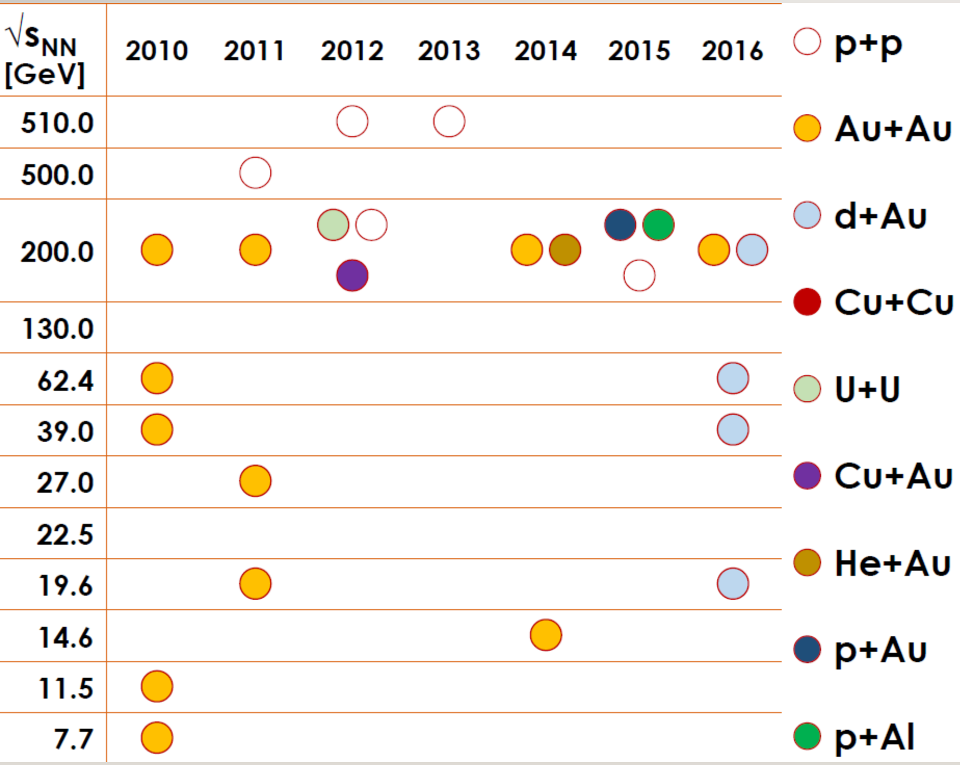
2- AND 3-PION LÉVY FEMTOSCOPY WITH PHENIX

MÁTÉ CSANÁD FOR PHENIX @ WWND 2018, MARCH 30

EÖTVÖS UNIVERSITY, BUDAPEST, HUNGARY

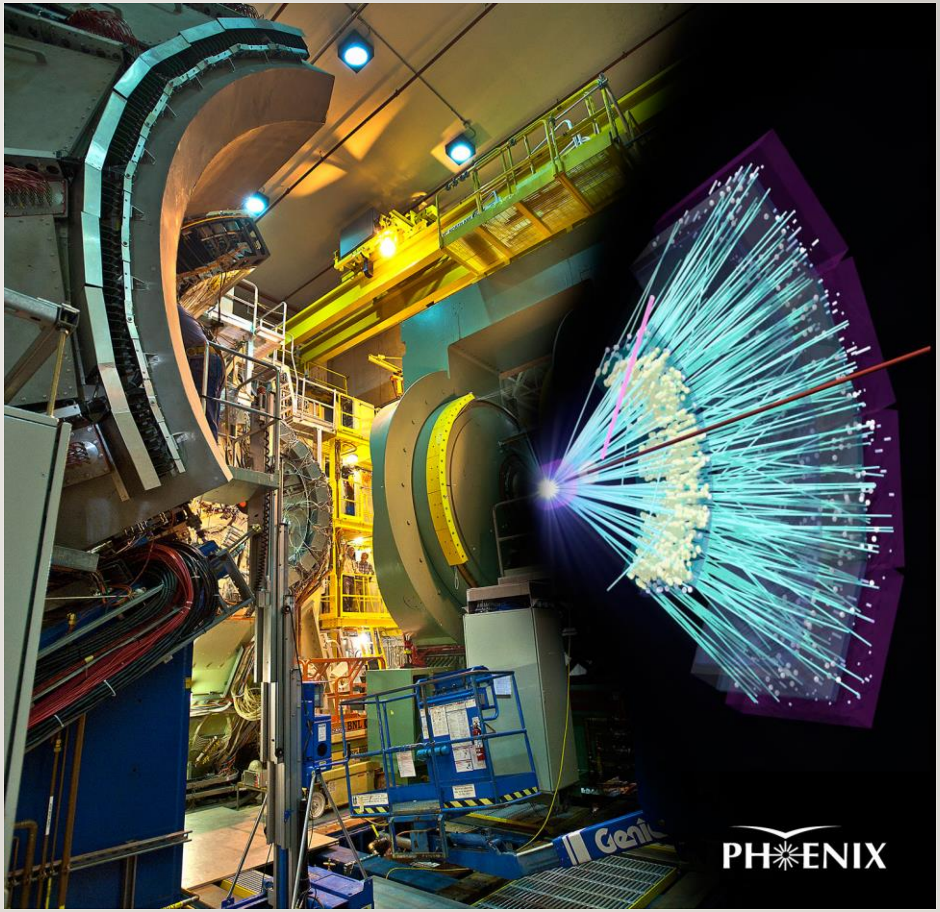
THE PHENIX EXPERIMENT AND THE BES

- Collision energies: 7.7 to 200 GeV (20-400 MeV in μ_B, 140-170 MeV in T)
- What changes with $\sqrt{s_{NN}}$?



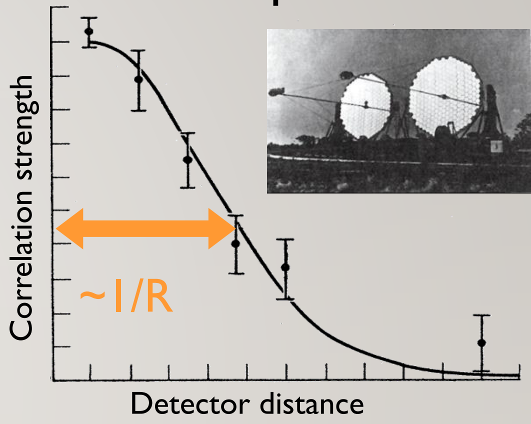
$\sqrt{s_{NN}}$ [GeV]	2010	2011	2012	2013	2014	2015	2016
510.0			○	○			
500.0		○					
200.0	🟠	🟠	🟩 ○ 🟣		🟠 🟤	⚫ 🟢 ○	🟠 🔵
130.0							
62.4	🟠						🔵
39.0	🟠						🔵
27.0		🟠					
22.5							
19.6		🟠					🔵
14.6					🟠		
11.5	🟠						
7.7	🟠						

○ p+p
🟠 Au+Au
🔵 d+Au
🔴 Cu+Cu
🟩 U+U
🟣 Cu+Au
🟤 He+Au
⚫ p+Au
🟢 p+Al

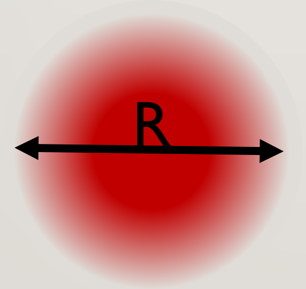


FEMTOSCOPY: THE HBT EFFECT

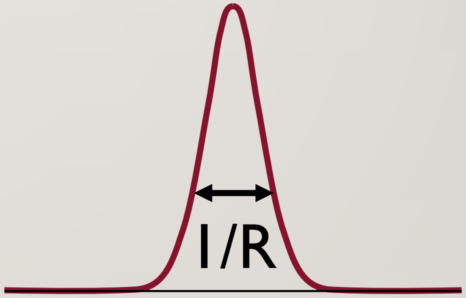
- R. Hanbury Brown, R. Q. Twiss - observing Sirius with radio telescopes
  - Intensity correlations vs detector distance ⇒ source size
  - Measure the sizes of apparently point-like sources!



- Goldhaber et al: applicable in high energy physics
  - Momentum correlation $C(q)$ related to source $S(r)$
  - $C(q) \cong 1 + \left|\int S(r) e^{iqr} dr\right|^2$ (under some assumptions)



source function S(r)



correlation function C(q)

- Measure C(q): map out source space-time geometry on femtometer scale!

LÉVY DISTRIBUTIONS IN HEAVY ION PHYSICS

- Expanding medium, increasing mean free path: anomalous diffusion

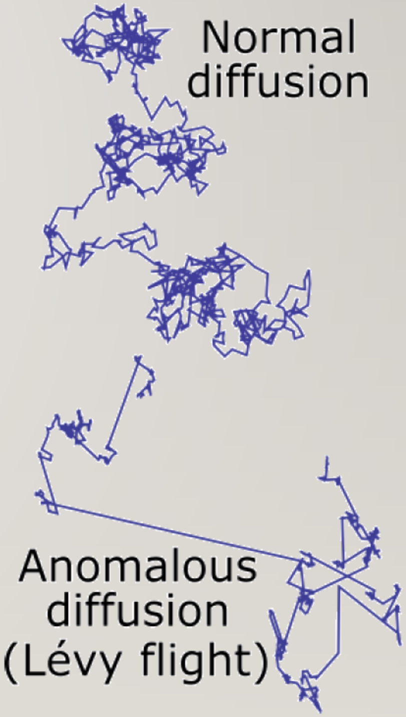
  Metzler, Klafter, Physics Reports 339 (2000) 1-77, Csanad, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002
- Lévy-stable distribution: $\mathcal{L}(\alpha, R; r) = \frac{1}{(2\pi)^3} \int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$
  - Generalized Gaussian from generalized central limit theorem
  - $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy
  - Power-law in spatial correlations ~ $r^{-(1+\alpha)}$
- Shape of the correlation functions with Levy source:

  $$C_2(q) = 1 + \lambda \cdot e^{-|qR|^\alpha}$$

  $\alpha = 2$: Gaussian

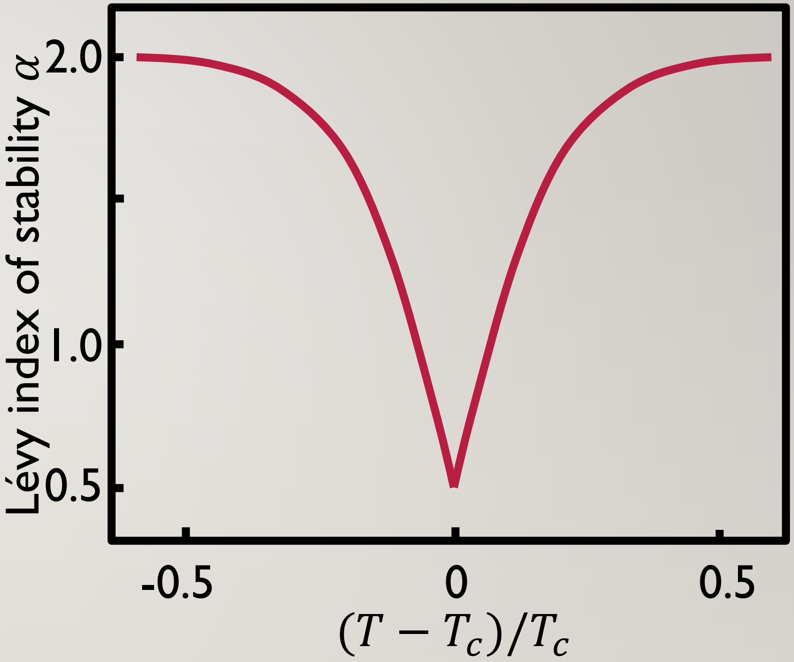
  $\alpha = 1$: Exponential
- Critical spatial correlation ~ $r^{-(d-2-\eta)}$ → critical exponent
  - α alpha can be associated with the critical exponent η?

    Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042
  - How about dynamics?



LÉVY INDEX AS A CRITICAL EXPONENT?

- QCD universality class ↔ 3D Ising
  - Halasz et al., Phys.Rev.D58 (1998) 096007
  - Stephanov et al., Phys.Rev.Lett.81 (1998) 4816
- At the critical point:
  - Random field 3D Ising: η = 0.50±0.05
    Rieger, Phys.Rev.B52 (1995) 6659
  - 3D Ising: η = 0.03631(3)
    El-Showk et al., J.Stat.Phys.157 (4-5): 869
- Motivation for precise Lévy HBT!
- Change in α_{Levy} proximity of CEP?
- Modulo finite size/time and non-equilibrium effects
- → what does power law exponent mean?

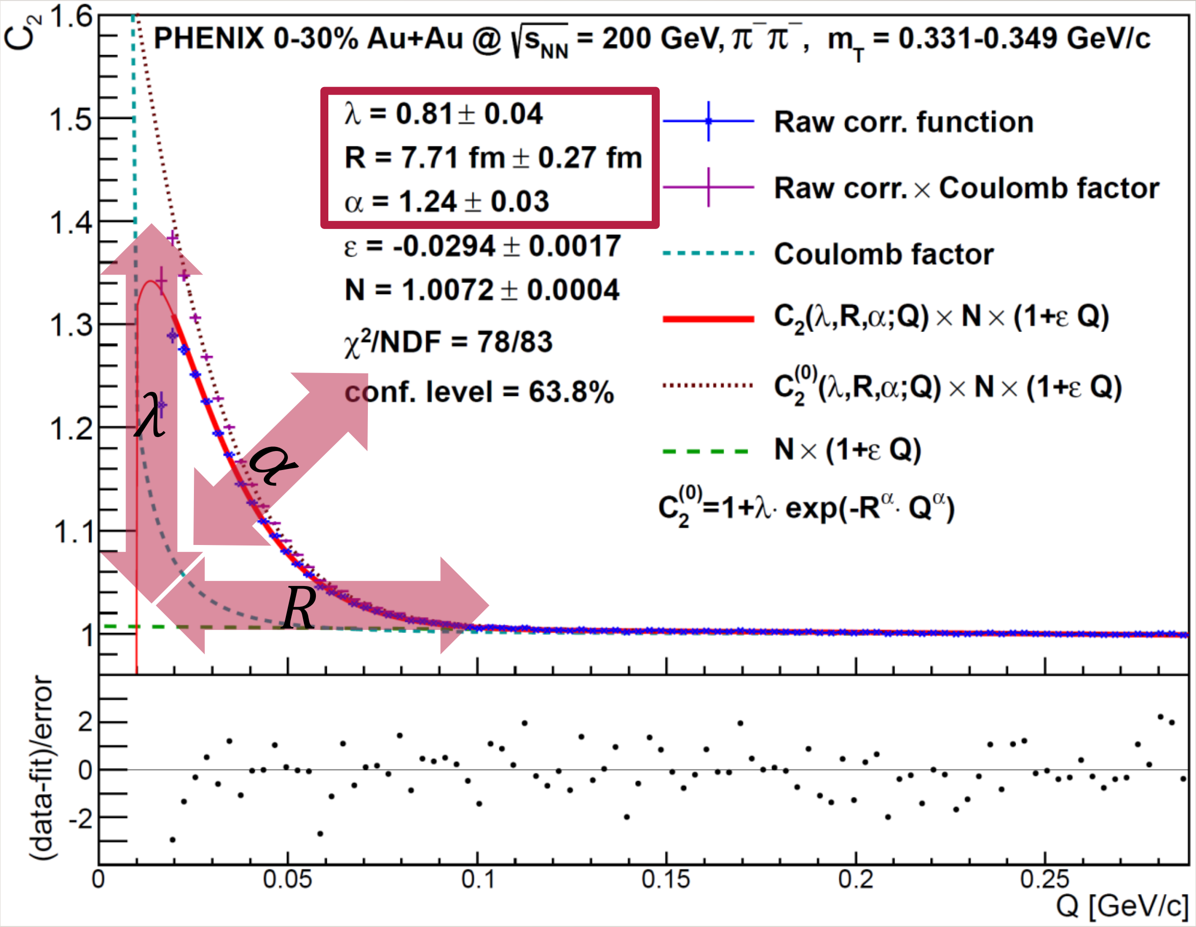


LEVY HBT ANALYSIS

- Dataset used for the analysis:
  - Events: Run-10, Au+Au, $\sqrt{s_{NN}}$ = 39 to 200 GeV, varying centrality, zvertex cut
  - Particle identification:
    - time-of-flight data from PbSc East/West, TOF East/West, momentum, flight length
    - 2σ cuts on m^2 distribution
  - Single track cuts: 2 σ matching cuts in TOF & PbSc for pions
  - Pair-cuts:
    - A random member of pairs assoc. with hits on same tower were removed
    - customary shaped cuts in $\Delta\phi$ - Δz plane for Drift Chamber, PbSc East/West, TOF East/West
- 1D($2\pi^{\pm}$) or 3D($3\pi^{\pm}$) corr. func. as a function of Q_{LCMS} in various m_T bins
  - Q_{LCMS} is 3-momentum difference in longitudinal co-moving system
  - Q_{12}, Q_{23}, Q_{31} for the three-particle case
  - Levy fits for 31 m_T bins ($0.228 < m_T < 0.871$ GeV/c) with Coulomb effect

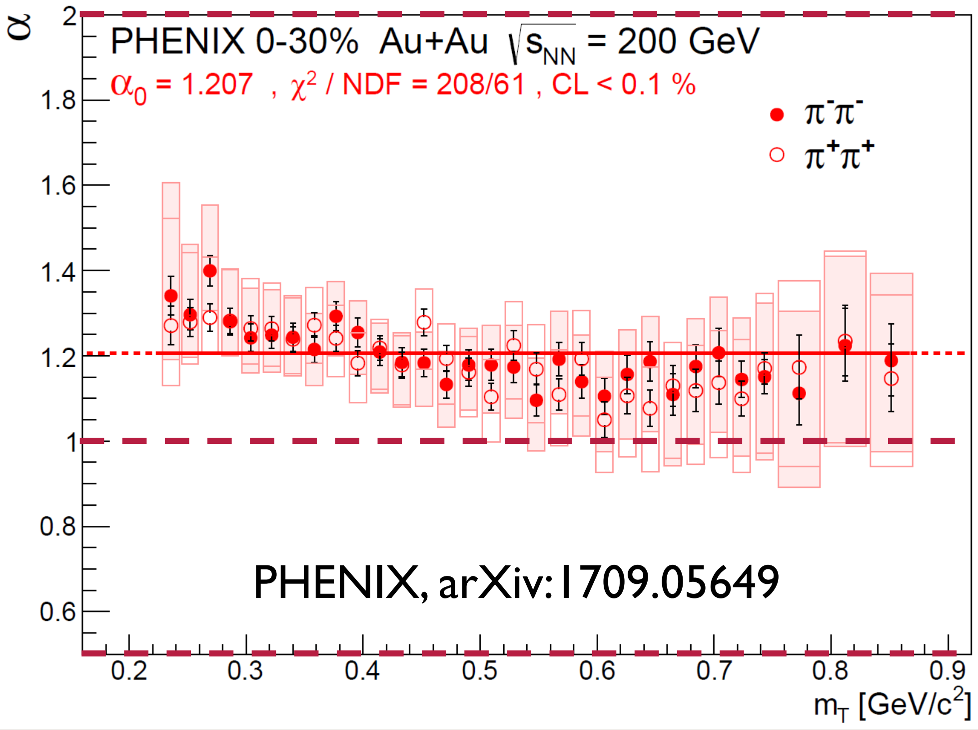
EXAMPLE $C_2(Q_{LCMS})$ CORRELATION FUNCTION

- Measured in 31 m_T bins
- Fitted with Coulomb-incorporated function
- Coulomb-factor displayed separately
- All fits converged
- Confidence levels all acceptable
- χ values scatter around 0 properly
- Physical parameters: R, λ, α measured versus pair m_T



PHENIX, arXiv:1709.05649

LÉVY EXPONENT (SHAPE PARAMETER) α



PHENIX, arXiv:1709.05649

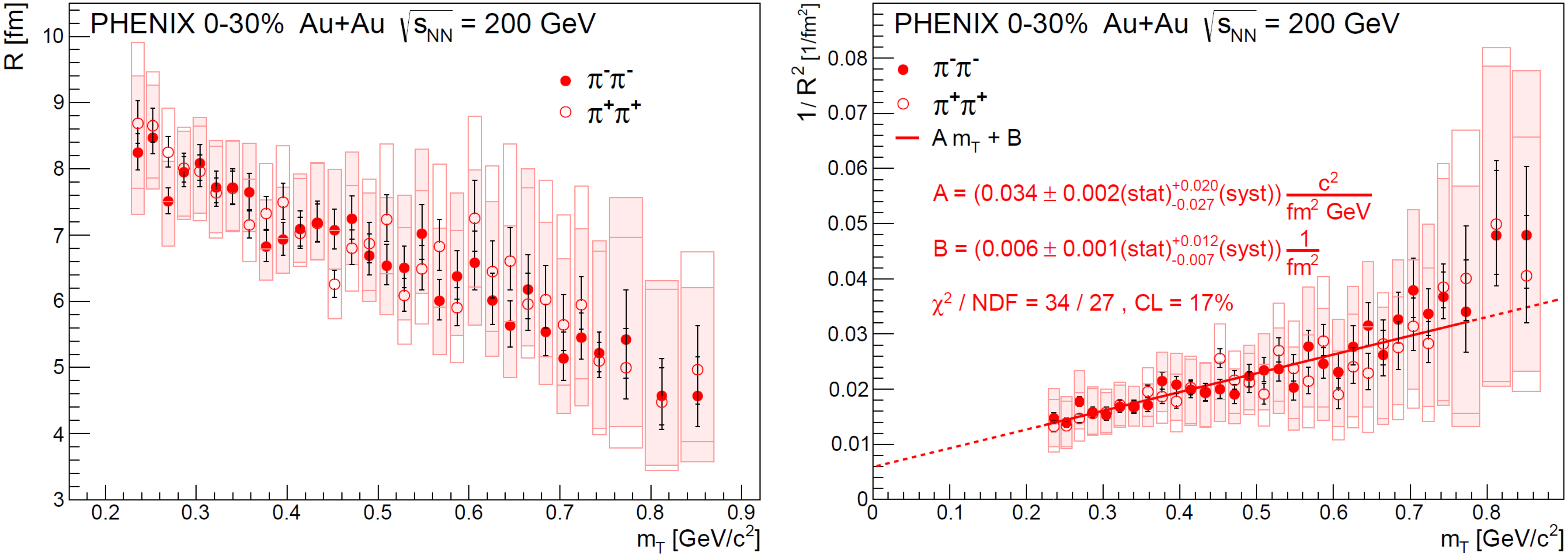
$\alpha = 2.0$ (Gauss)

$\alpha = 1.0$ (Cauchy)

$\alpha = 0.5$ (rfd Ising CEP)

- Measured value far from Gaussian (α = 2), inconsistent with expo. (α = 1)
- Also far from the random field 3D Ising value at CEP (α = 0.5)
- More or less constant (at least within systematic uncertainties)
- What do models and calculations say?

LÉVY SCALE PARAMETER R



- Similar decreasing trend as Gaussian HBT radii, but it is not an RMS!
- Hydro behavior not invalid
- The linear scaling of $1/R^2$, breaks for high m_T?

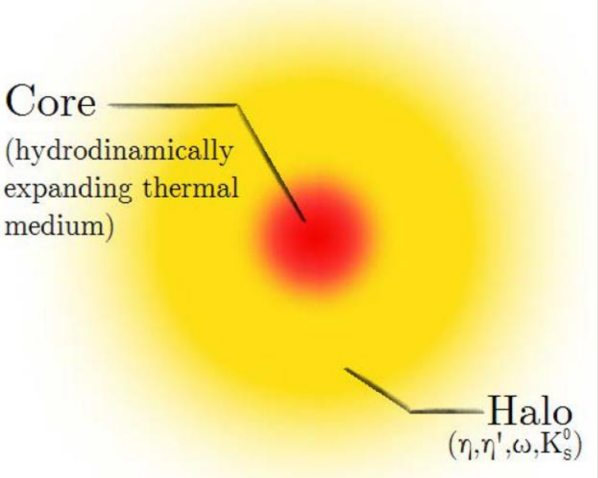
PHENIX, arXiv:1709.05649

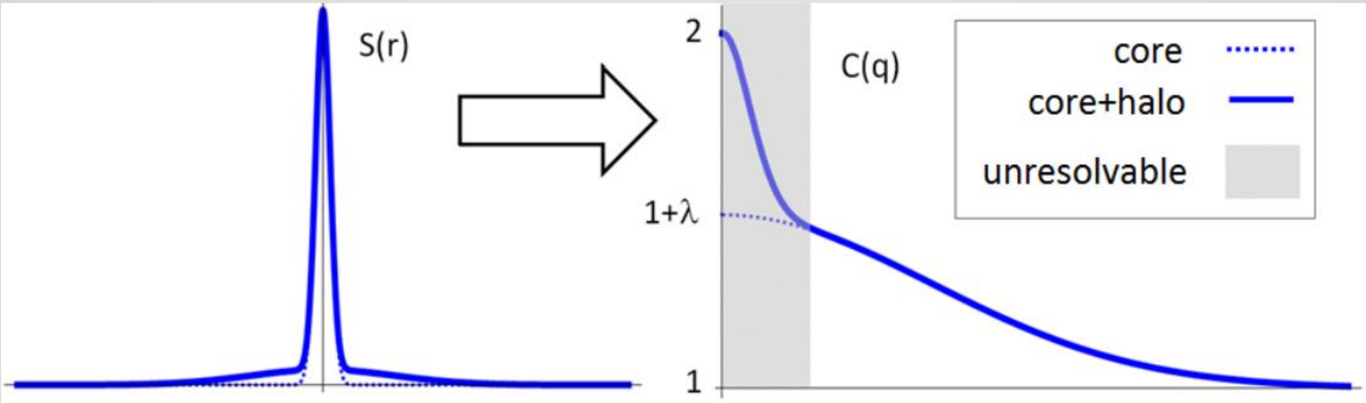
CORRELATION STRENGTH λ: CORE/HALO

- Two-component source
  - Core: hydrodynamically expanding
  - Halo: lived resonances (≳ 10 fm/c), unresolvable experimentally
  - Define $f_C = N_{\text{core}}/N_{\text{total}}$
- True $q \to 0$ limit: $C(0) = 2$
- Apparently $C(q \to 0) \to 1 + \lambda$
- $\lambda(m_T) = f_C^2(m_T)$

Bolz et al, Phys.Rev. D47 (1993) 3860-3870

Csörgő, Lörstad, Zimányi, Z.Phys. C71 (1996) 491-497



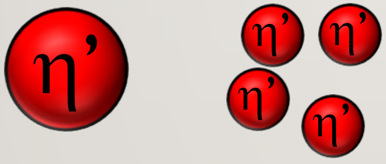


CORRELATION STRENGTH λ: IN-MEDIUM MASS?

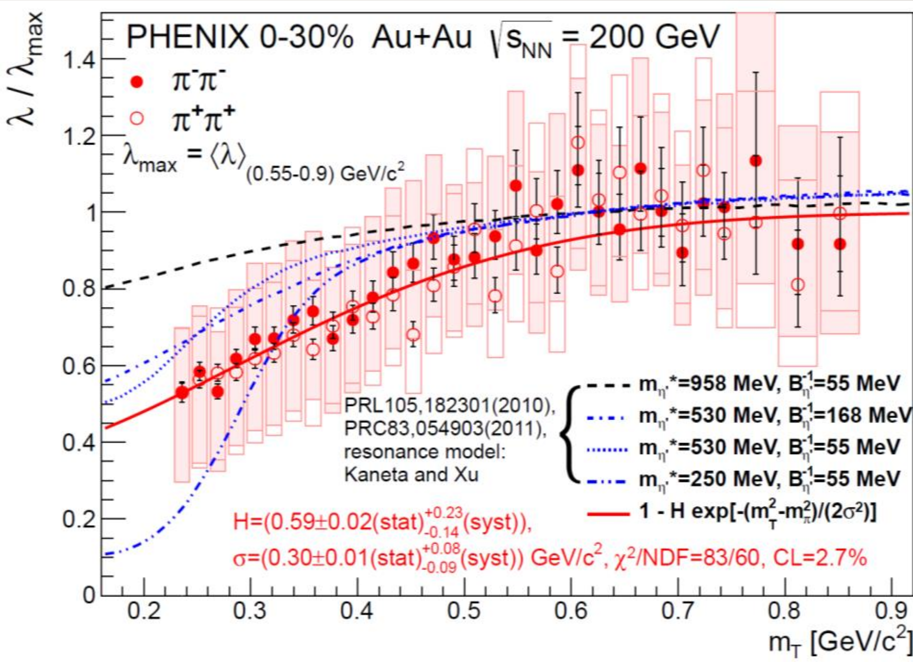
- Connection to chiral restoration
  - Decreased η’ mass → η’ enhancement → halo enhancement
  - Kinematics: η’ → ππππ with low m_T → decreased $\lambda(m_T)$ at low m_T
  - Dependence on in-medium η’ mass?

Kapusta, Kharzeev, McLerran, PRD53 (1996) 5028
Vance, Csörgő, Kharzeev, PRL 81 (1998) 2205
Csörgő, Vértesi, Sziklai, PRL105 (2010) 182301

  - Results compatible with modified mass!

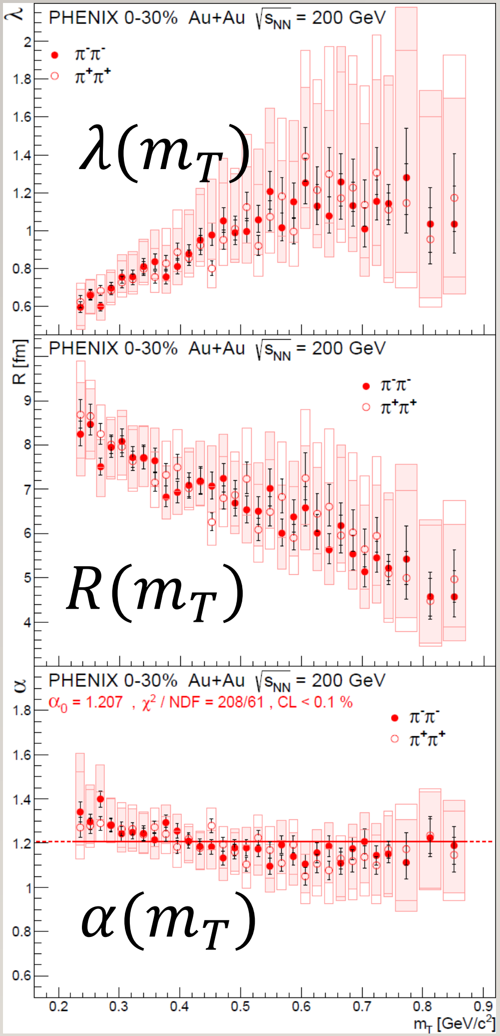


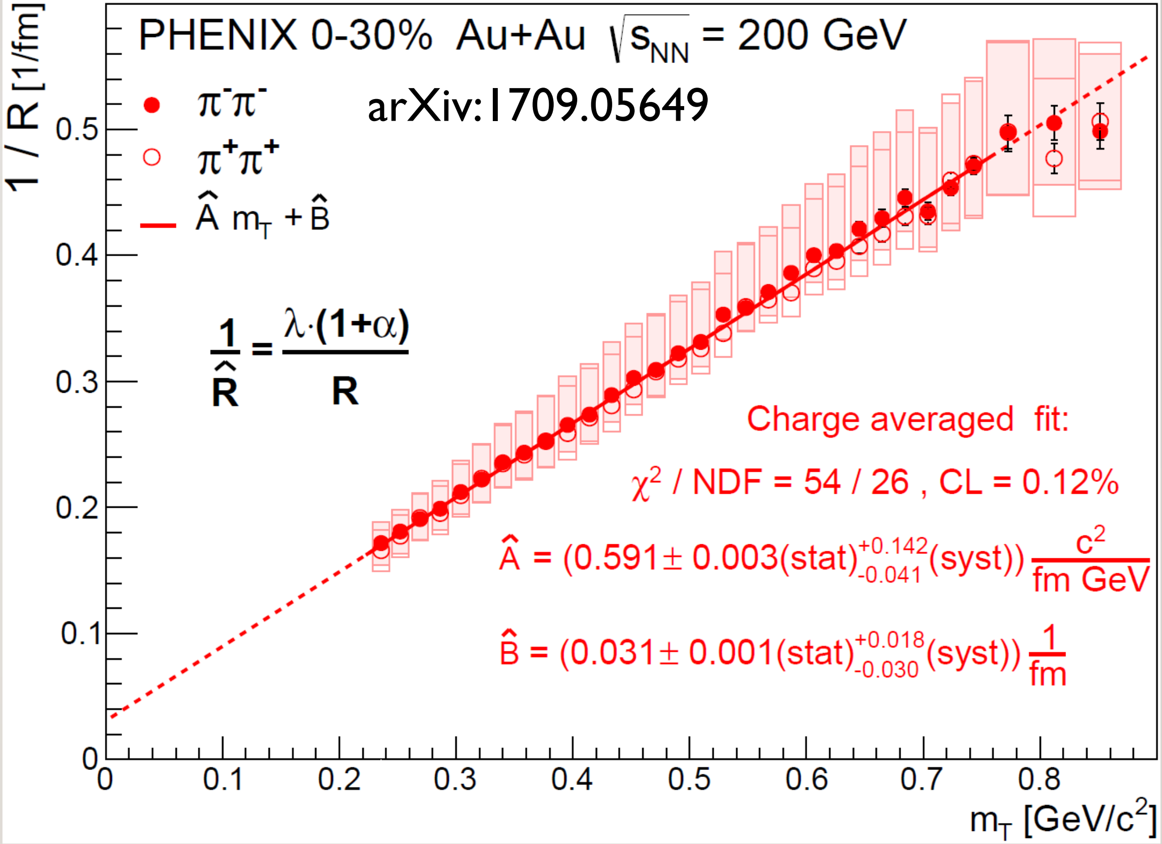
$$T < T^*$$
$$m_{\eta'} > m^*_{\eta'}$$
$$N_{\eta'} < N^*_{\eta'}$$
$$\lambda > \lambda^*$$



PHENIX, arXiv:1709.05649

NEW SCALING PARAMETER $\hat{R}$





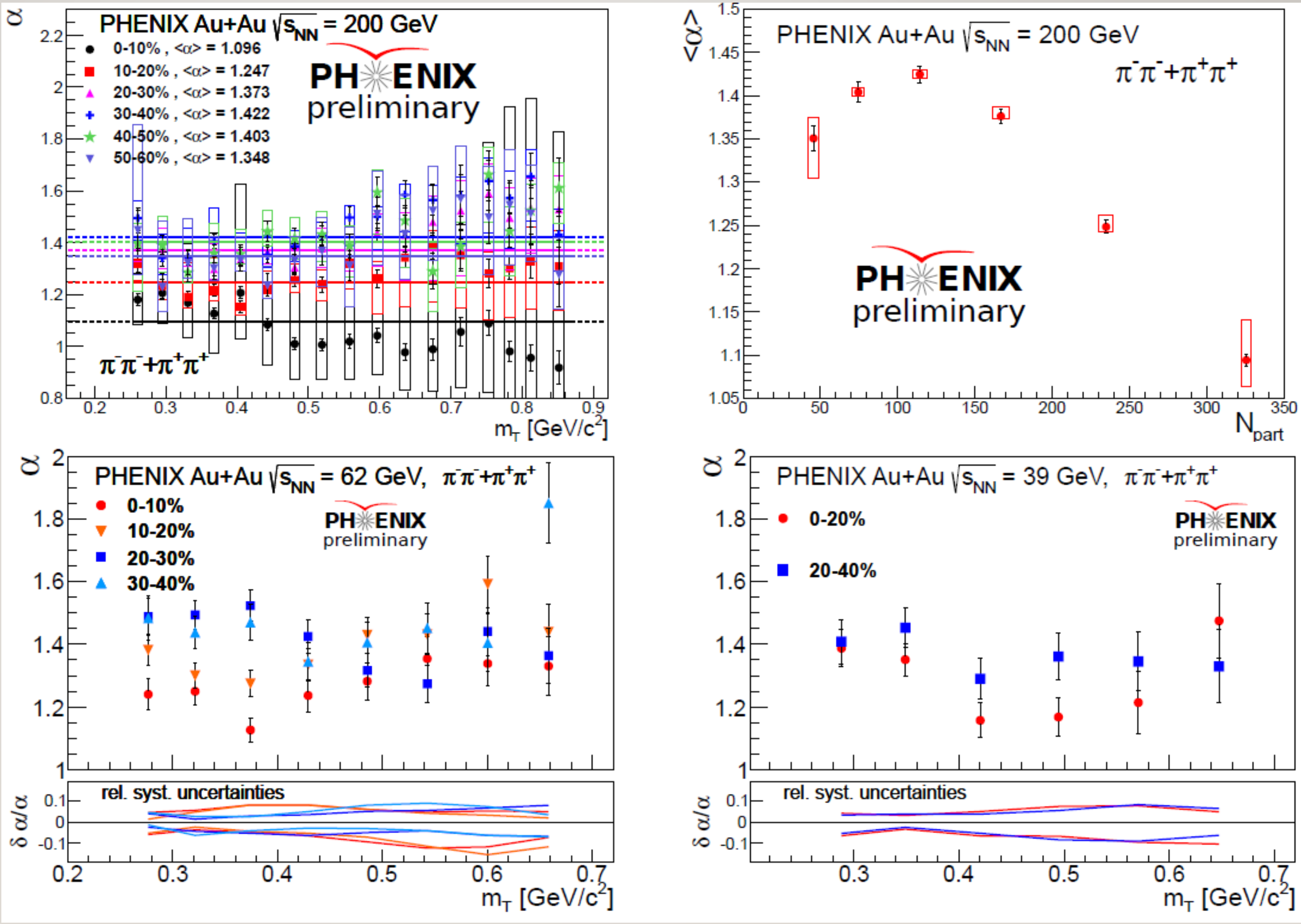
- Empirically found scaling parameter
- Linear in m_T
- Physical interpretation: open question

LÉVY EXPONENT α VS CENTRALITY AND $\sqrt{s_{NN}}$

- Slightly non-monotonic vs m_T
- Non-monotonic vs N_{part}
- No significant change vs $\sqrt{s_{NN}}$

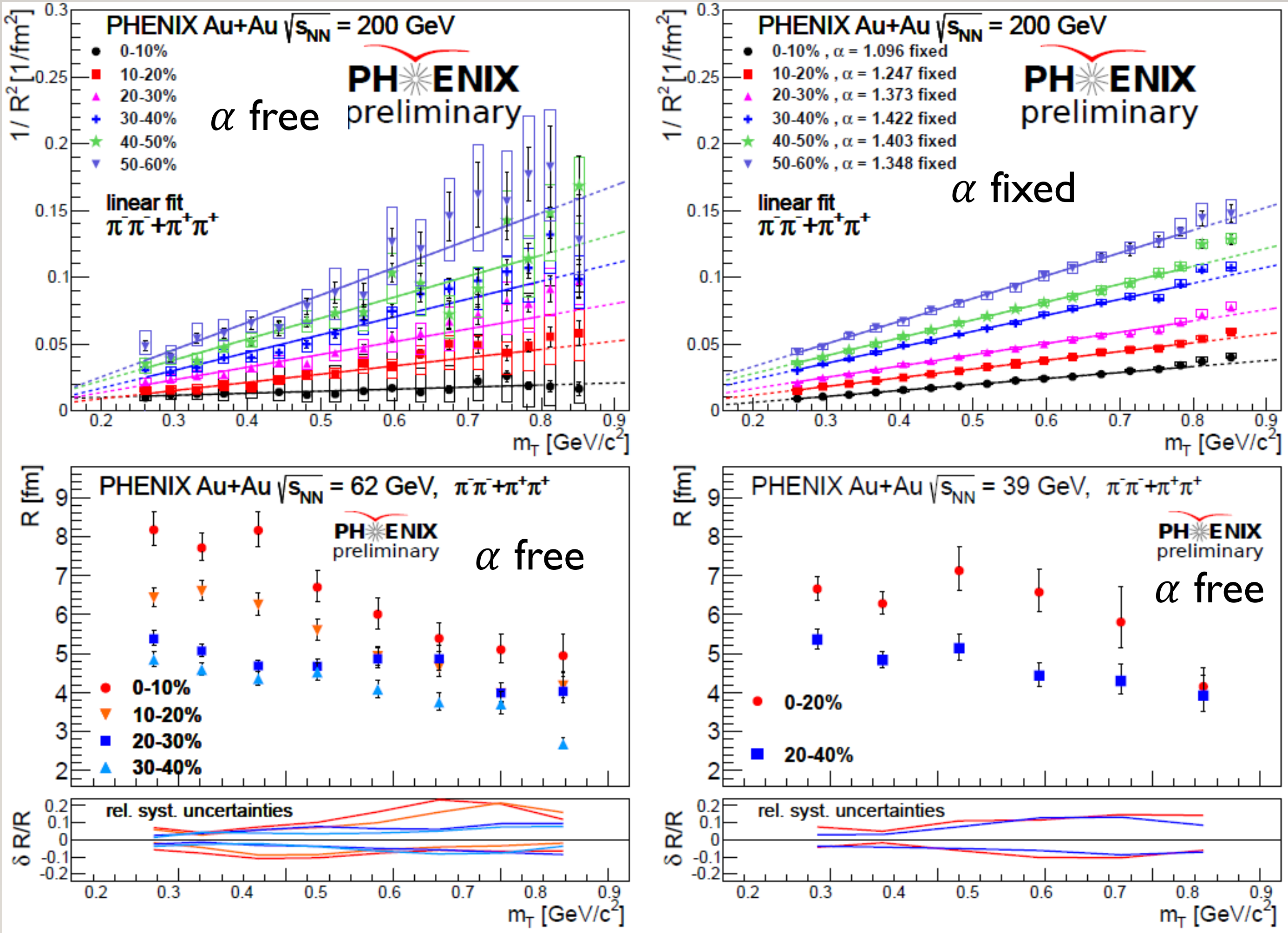
arXiv:1801.08827

arXiv:1711.06891



LEVY R: SIMILAR HYDRO TRENDS FOR ALL CASES

arXiv:1801.08827
arXiv:1711.06891

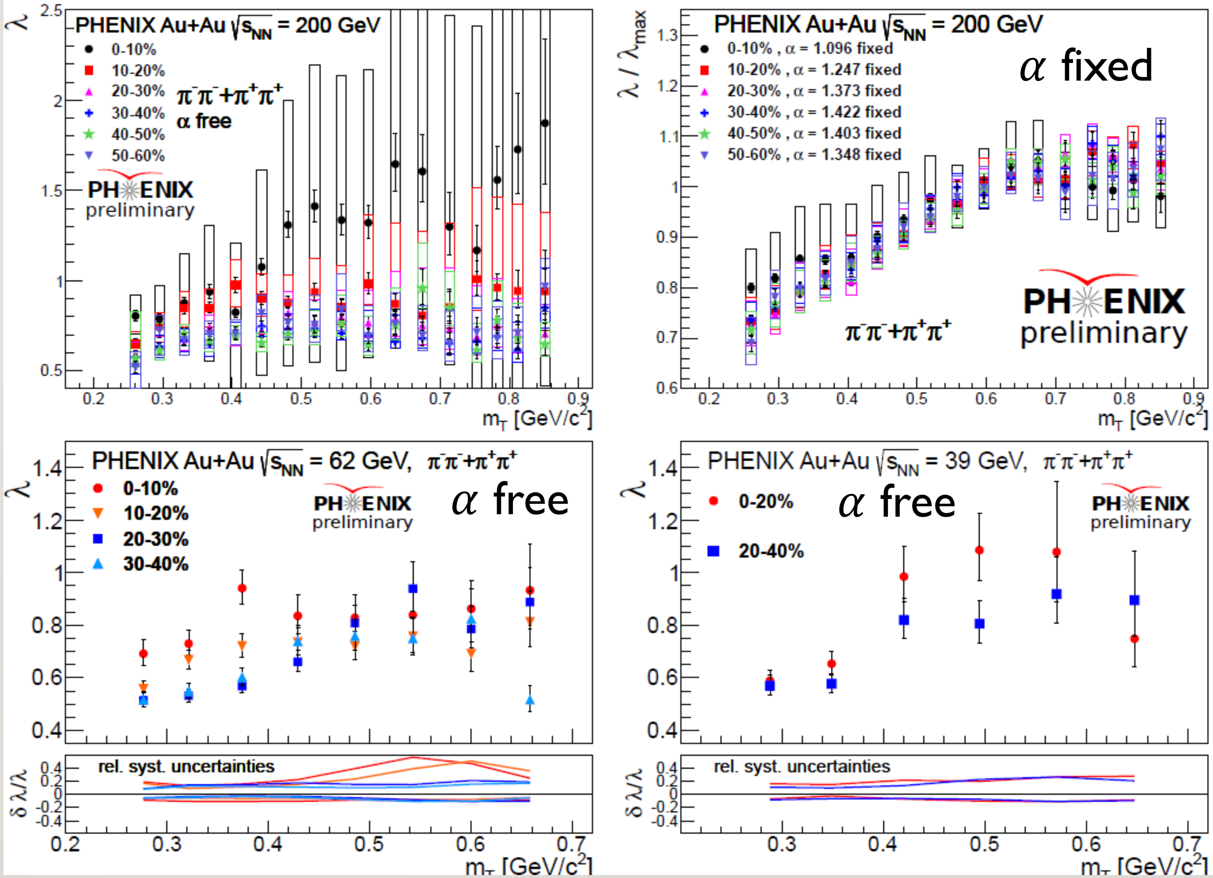


HOLE IN $\lambda(m_T)$:ALL INVESTIGATED ENERGIES

- Hole apparent for $\sqrt{s_{NN}} \geq 39$ GeV, all centralities
- Due to reduced η' mass?
- Sign for chiral restoration?
- To be cross-checked with photons, dileptons, etc.
- No hole found at SPS (Beker et al., PRL74)

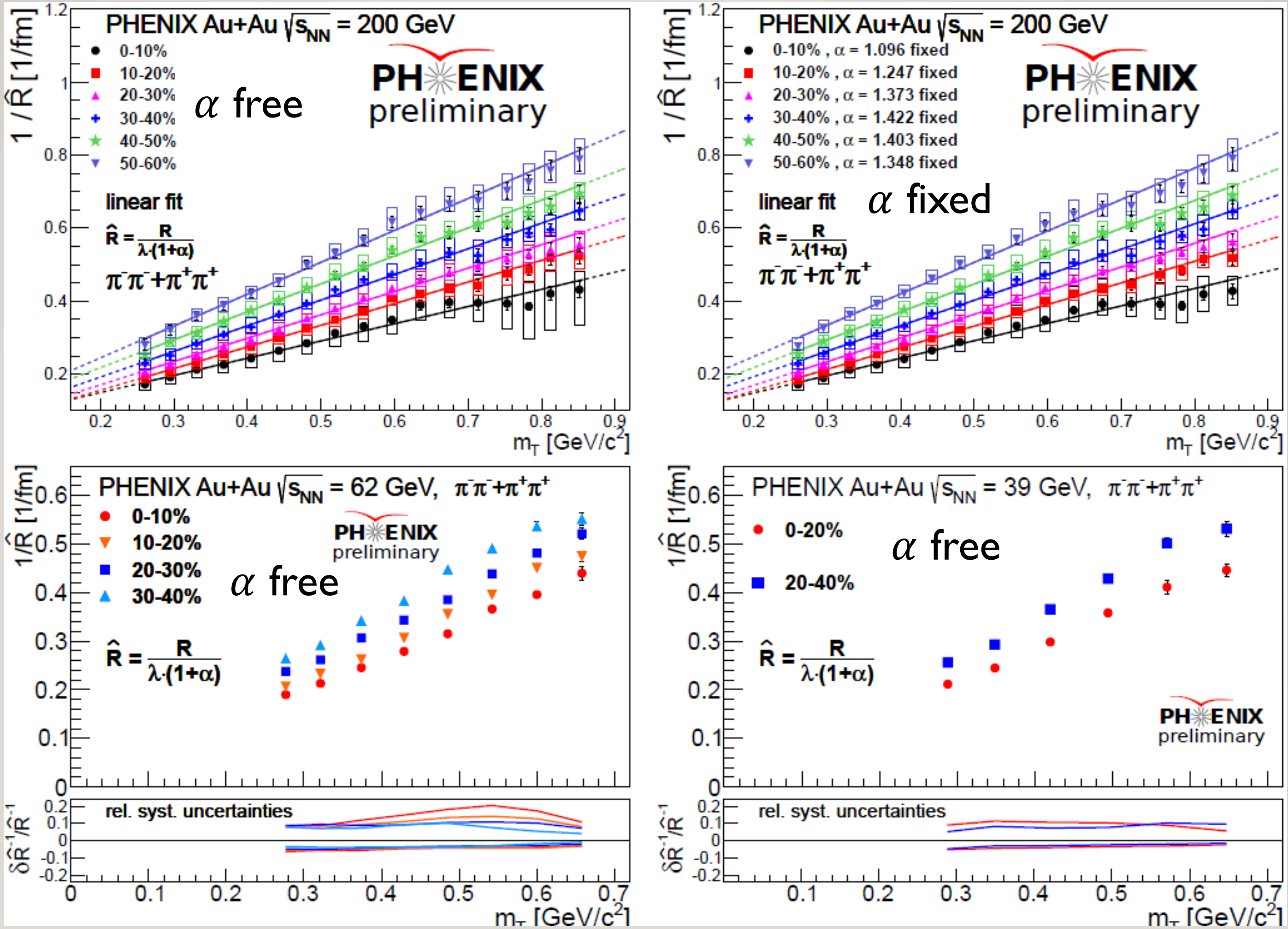
arXiv:1801.08827

arXiv:1711.06891



$\hat{R}$ SCALING: ALL ENERGIES AND CENTRALITIES

arXiv:1801.08827
arXiv:1711.06891



THREE-PION CORRELATIONS: MOTIVATION

- Recall: two particle correlation strength $\lambda = f_C^2$ where $f_C = N_{\text{core}}/N_{\text{total}}$
- Generalization for higher order correlations: $\lambda_2 = f_C^2, \lambda_3 = 2f_C^3 + 3f_C^2$
- If there is partial coherence (p_C):

$$\lambda_2 = f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$

$$\lambda_3 = 2f_C^3[(1-p_C)^3 + 3p_C(1-p_C)^2] + 3f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$

- Introduce core-halo independent parameter $\kappa_3 = \frac{\lambda_3 - 3\lambda_2}{2\sqrt{\lambda_2}^3}$
  - does not depend on f_C
  - $\kappa_3 = 1$ if no coherence
- Finite meson sizes?

  Gavrilik, SIGMA 2 (2006) 074 [hep-ph/0512357]

- Phase shift (a la Aharonov-Bohm) in hadron gas?

EXAMPLE CORRELATION FUNCTION FITS

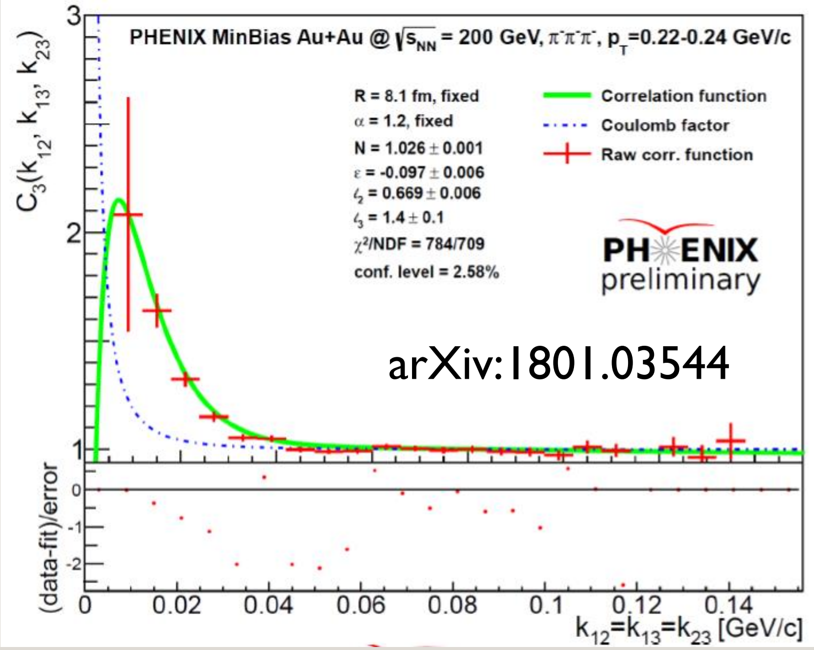
- Coulomb-correction: generalized Riverside method

$$K_3(Q_{12},Q_{23},Q_{31}) \approx K_2(Q_{12})K_2(Q_{23})K_2(Q_{31})$$

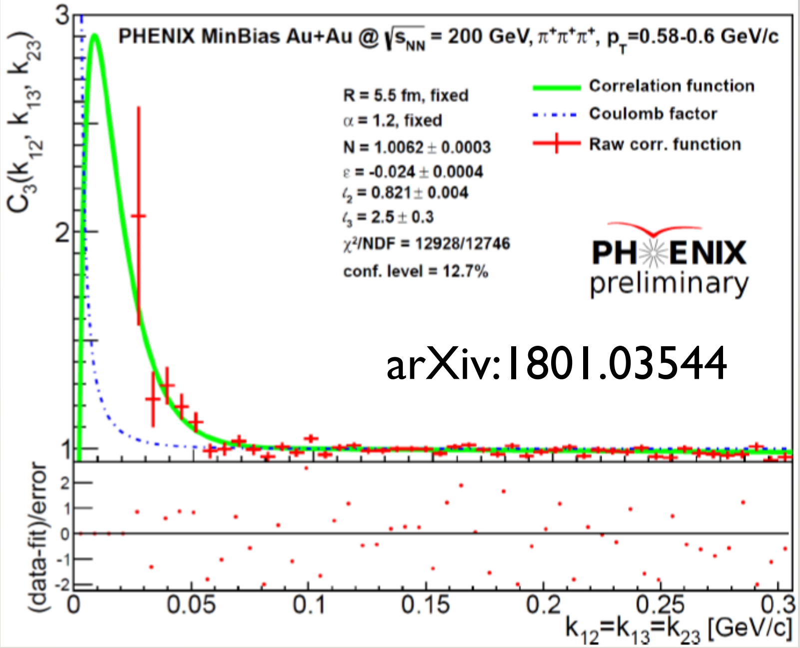
- Pure Bose-Einstein part:

$$1+\ell_2\left(e^{-(RQ_{12})^\alpha}+e^{-(RQ_{23})^\alpha}+e^{-(RQ_{31})^\alpha}\right)+\ell_3 e^{-0.5\left((RQ_{12})^\alpha+(RQ_{23})^\alpha+(RQ_{31})^\alpha\right)}$$

- Fitted $\ell_{2,3}$ only, R,α fixed from two-pion results



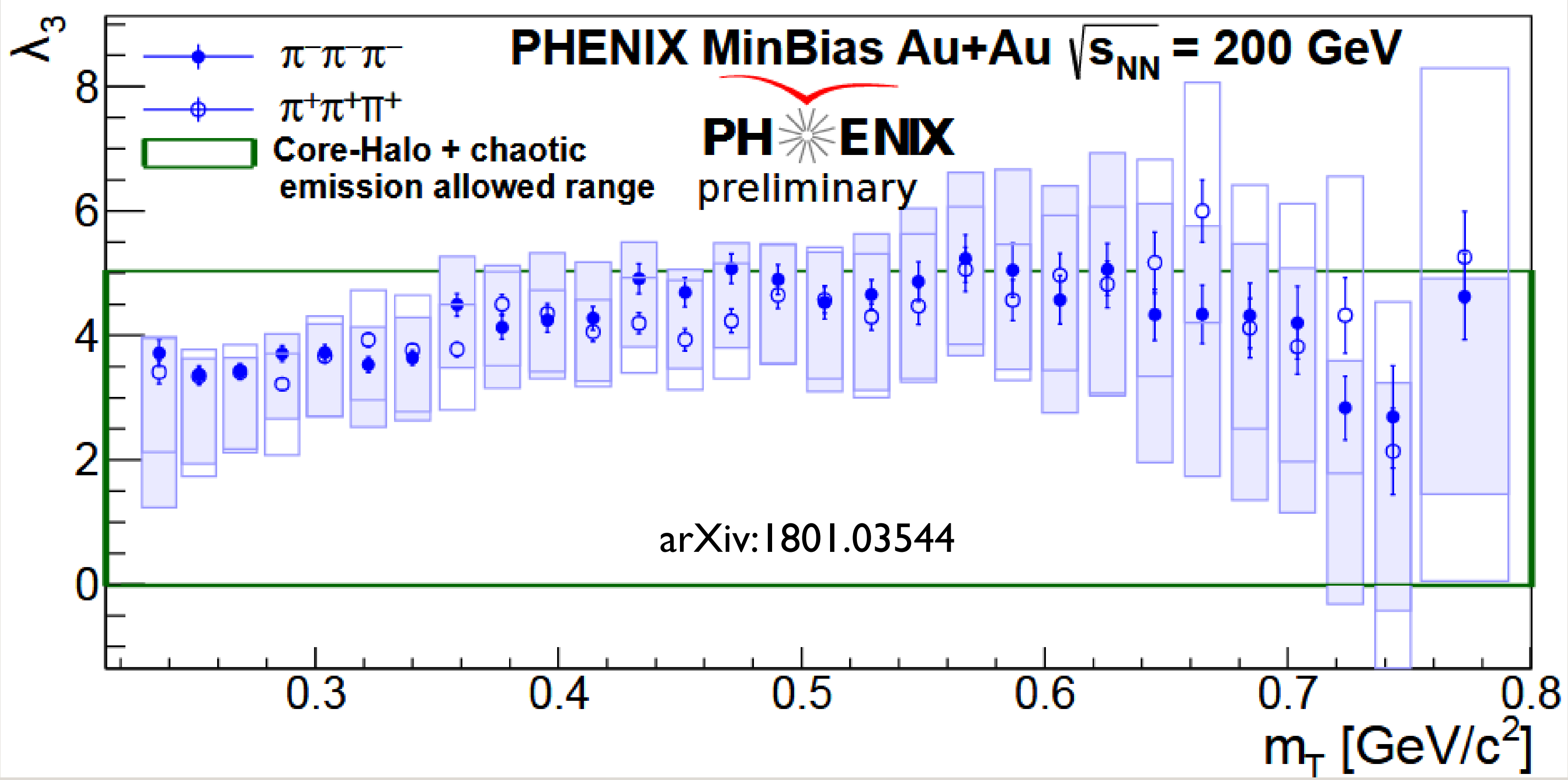
arXiv:1801.03544



arXiv:1801.03544

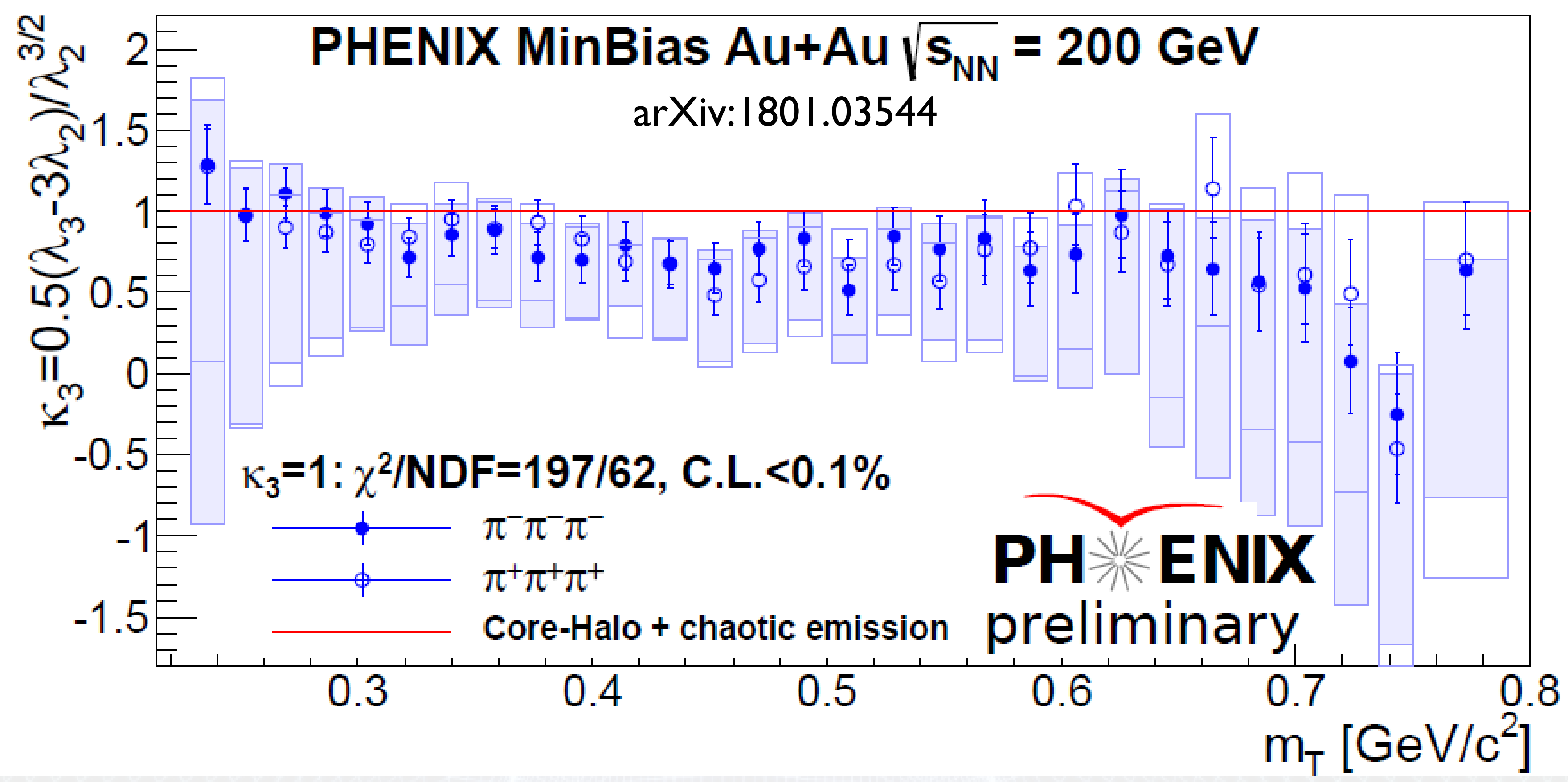
THREE-PION CORRELATION STRENGTH

- Core-halo model, with or without coherence: $0 \leq \lambda_3 \leq 5$



TEST OF CORE-HALO MODEL / COHERENCE

- Recall: $\kappa_3 = 1$ in pure core-halo model, $\kappa_3 \neq 1$ if coherence



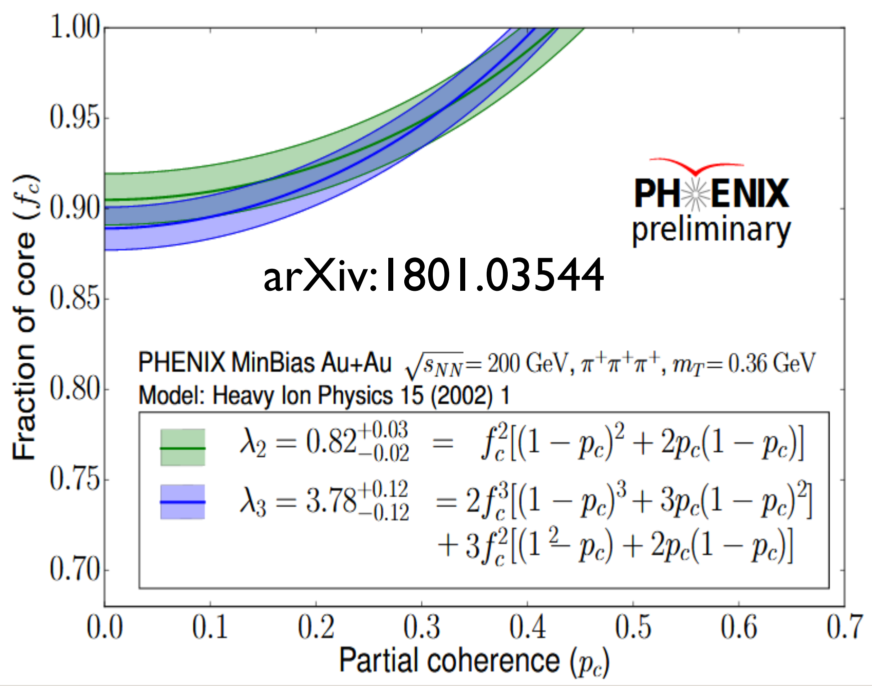
DETERMINE CORE AND COHERENCE FRACTION

- Recall:

$$\lambda_2 = f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$

$$\lambda_3 = 2f_C^3[(1-p_C)^3 + 3p_C(1-p_C)^2] + 3f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$

- Calculate f_C, p_C from $\lambda_{2,3}$ at given m_T
- Strong correlation: test allowed regions on (f_c, p_C) from $\lambda_{2,3}$
- If indeed coherence: should be centrality dependent!
- Higher order correlations?



arXiv:1801.03544

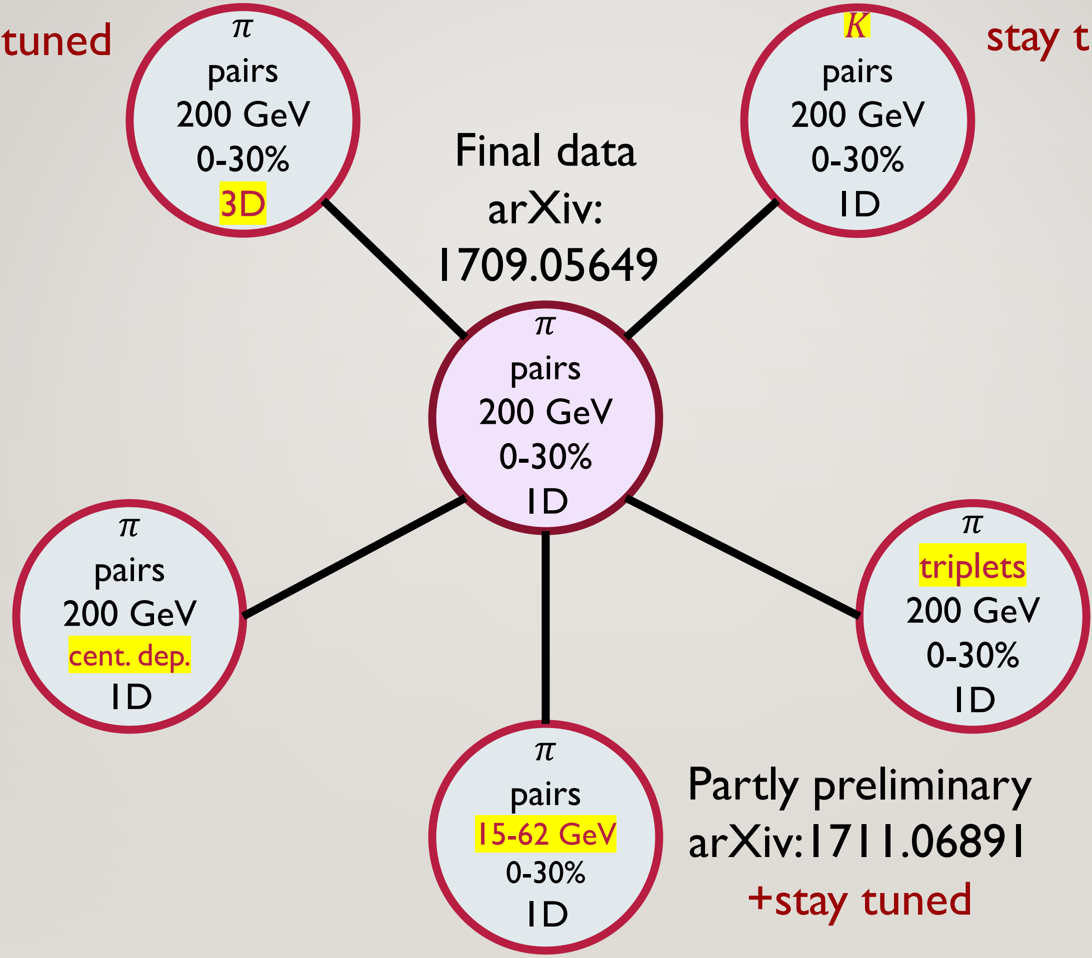
LÉVY HBT STATUS FROM 39 TO 200 GEV

- Bose-Einstein correlations measured from 39 to 200 GeV
- Levy fits yield statistically acceptable description
- Levy parameters R, λ, α: m_T, centrality and $\sqrt{s_{NN}}$ dependence
    - Scale parameter α:
      slight m_T and $\sqrt{s_{NN}}$ dependence, non-monotonic vs Npart,
    - Linear scaling of $1/R^2$ vs m_T ↔ hydro (but non-Gaussian source!)
    - Low-m_T decrease in $\lambda(m_T)$ down to 39 GeV ↔ in-medium η’ mass?
    - New, empirically found scaling parameter $\hat{R} = R/(\lambda \cdot (1+\alpha))$
- Three-particle correlations
    - Consistent with two-pion data
    - Core-halo independent parameter κ_3: sign of coherence?

OPEN QUESTIONS

- Collision energy and centrality dependence?
  - Non-monotonicity in $\alpha(\sqrt{s_{NN}})$ or $\alpha(\text{centrality})$? Hole in $\lambda(m_T)$ at low $\sqrt{s_{NN}}$? Really due to η'?
  - Lower energies (<39 GeV) currently analyzed, filtering η' decay products investigated
- How does the shape look in 3D (out-side-long)?
  - Is the Lévy exponent still around unity?
  - How are the radii modified as compared to Gaussian ones? The $1/R^2{\sim}mT$ scaling still valid?
  - $R^2_{\text{out}} - R^2_{\text{side}}$ non-monotonicity modified if R is the Lévy scale?
- What about kaons?
  - What is the Lévy exponent for kaons?
  - Kaons have smaller total cross-section thus larger mean free path, heavier tail?
  - Does m_T scaling hold for Lévy scale R?
- Correlation strenght versus core-halo picture: are there other effects?
  - Three-particle correlations may show if coherence or other effects play a role
  - Other effects may also play a role (finite meson sizes, random field phase shift, etc)

LÉVY HBT WITH PHENIX



stay tuned

π
pairs
200 GeV
0-30%
3D

K
pairs
200 GeV
0-30%
1D

stay tuned

Final data
arXiv:
1709.05649

π
pairs
200 GeV
0-30%
1D

Preliminary
arXiv:
1801.08827

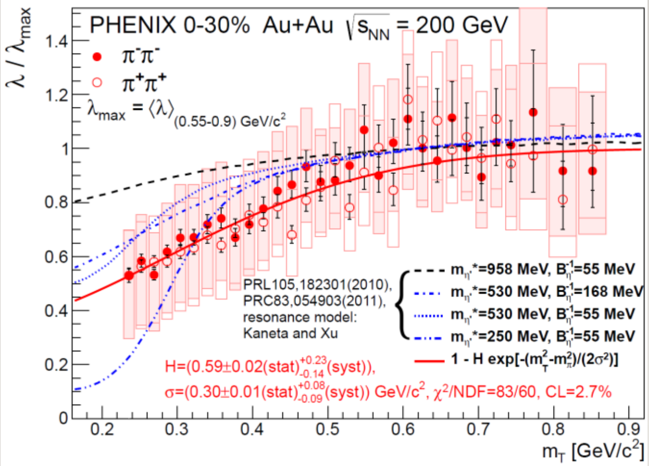
π
pairs
200 GeV
cent. dep.
1D

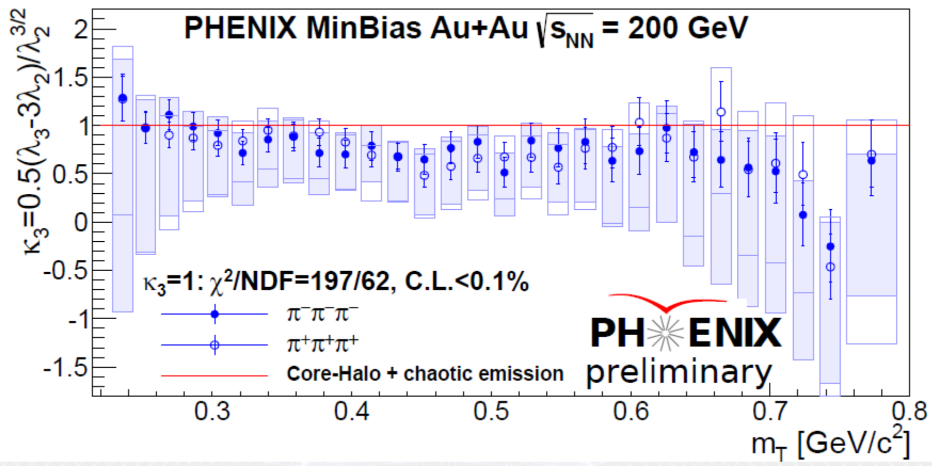
π
triplets
200 GeV
0-30%
1D

Preliminary
arXiv:
1801.03544

π
pairs
15-62 GeV
0-30%
1D

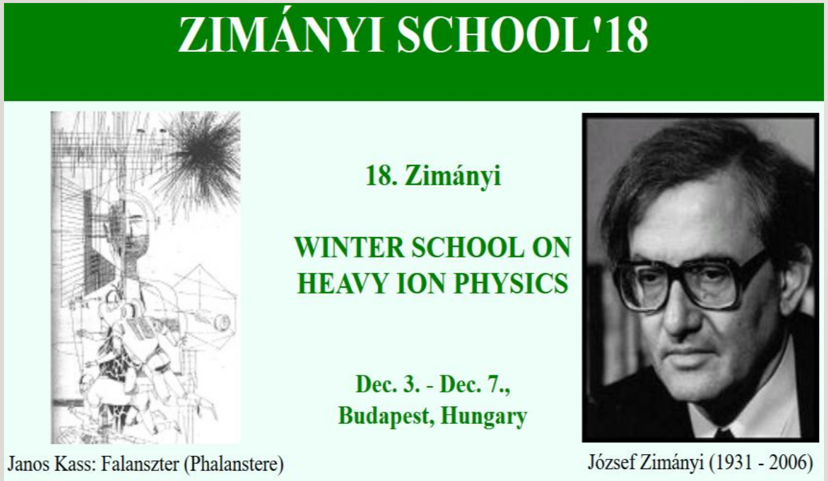
Partly preliminary
arXiv:1711.06891
+stay tuned





THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects, come to:



ZIMÁNYI SCHOOL'18

18. Zimányi

WINTER SCHOOL ON
HEAVY ION PHYSICS

Dec. 3. - Dec. 7.,
Budapest, Hungary

Janos Kass: Falanszter (Phalanstere)

József Zimányi (1931 - 2006)

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XIII Workshop on Particle Correlations and Femtoscopy

22-26 May 2018
Kraków, Poland

http://zimanyischool.kfki.hu/18

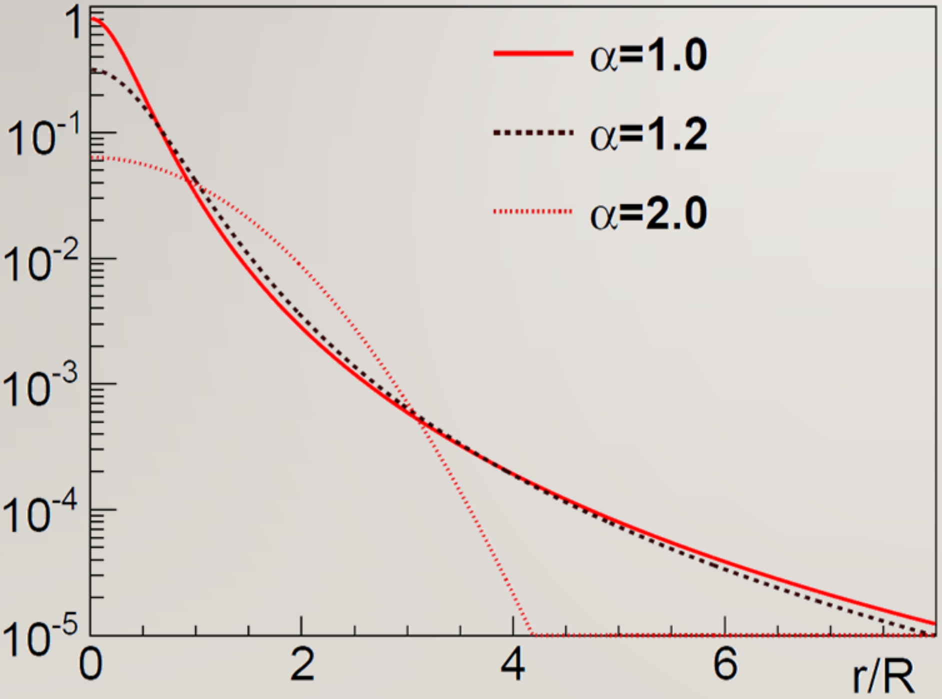
http://indico.ifj.edu.pl/event/199/

BACKUP

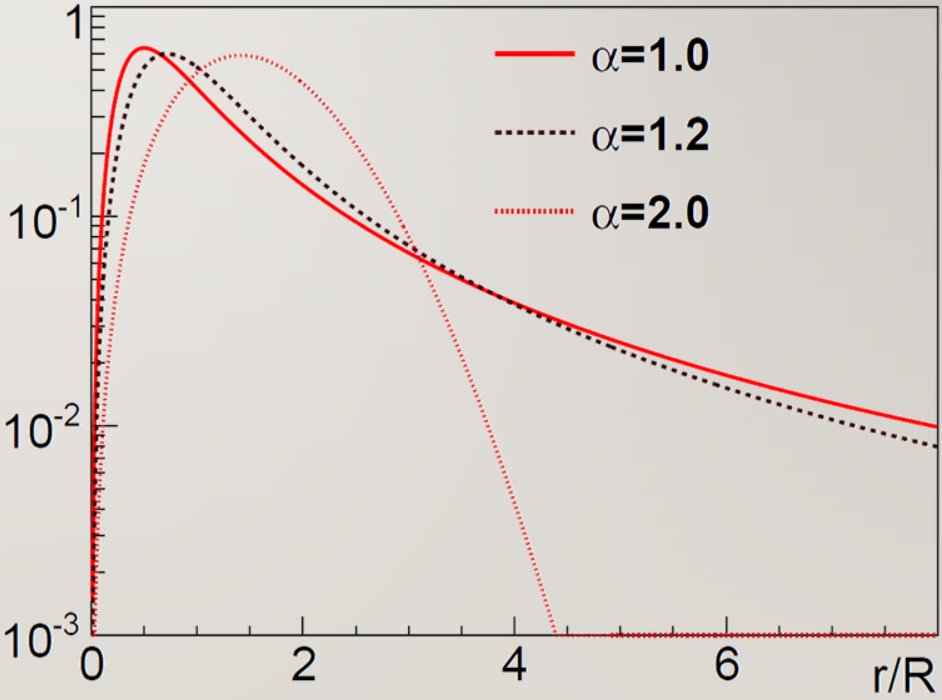
LÉVY VERSUS GAUSS VERSUS EXPONENTIAL

- No tail if $\alpha = 2$, power law if $\alpha < 2$

$R^3 S_{\text{core}}(r)$

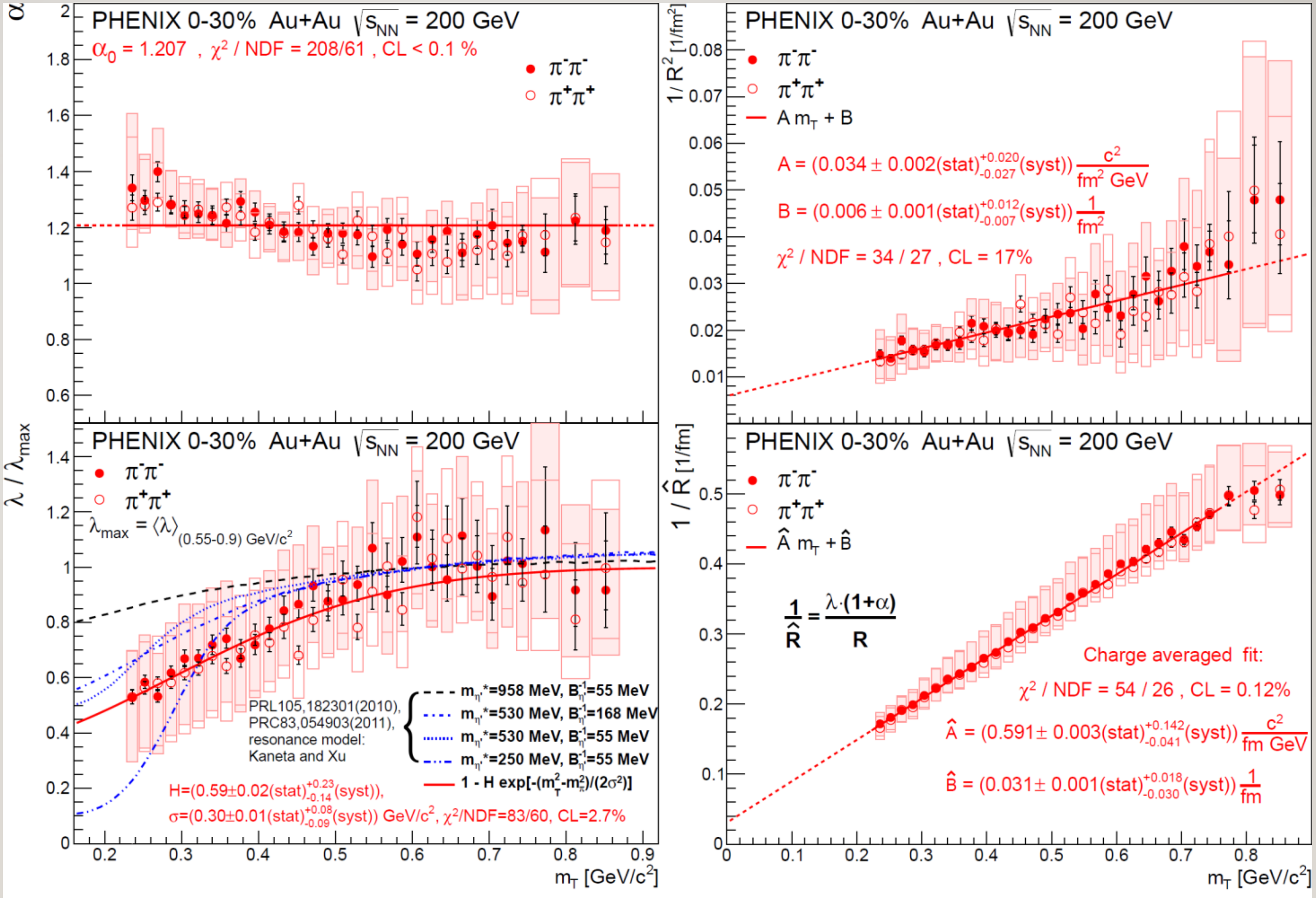


$R 4\pi r^2 S_{\text{core}}(r)$



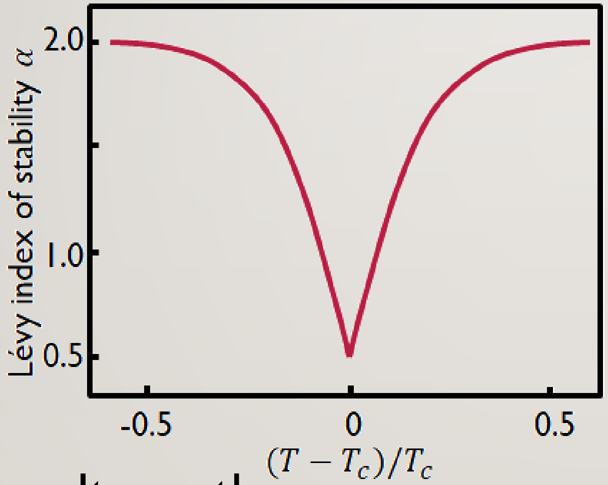
PHYSICAL FIT PARAMETER RESULTS

- α: not 0.5 and not 2.0
- R: hydro scaling
- λ: „hole", compatible with mass modification
- $\hat{R}$: new scaling variable

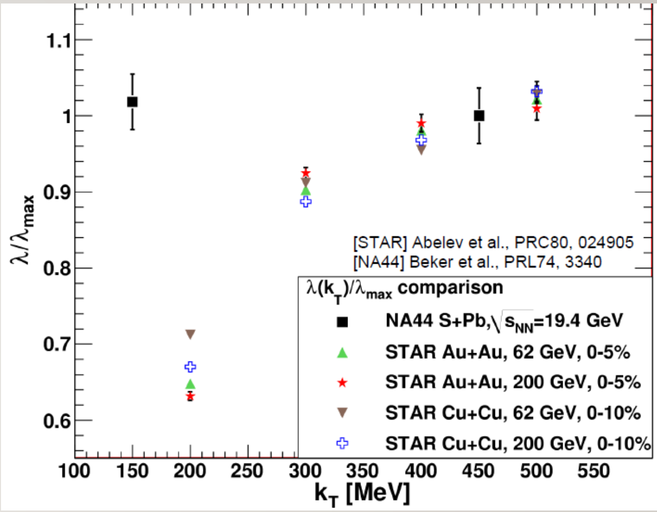


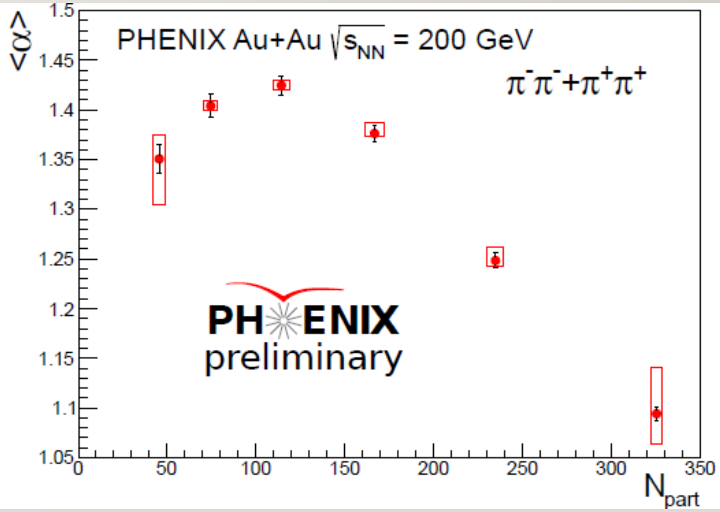
COLL. ENERGY & CENTRALITY DEPENDENCE

- Hole in $\lambda(m_T)$ at lower energies?
  - Filtering of η' decay products to be investigated, based on Eur. Phys. J. A (2011) 47: 76
- Non-monotonicity in α vs centrality or s_{NN}?



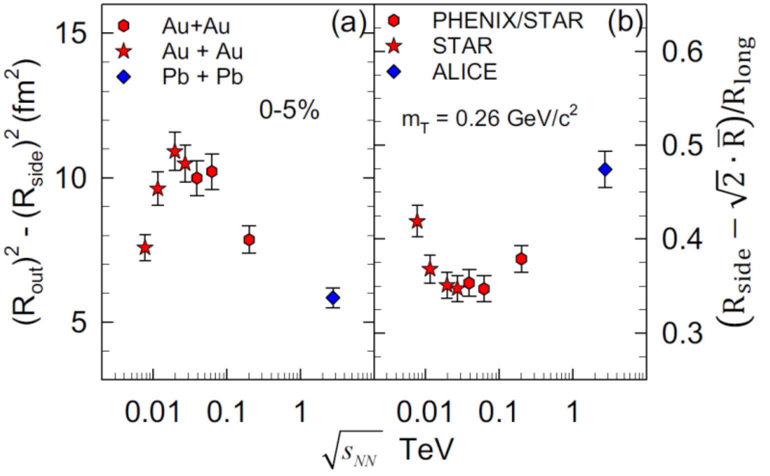
- New results on the way





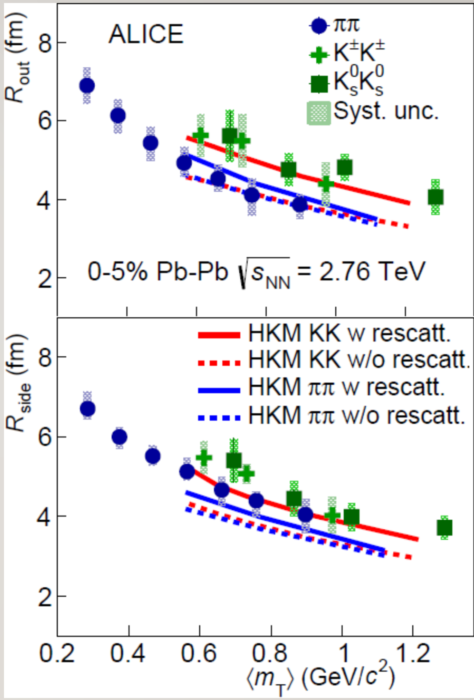
3D ANALYSIS

- B. Kurgyis, M. Csanád
- Lévy radii at 200 GeV:
  - $R_{\mathrm{out}} \approx R_{\mathrm{side}}$ still true for Lévy scales?
  - $1/R^2 \sim m_T$ scaling still true?
- How do Lévy radii change with energy?
  - Non-monotonicity still there in $R^2_{\mathrm{out}} - R^2_{\mathrm{side}}$?
  - α versus energy in 3D: same as for 1D?
- New results on the way

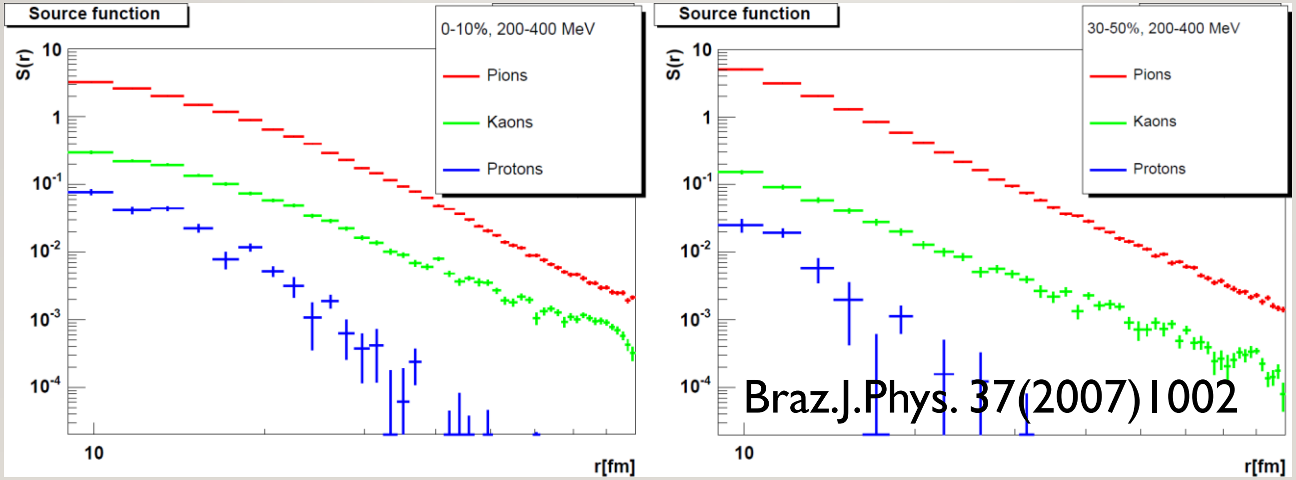


KAON ANALYSIS

- Kaon PID works well
- Transverse mass scaling of Lévy HBT radii for kaons?
- HRC prediction for kaons:
  - Smaller cross-section, larger mean free path, heavier tail
- New results on the way



ALICE Coll. arXiv:1709.01731



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