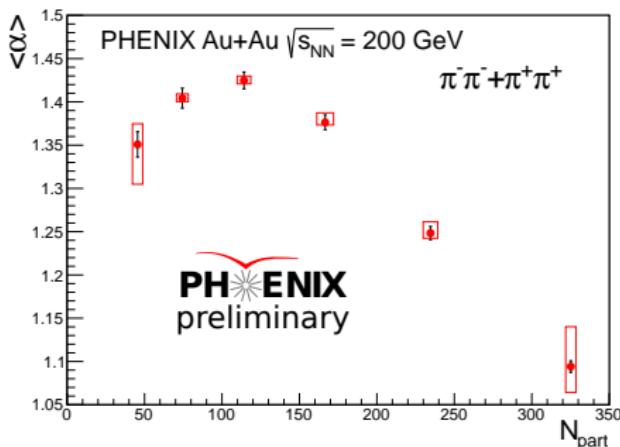
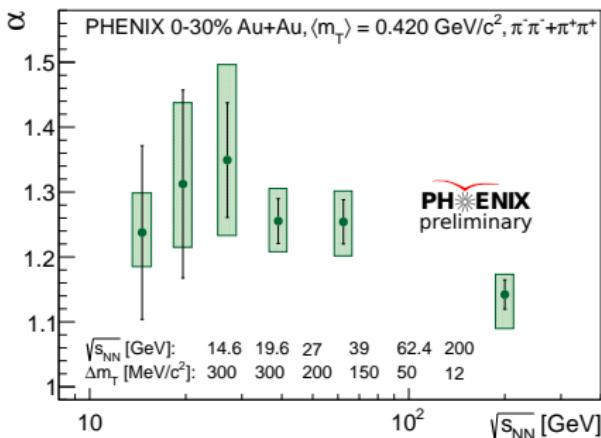


## Levy exponent from two particle correlations



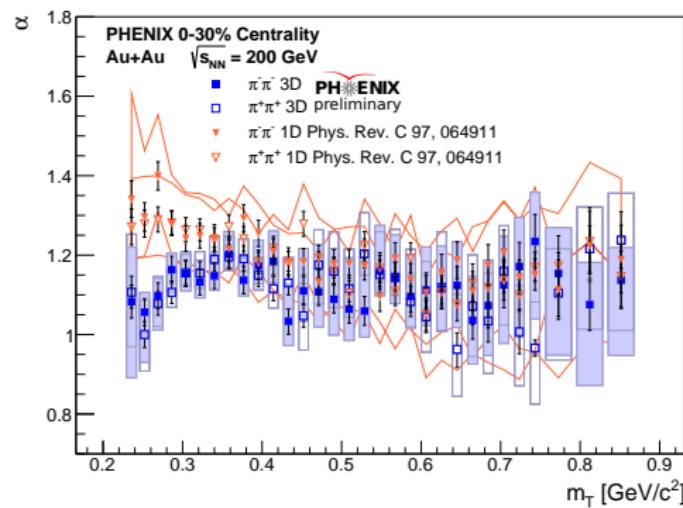
- Lévy-exponent vs.  $m_T$   
A. Adare et al. PRC97 (2018) 064911
- Far from Gaussian ( $\alpha = 2$ )
- Inconsistent with Cauchy ( $\alpha = 1$ )
- Far from CEP ( $\alpha \leq 0.5$ )
- Constant within systematics

# Centrality and energy dependence



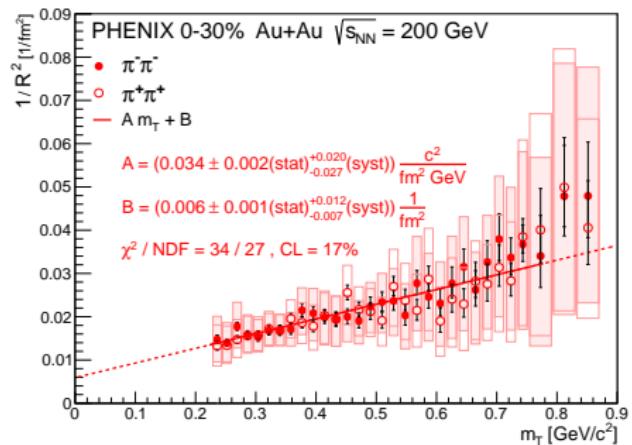
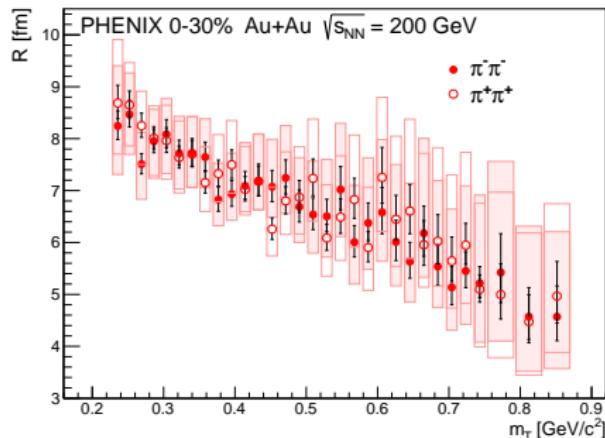
- Non-monotonic behavior of  $\alpha$  vs.  $N_{\text{coll}}$  (arXiv:1801.08827)
  - No clear interpretation
- $\alpha$  is far from CEP value for these energies (arXiv:1811.08311)
  - $m_T$  bin width dependent values

# Cross check with 3D analysis



- Similar to 1D results  
[arXiv:1809.09392](https://arxiv.org/abs/1809.09392)
- Still far from Gaussian ( $\alpha = 2$ )
- Differences at low  $m_T$ 
  - Due to non-spherical source?

# Scale parameter from two-particle correlations



- Lévy scale parameter  $\neq$  RMS
- Same behavior as for Gaussian HBT radii
- Hydro scaling observable:  $1/R^2 = Am_T + B$

# Correlation strength, core-halo independent parameter

- Two component source:  $f_c = N_{core}/N_{total}$
- If there are pions emitted coherently:  $p_c = N_{coherent}/N_{core}$
- Partial coherence + Core-Halo:

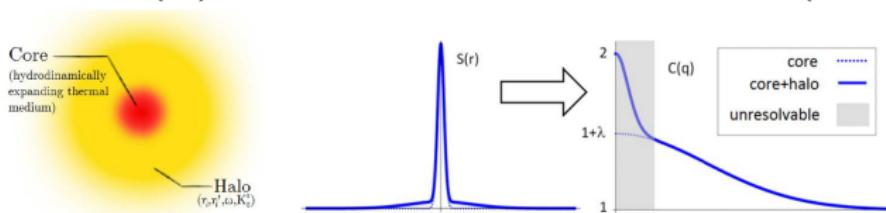
T. Csörgő, B. Lörstad, J. Zimányi, Z. Phys. C71 , 491 (1996), arXiv:9411307

T. Csörgő et al. Eur. Phys. J. C9 275-281 (1999) arXiv:9812422

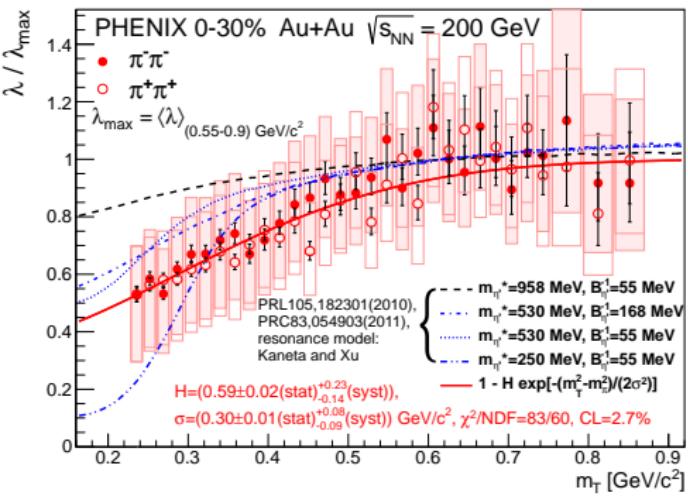
$$\lambda_2 = f_c^2 [(1 - p_c)^2 + 2p_c(1 - p_c)]$$

$$\lambda_3 = 2f_c^3 [(1 - p_c)^3 + 3p_c(1 - p_c)^2] + 3f_c^2 [(1 - p_c)^2 + 2p_c(1 - p_c)]$$

- Experimentally:  $\lambda_n = C_n(q_1 = q_2 \dots = 0) - 1$
- Core-halo ( $f_c$ ) independent parameter:  $\kappa_3 = 0.5(\lambda_3 - 3\lambda_2)/\lambda_2^{3/2}$



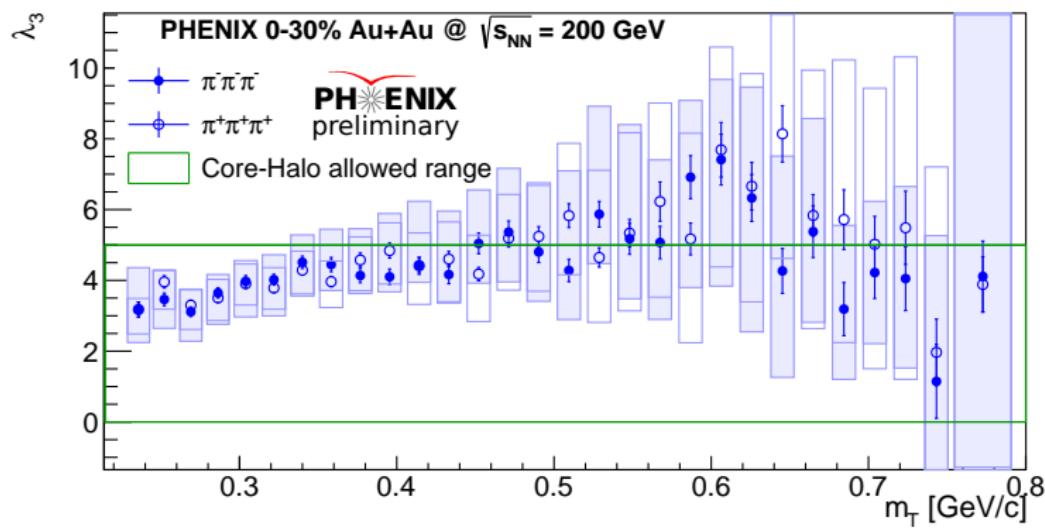
# Two particle correlation strength from previous analysis



- Hole in  $\lambda_2$  at low  $m_T$
- In medium  $\eta'$  mass modification?
- Decreased  $\eta'$  mass  $\rightarrow \eta'$  enhancement
- $\eta' \rightarrow \pi\pi\pi\pi$
- Halo enhancement  $\rightarrow$  lower  $\lambda_2$ 
  - J. I. Kapusta et al., PRD53 (1996) 5028
  - S. E. Vance et al., PRL81 (1998) 2205
  - T. Csörgő et al., PRL105 (2010) 182301
- Results aren't incompatible
- From  $\lambda_2$ ,  $\lambda_3$  calculate  $\kappa_3$

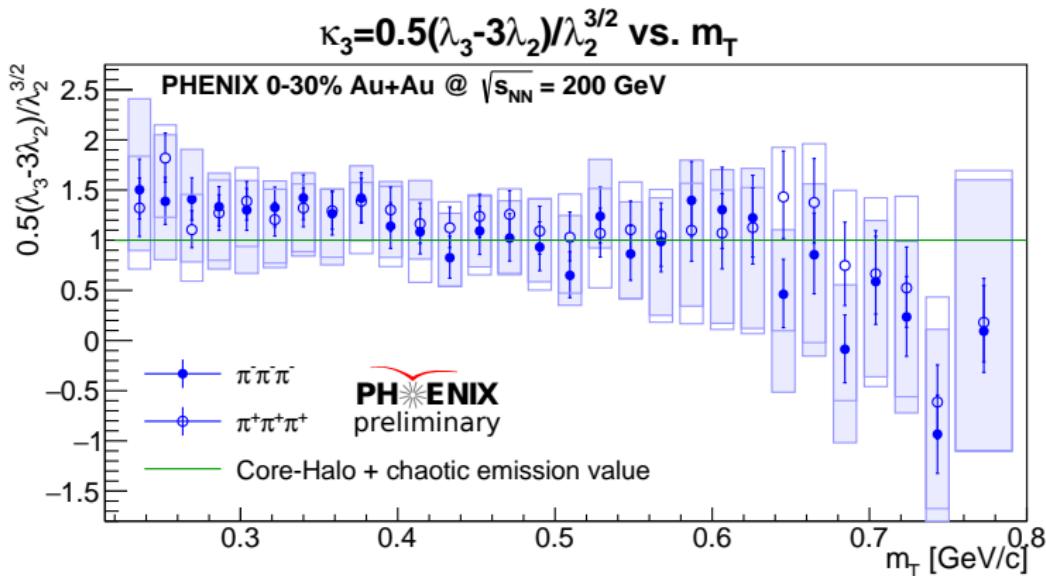
# Three particle correlation strength

- From Core-Halo model:  $0 < \lambda_3 < 5$



# Core-Halo independent parameter

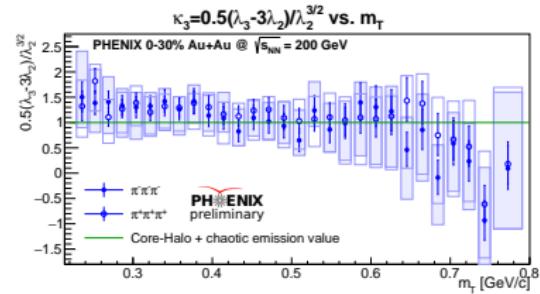
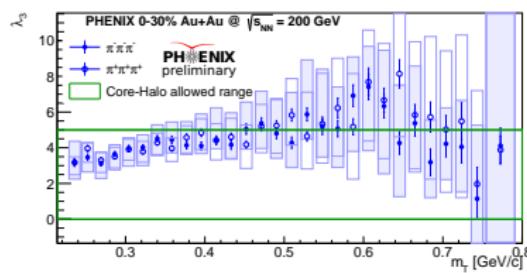
- Independent from  $f_c$
- Expectation for fully chaotic, core+halo type source:  $\kappa_3 = 1$



# Summary

## Results:

- Levy sources ( $\alpha < 2$ ) seen in 1D, 3D,  $2\pi$ ,  $3\pi$  analyses
- $\kappa_3 = 1$  consistent with chaotic emission
- $0 < \lambda_3 < 5$  within errors



Thank you for your attention!

"Supported by the ÚNKP-19-2 New National Excellence Program of the Ministry for Innovation and Technology."

# Three particle correlation functions

- Correlation function:

$$C_3(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \frac{N_3(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)}{N_1(\mathbf{k}_1)N_1(\mathbf{k}_2)N_1(\mathbf{k}_3)}$$

- Single particle momentum distribution:

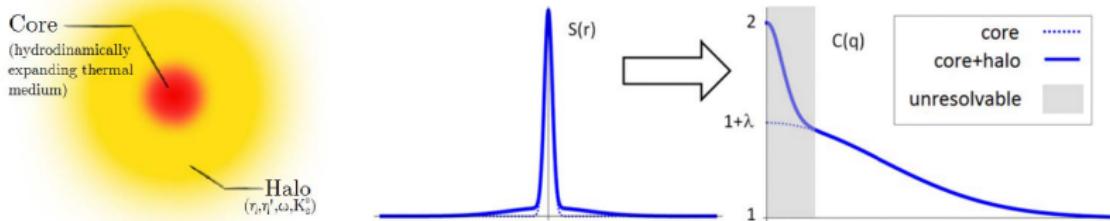
$$N_1(\mathbf{k}) = \int S(\mathbf{k}, \mathbf{r}) |\Psi_{\mathbf{k}}(r)|^2 d^4 r$$

- Three particle momentum distribution:

$$N_3(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \int |\Psi_{\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)|^2 \prod_{i=0}^3 S(\mathbf{k}_i, \mathbf{r}_i) d^4 \mathbf{r}_i$$

# Core-Halo model

- Two component source:  $S = S_c + S_h$   
T. Csörgő, B. Lörstad, J. Zimányi, Z. Phys. C71 , 491 (1996), arXiv:9411307
  - Core: thermalized medium, expanding source
  - Halo: long lived resonances ( $\tau > 10 \text{ fm}/c$ ) → experimentally unresolvable
- Fraction of core:  $f_c = N_{core}/(N_{core} + N_{halo})$
- Two particle correlation strength:  $\lambda_2 = f_c^2$
- Three particle correlation strength:  $\lambda_3 = 2f_c^3 + 3f_c^2$
- Core-Halo independent parameter:  $\kappa_3 = 0.5(\lambda_3 - 3\lambda_2)/\lambda_2^{3/2} = 1$



# Partial coherence

- If there are pions emitted coherently:

$$S_c = S_c^{coherent} + S_c^{incoherent}$$

- Fraction of pions emitted coherently:

$$p_c = N_{coherent} / (N_{coherent} + N_{incoherent})$$

- Partial coherence + Core-Halo:

T. Csörgő et al. Eur. Phys. J. C9 275-281 (1999) arXiv:9812422

$$\lambda_2 = f_c^2 \left[ (1 - p_c)^2 + 2p_c(1 - p_c) \right]$$

$$\lambda_3 = 2f_c^3 \left[ (1 - p_c)^3 + 3p_c(1 - p_c)^2 \right] + 3f_c^2 \left[ (1 - p_c)^2 + 2p_c(1 - p_c) \right]$$

# Three pion Levy HBT

The correlation function (without final Coulomb-interaction):

$$C_3^{(0)}(q_{12}, q_{13}, q_{23}) = 1 + \ell_3 e^{-0.5(|q_{12}R|^\alpha + |q_{13}R|^\alpha + |q_{23}R|^\alpha)} \\ + \ell_2 \left( e^{|q_{12}R|^\alpha} + e^{|q_{13}R|^\alpha} + e^{|q_{23}R|^\alpha} \right)$$

Parameters:

- Already known from two particle measurements:  $\alpha$ ,  $R$   
A. Adare et al. Phys. Rev. C 97, 064911 (2018) arXiv:1709.05649
- Now measured:  $\ell_2$ ,  $\ell_3$

We are looking for three-particle correlation strength:  $\lambda_3$

$$\lambda_3 = C_3(q_{12} = q_{13} = q_{23} \rightarrow 0) - 1 = \ell_3 + 3\ell_2$$

# Analysis details

- 200 GeV Au+Au collisions
- 29  $m_T$  bins
- Correlation functions of identified, same charged pion triplets
- Cuts:
  - Event selection: z-vertex, 0-30% Centrality
  - Particle selection:  $2\sigma$  cuts for PID
  - Single track cuts:  $2\sigma$  matching
  - Pair cuts: customary shaped cuts for  $\Delta z - \Delta\varphi$  distributions

# Fit function

Fit function:

$$C_3^{(fit)} = N(1 + \varepsilon q_{12})(1 + \varepsilon q_{13})(1 + \varepsilon q_{23})K_3 C_3^{(0)}$$

Background and normalisation:  $\varepsilon, N$

Coulomb-correction:

- Generalized Riverside method:

$$K_3(q_{12}, q_{13}, q_{23}) \approx K_1(q_{12})K_1(q_{13})K_1(q_{23})$$

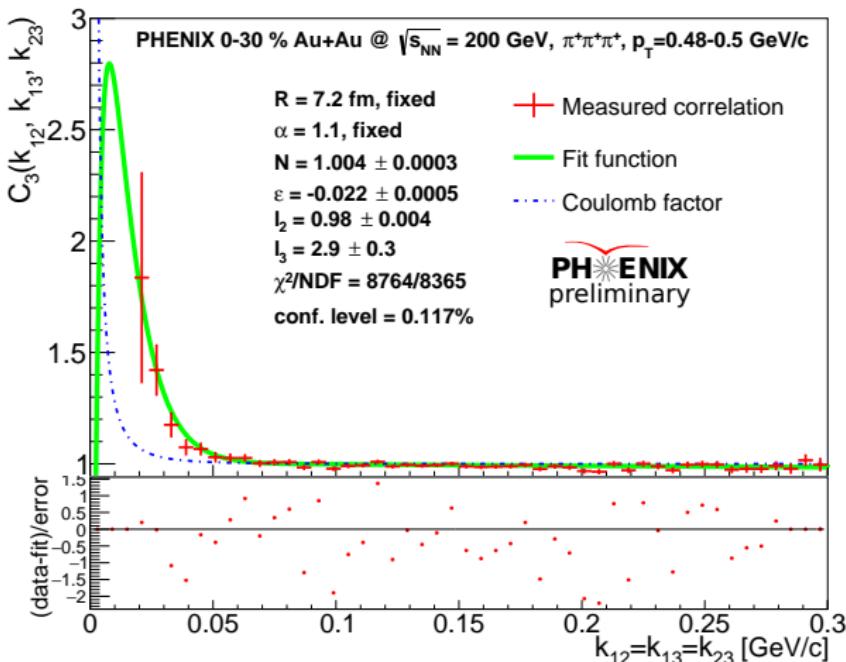
- Detailed numerical table for  $K_1(q, \alpha, R)$

Fit parameters:  $\ell_2, \ell_3, N, \varepsilon$

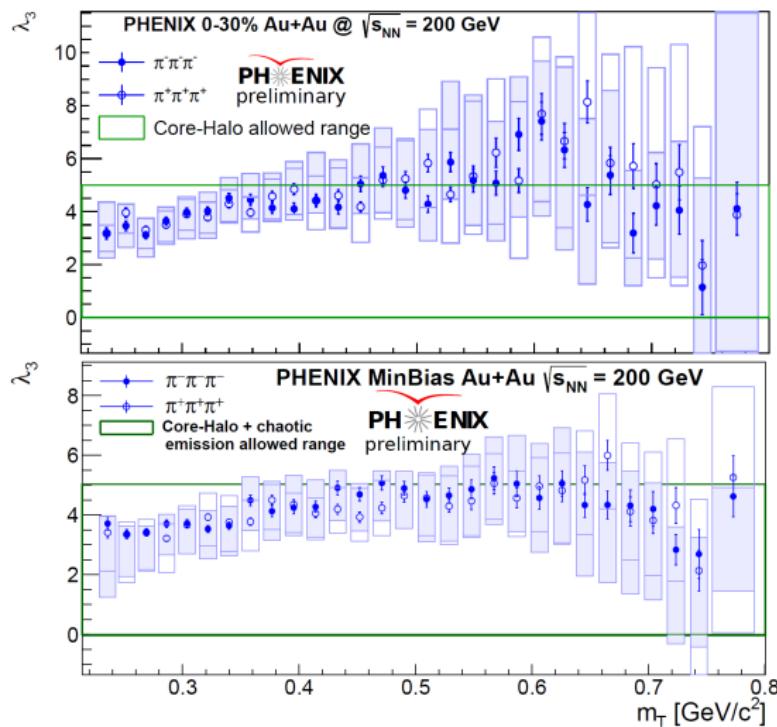
Already known from 2-particle correlations:  $\alpha, R$

# Example fit

- Diagonal visualization of 3D correlation function

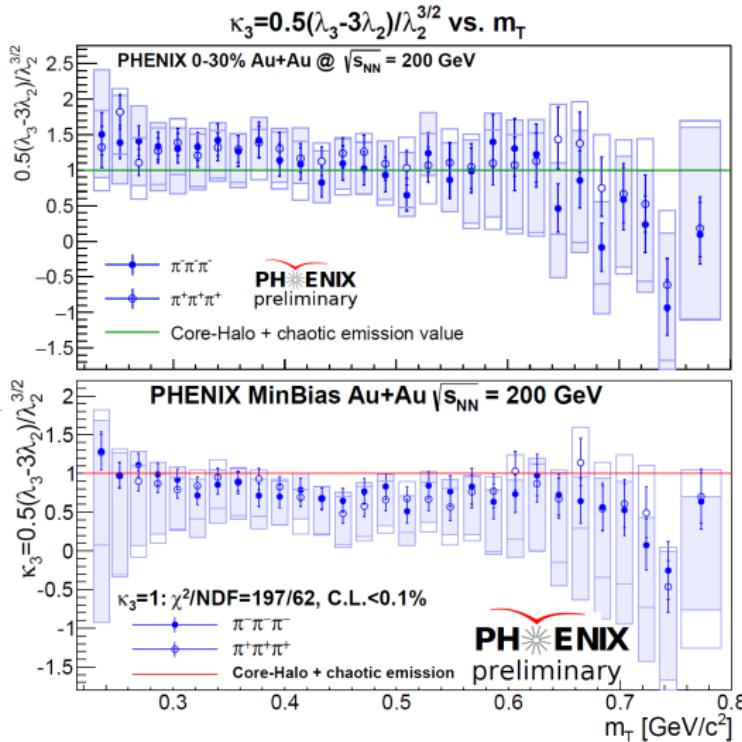


# MinBias vs 0-30% Centrality: $\lambda_3$



- 0-30% Centrality
- Density & size dependence
- Similar to MinBias
- Within Core-Halo range

# MinBias vs 0-30% Centrality: $\kappa_3$



- 0-30% Centrality
- Density & size dependence
- Similar to MinBias
- 0-30% compatible with 1