3 DIMENSIONAL LÉVY FEMTOSCOPY WITH PHENIX

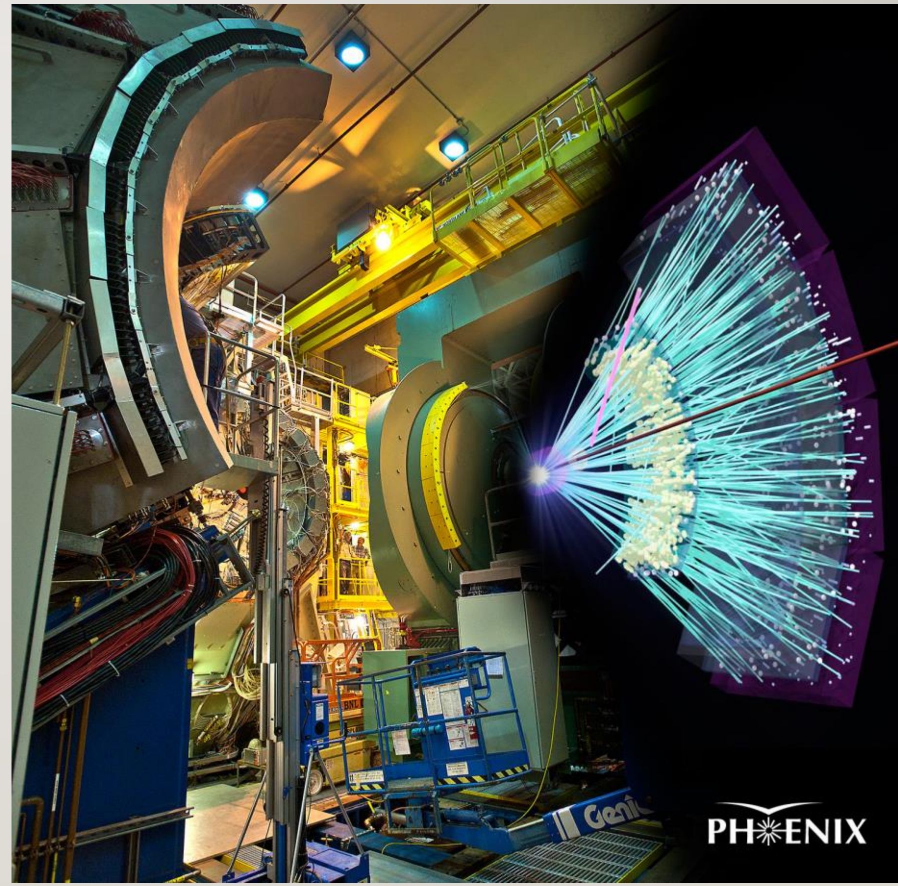
MÁTÉ CSANÁD FOR PHENIX @ WPCF 2018, MAY 24

EÖTVÖS UNIVERSITY, BUDAPEST, HUNGARY

THE PHENIX EXPERIMENT AND THE BES

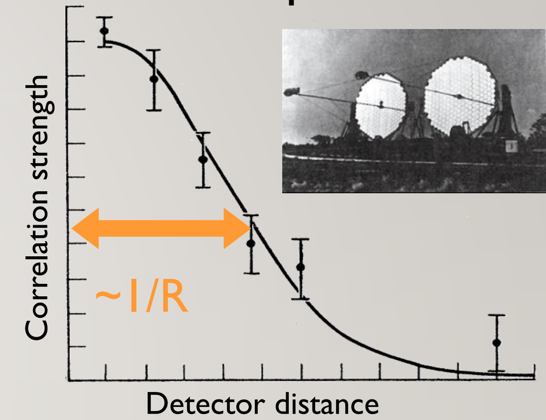
- Collision energies: 7.7 to 200 GeV (20-400 MeV in μ_B, 140-170 MeV in T)
- This talk: 200 GeV Au+Au

$\sqrt{s_{NN}}$ [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								✓	

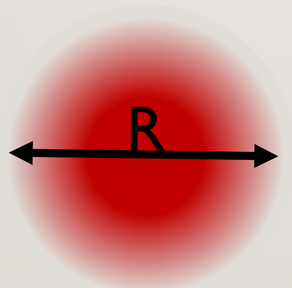


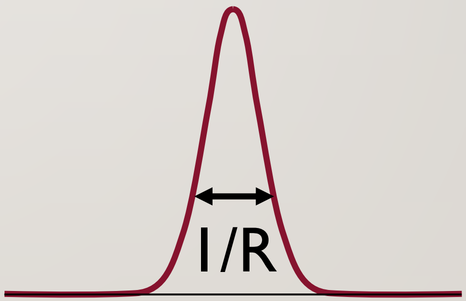
FEMTOSCOPY: THE HBT EFFECT

- 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)



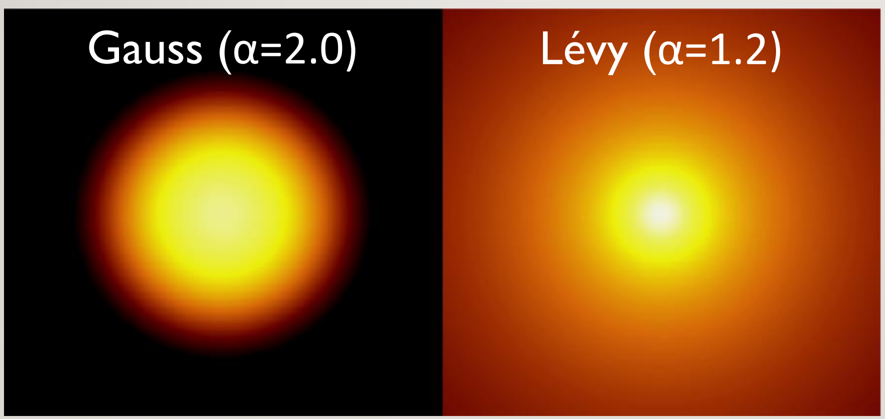


source function S(r)   correlation function C(q)

- 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: $\mathcal{L}(\alpha, R; r) = \frac{1}{(2\pi)^3} \int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$
  - From generalized central limit theorem, power-law tail ~ $r^{-(1+\alpha)}$
  - Special cases: $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy



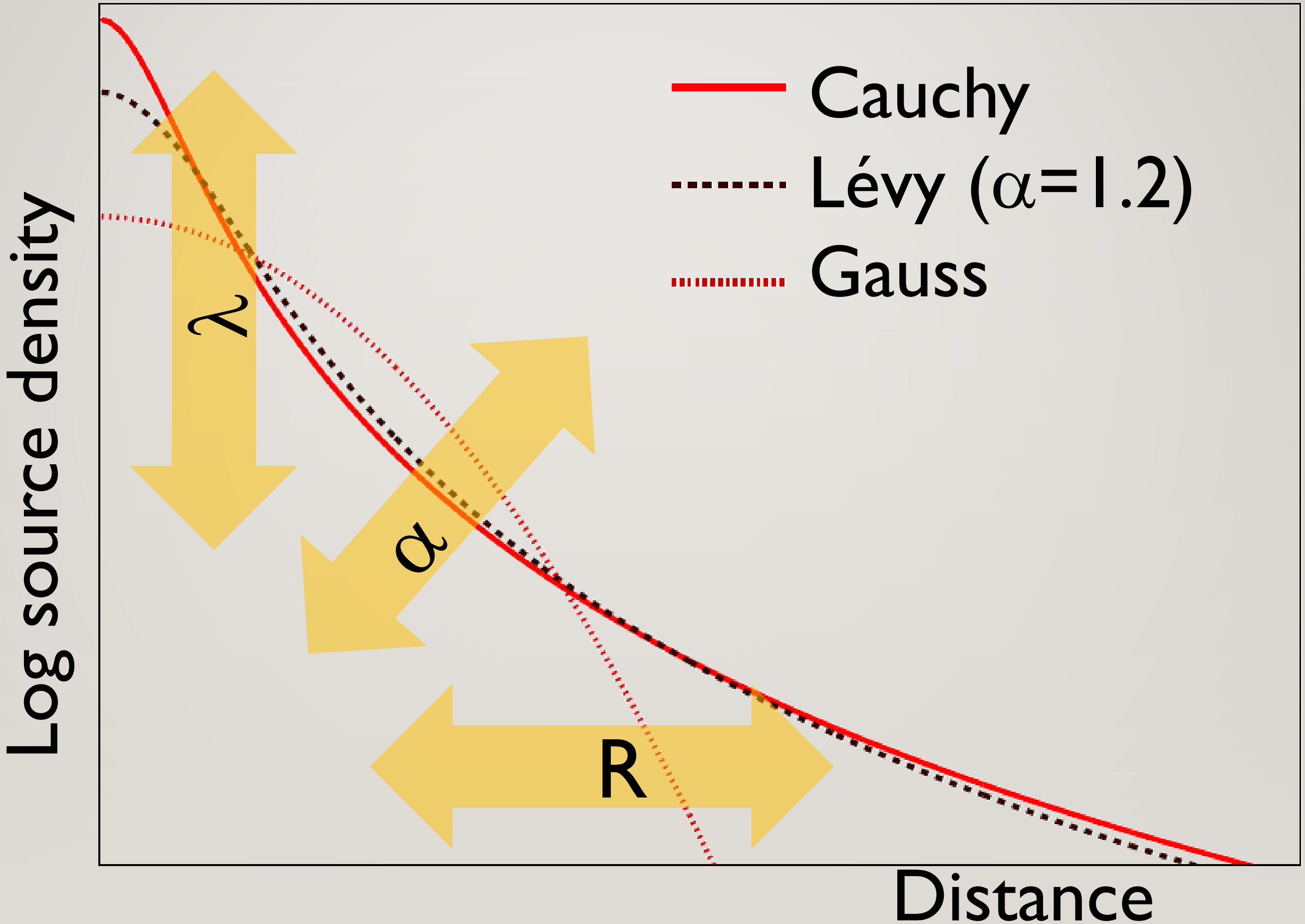
- Shape of the correlation functions with Levy source:

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

$\alpha = 2$: Gaussian
$\alpha = 1$: Exponential

5/22 LÉVY VERSUS GAUSS VERSUS EXPONENTIAL

- No tail if $\alpha = 2$, power law if $\alpha < 2$; correlation between α and R,λ



SPATIAL CORRELATION VERSUS DISTRIBUTION

- Assuming several things (thermal emission, no interactions, etc):

$$C_2(q,K) = \int S\left(r_1, K+\frac{q}{2}\right) S\left(r_2, K-\frac{q}{2}\right) \left|\Psi_2^{(0)}(r_1,r_2)\right|^2 dr_1 dr_2$$
$$\cong 1 + \left|\int S(r,K) e^{iqr} dr\right|^2$$

- Let us introduce pair distribution (a.k.a. spatial correlation)

$$D(r,K) = \int S\left(\rho+\frac{r}{2}, K\right) S\left(\rho-\frac{r}{2}, K\right) d\rho$$

- With this, the correlation function becomes

$$C_2(q,K) \cong \int D(r,K) \left|\Psi_2^{(0)}(r)\right|^2 dr = 1 + \int D(r,K) e^{iqr} dr$$

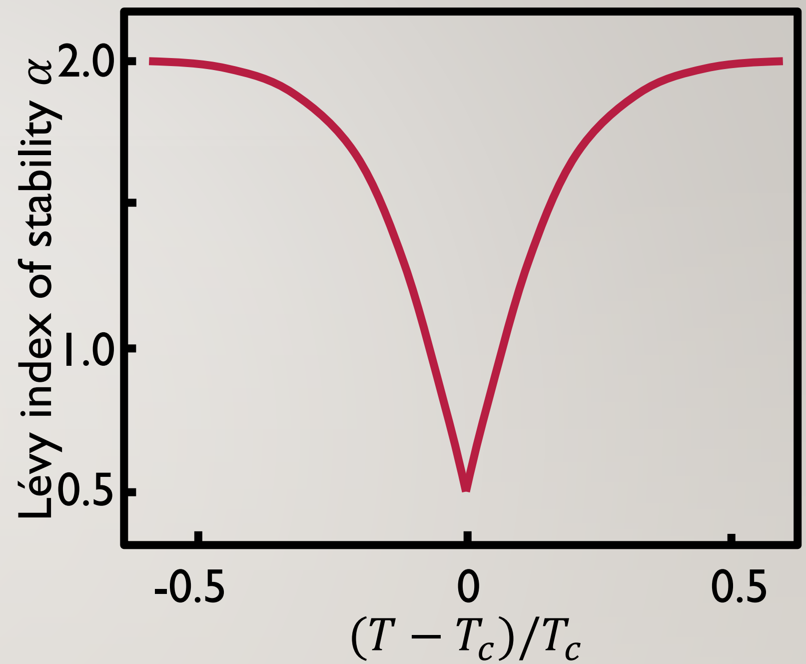
- **Correlation function measures spatial correlation function**

LÉVY INDEX AS A CRITICAL EXPONENT?

- Critical spatial correlation: $\sim r^{-(d-2+\eta)}$; Lévy source: $\sim r^{-(1+\alpha)}$; $\alpha \Leftrightarrow \eta$?

  Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67,
- 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?



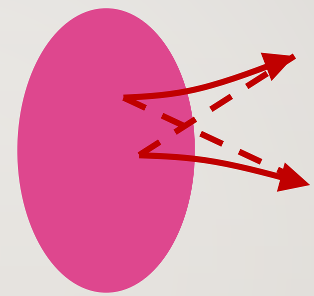
8/22 THE COULOMB-EFFECT

- Plane-wave result, based on $\left|\Psi_2^{(0)}(r)\right|^2 = 1 + e^{iqr}$:

$$C_2(q,K) \cong \int D(r,K)\left|\Psi_2^{(0)}(r)\right|^2 dr = 1 + \int D(r,K)e^{iqr}dr$$

- If interaction:

$$\Psi_2^{(0)}(r) \to \Psi_2^{(\mathrm{int})}(r_1, r_2)$$



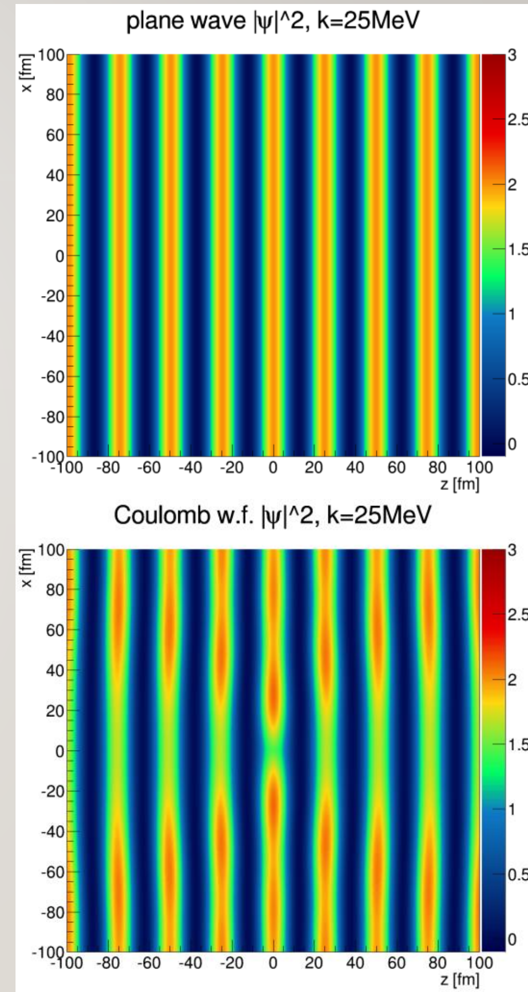
- For Coulomb:

$$\left|\Psi_2^{(C)}(r)\right|^2 = \frac{\pi\eta}{e^{2\pi\eta}-1}\cdot\left(\text{complicated hypergeometric expression}\right)$$

- Direct fit with this, or the usual iterative Coulomb-correction:

$$C_{\mathrm{Bose-Einstein}}(q)K(q), \text{where } K(q) = \frac{\int D(r,K)\left|\Psi_2^{(C)}(r)\right|^2 dr}{\int D(r,K)\left|\Psi_2^{(0)}(r)\right|^2 dr}$$

- In this analyis: assuming spherical source

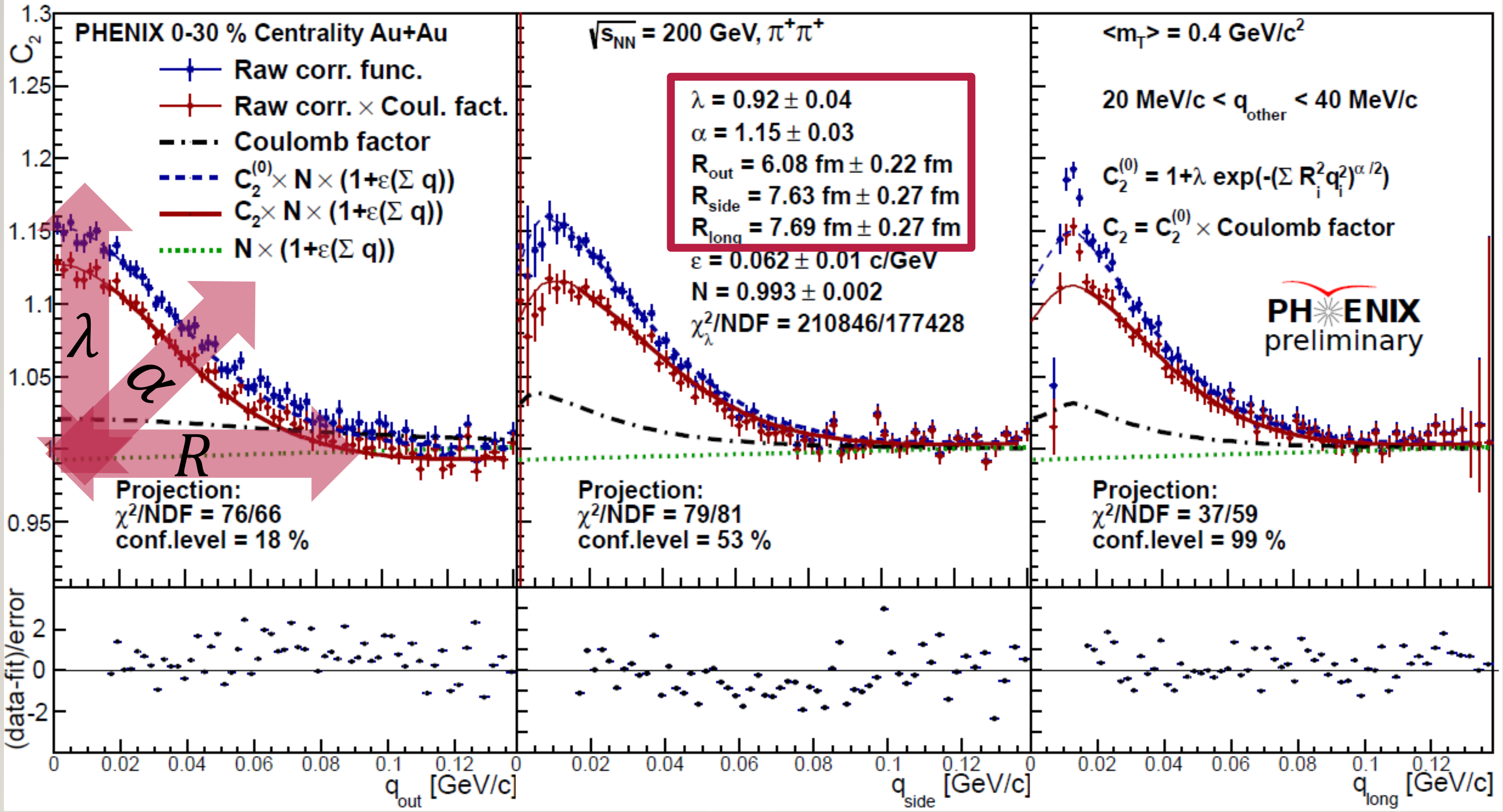


LEVY HBT ANALYSIS

- Dataset used for the analysis:
  - Events: Run-10, Au+Au, $\sqrt{s_{NN}}$ = 200 GeV, 0-30% centrality: ~2 billion events
  - 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 Δϕ - Δz plane for Drift Chamber, PbSc East/West, TOF East/West
- 3D corr. func. as a function of $\vec{q}_{\mathrm{LCMS}}$ in various m_T bins
  - $\vec{q}_{\mathrm{LCMS}}$ is momentum difference longitudinal co-moving frame
  - Using Bertsch-Pratt frame: $\vec{q}_{\mathrm{LCMS}} = \left(q_{\mathrm{out}}, q_{\mathrm{side}}, q_{\mathrm{long}}\right)_{\mathrm{LCMS}}$
  - Levy fits for 31 m_T bins ($0.228 < m_T < 0.871$ GeV/c) with Coulomb effect

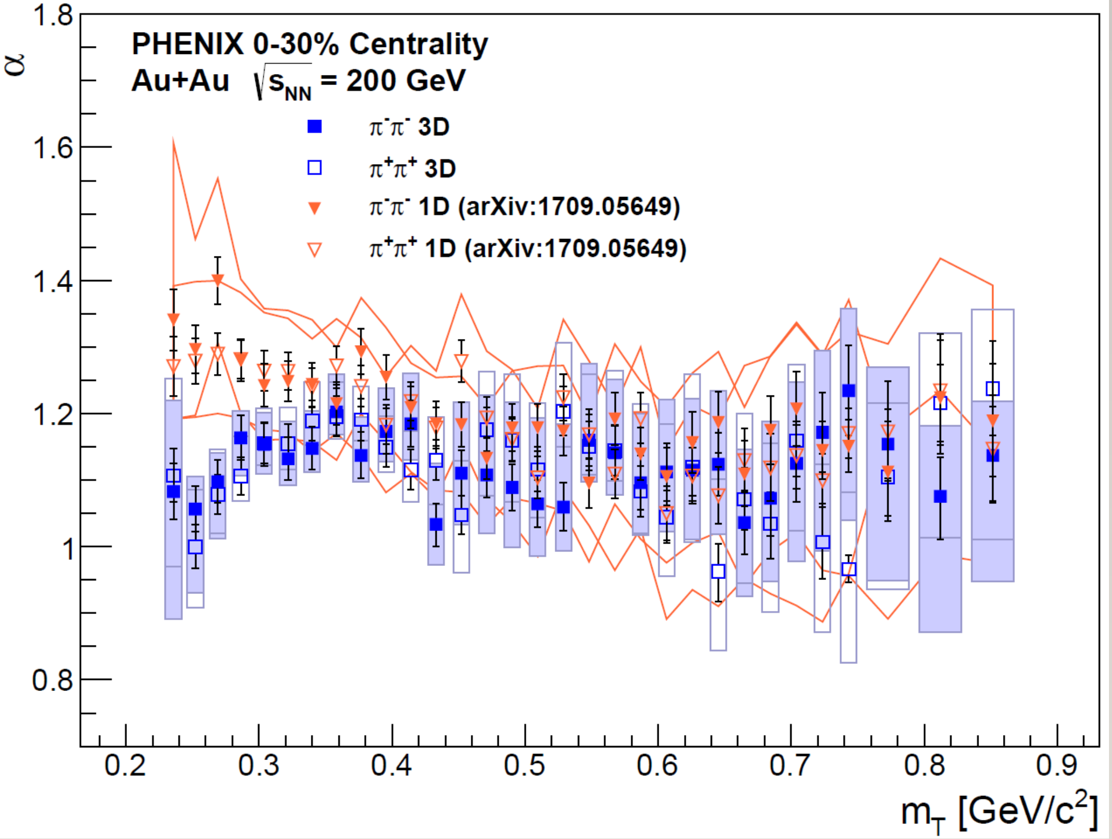
10/22 EXAMPLE $C_2(q_{LCMS})$ CORRELATION FUNCTION

- Fitted 31 m_T bins, modified log-likelihood fit, Coulomb-incorporated function
  E802: Phys.Rev. C66 (2002) 054906 [nucl-ex/0204001]; PHENIX: Phys.Rev.Lett. 93 (2004) 152302 [nucl-ex/0401003]
- Physical parameters: R, λ, α measured versus pair m_T



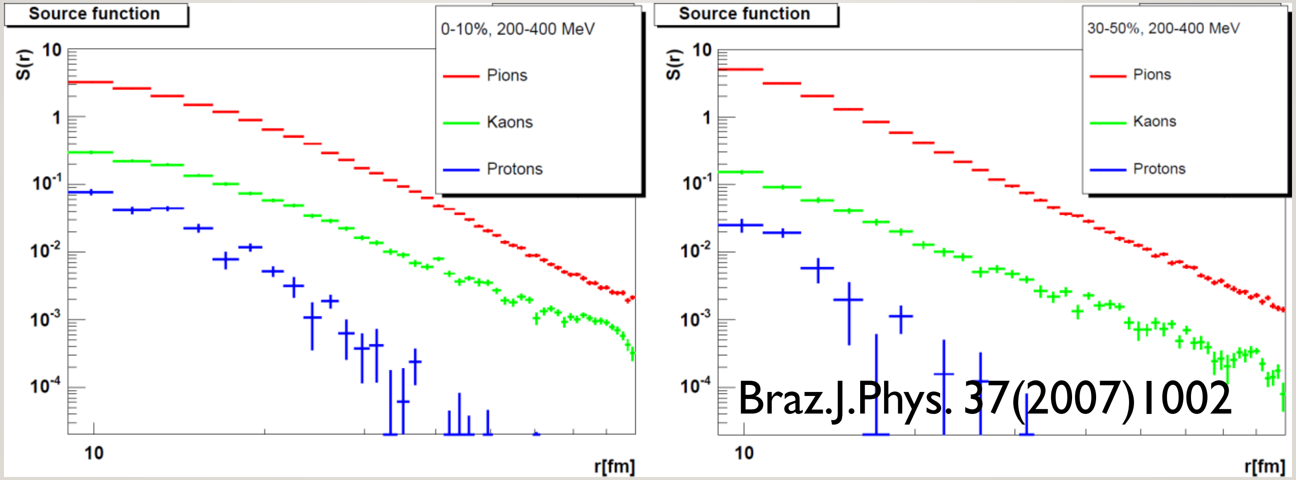
LÉVY EXPONENT (SHAPE PARAMETER) α

- Compatible with 1D (Q_{LCMS}) measurement of arXiv:1709.05649
- 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?



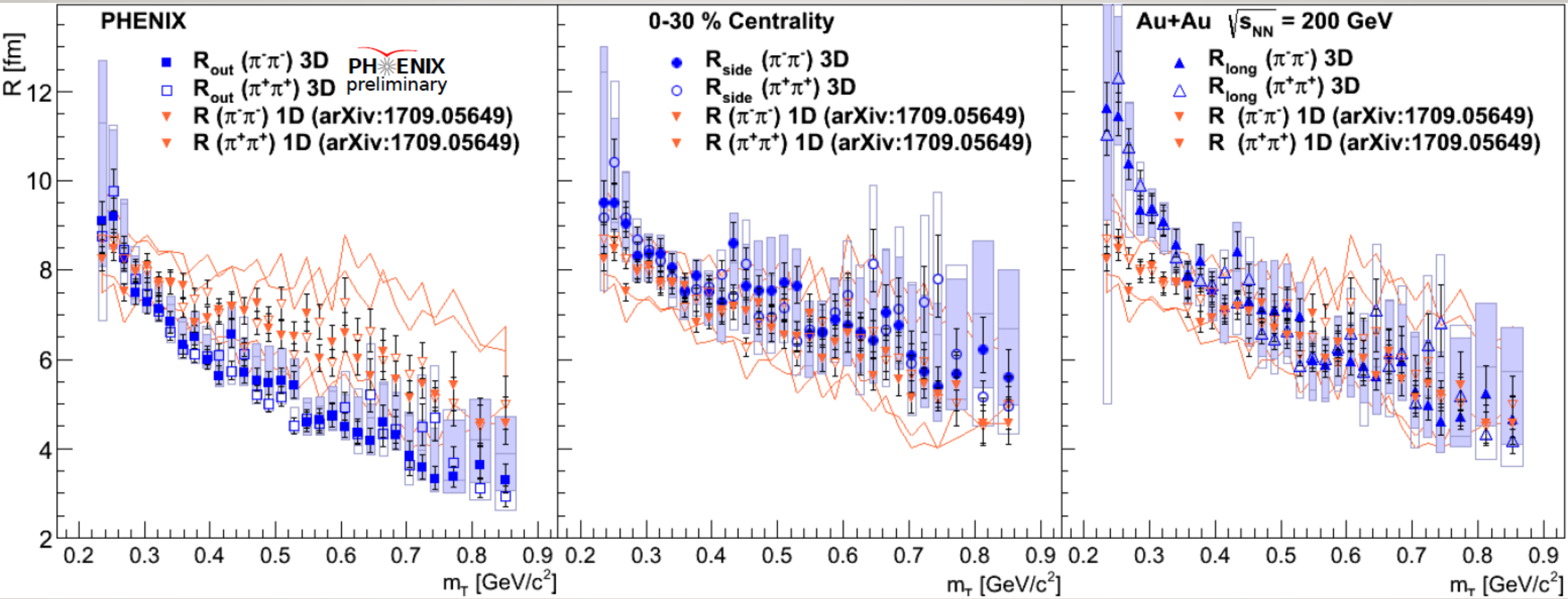
THE IMPORTANCE OF A KAON ANALYSIS

- Kaons: smaller cross-section, larger mean free path
- Heavier power-law tail?
- Prediction for π,K,p based on Humanic's Resonance Model (HRM): anomalous diffusion due to rescattering
  Humanic, Int.J.Mod.Phys. E15 (2006) 197 [nucl-th/0510049]
  Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002 [hep-ph/0702032]



- R_{HBT}(Kaon) mT-scaling or its violation for Lévy scale R?

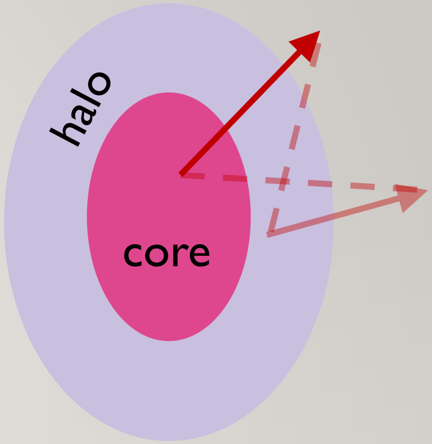
LÉVY SCALE PARAMETER R



- Compatibility with 1D Lévy analysis
- Similar decreasing trend as Gaussian HBT radii, but it is not an RMS radius!
  - There is no 2nd moment (variance or root mean square) for Lévy distributions with α<2!
- Asymmetric source for small mT, validity of Coulomb-approximation?

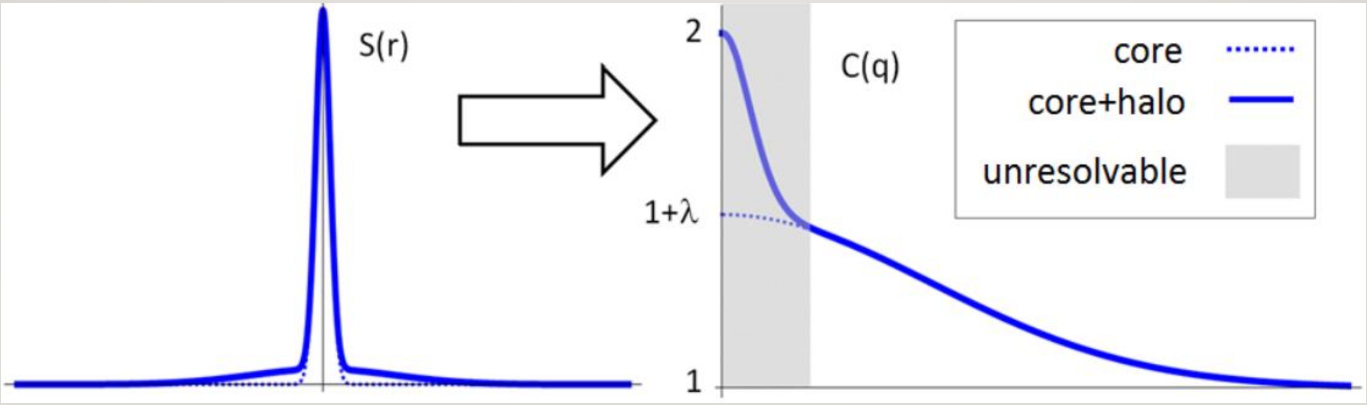
CORRELATION STRENGTH λ: CORE FRACTION

- Two-component source
  - Core: hydrodynamically expanding, thermal medium
  - Halo: long lived resonances (≳ 10 fm/c, ω,η,η',K_0^S,...), unresolvable experimentally
  - Define $f_C = N_{\text{core}}/N_{\text{total}}$
- True $q \to 0$ limit: $C(0) = 2$
- Apparently $C(q \to 0) \to 1 + \lambda$
- $\lambda(m_\text{T}) = f_C^2(m_\text{T})$



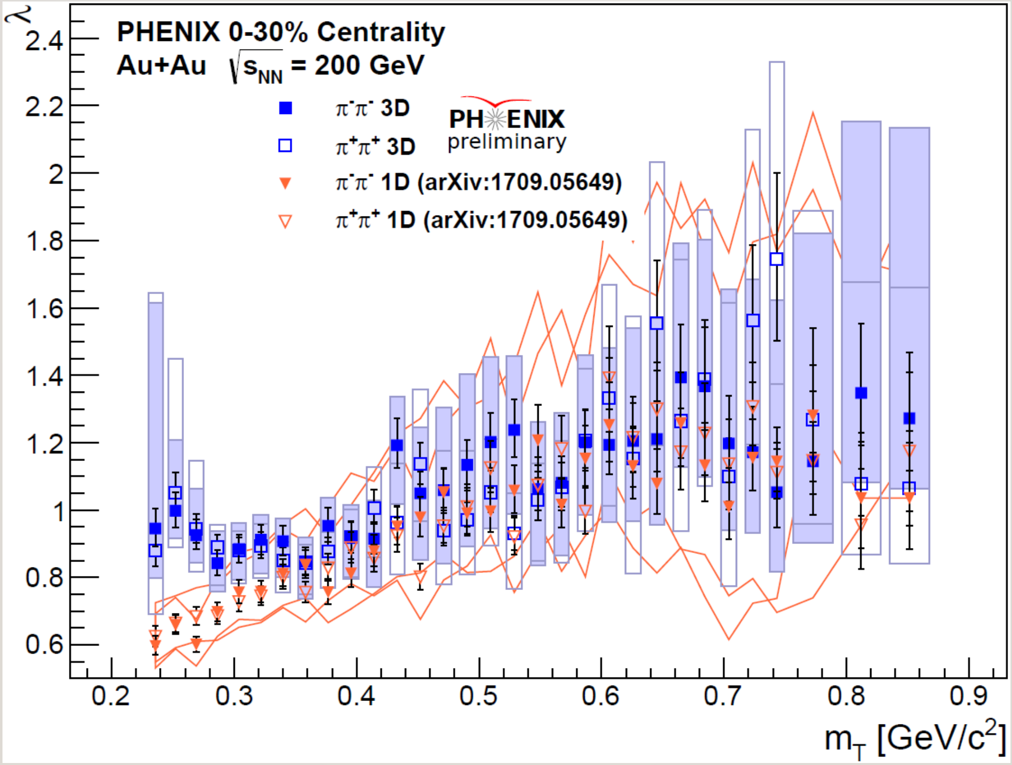
Bolz et al, Phys.Rev. D47 (1993) 3860-3870

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



15/22 LÉVY CORRELATION STRENGTH λ

- Compatibility of 1D and 3D results: low-mT decrease
- Small discrepancy at small mT: due to large Rlong at small mT?

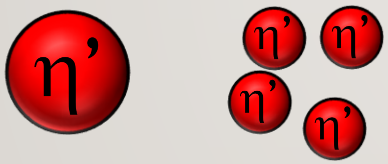


16/22 REMINDER: RELATION TO IN-MEDIUM η’ MASS

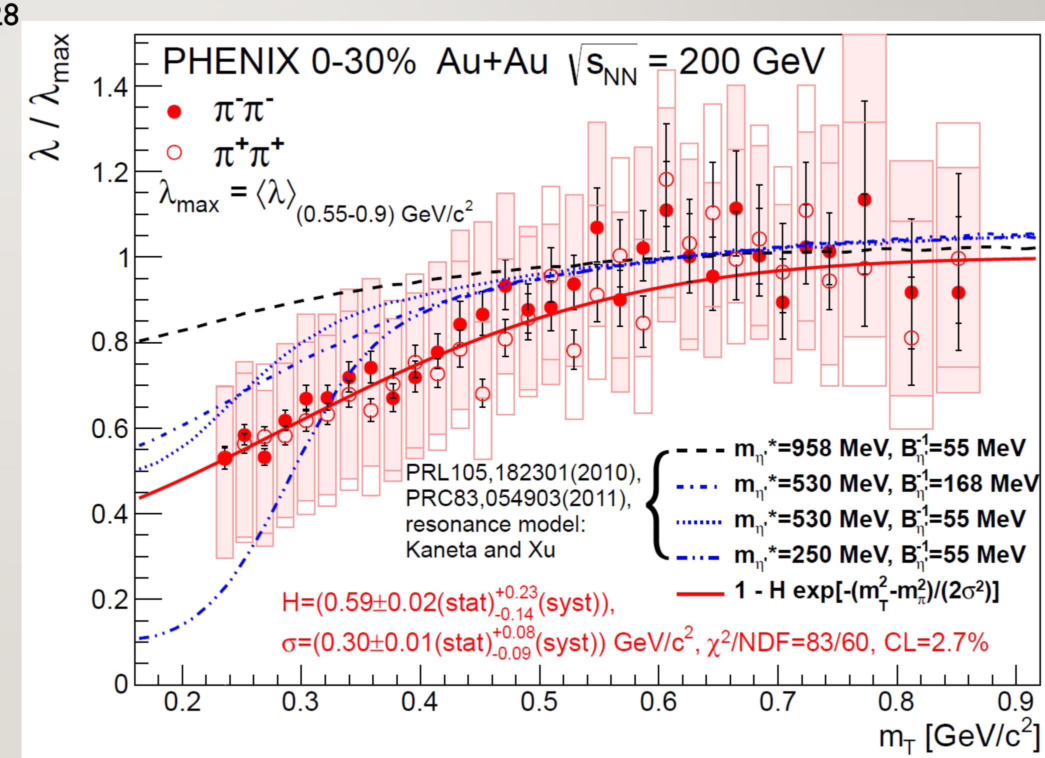
- Connection to chiral restoration
  - Decreased η’ mass → η’enhancement → halo enhancement
  - Kinematics: η’ → ππππ with low m_T → decreased $\lambda(m_T)$ at low m_T
  - Dependence on in-medium η’ mass?

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

  - 3D results compatible with 1D



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



SIDE-NOTE: THREE-PION LÉVY HBT

- 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):

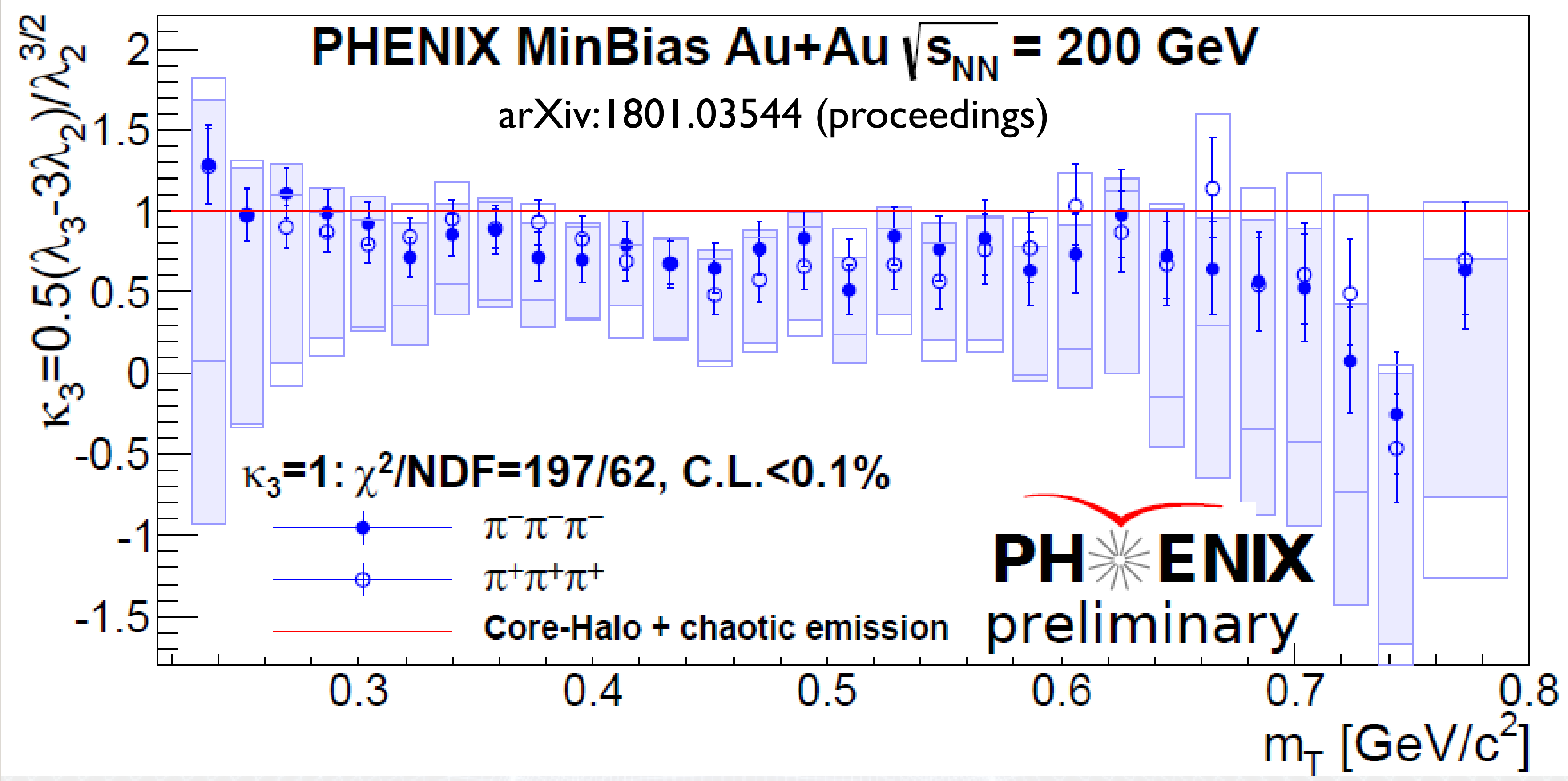
$$\lambda_2 = f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$
$$\lambda_3 = 2f_C^3[(1-p_C)^3 + 3p_C(1-p_C)^2] + 3f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$

- 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?
  - Random fields create random phase shift, on average distorts Bose-Einstein correlations

TEST OF CORE-HALO MODEL / COHERENCE

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



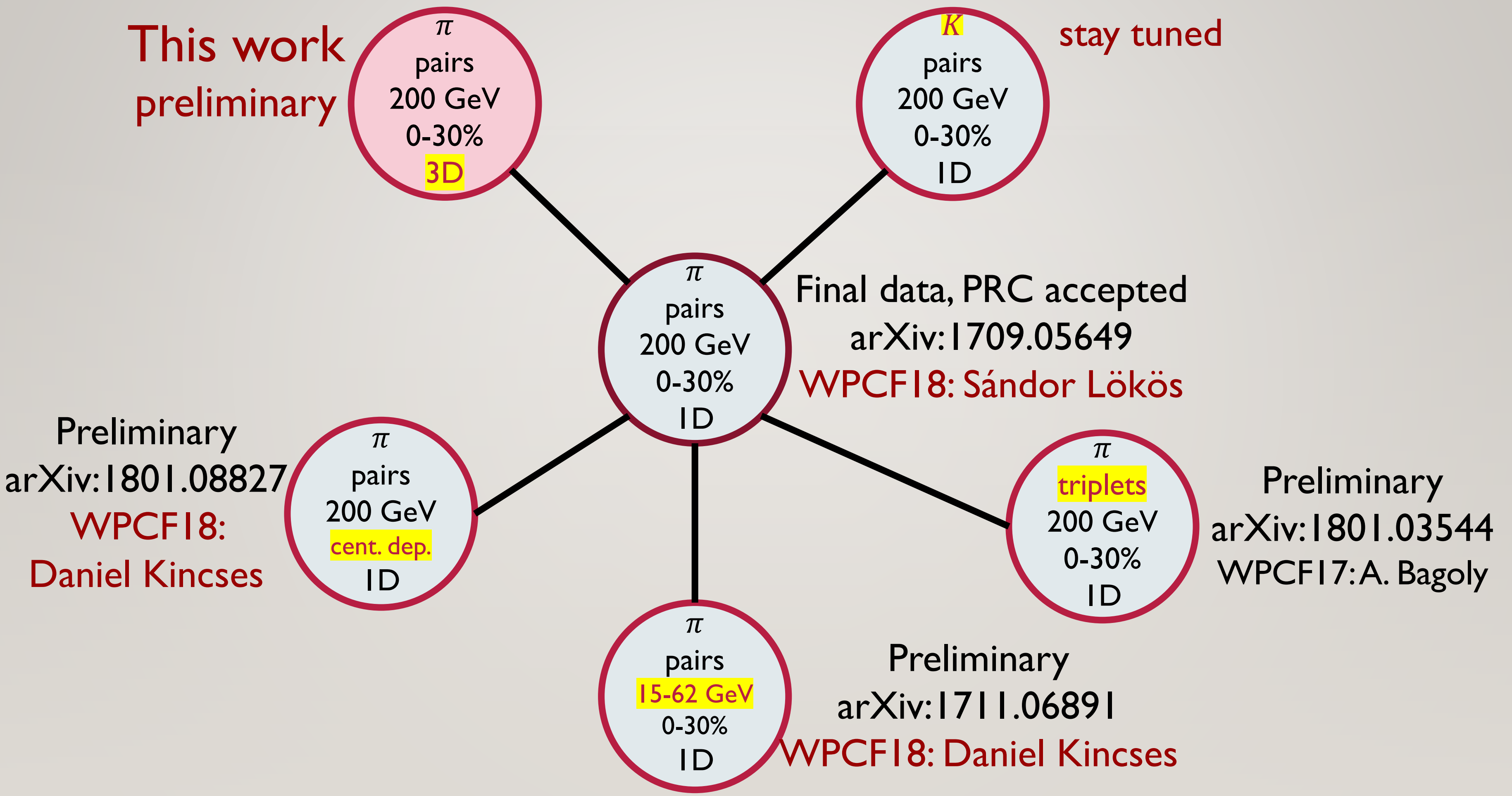
PHENIX LÉVY HBT STATUS

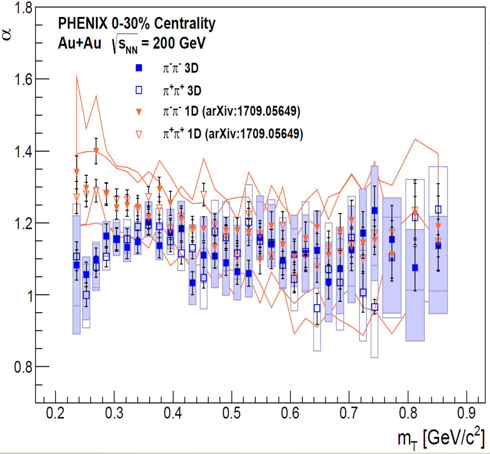
- Bose-Einstein correlations measured from 15 to 200 GeV
- Levy fits yield statistically acceptable description
- Levy parameters R, λ, α: 3D measurement confirms 1D results
  - Stability parameter $\alpha<2 \leftrightarrow$ anomalous diffusion?
  - Linear scaling of $1/R^2$ vs $m_T \leftrightarrow$ hydro (but non-Gaussian source!)
  - Low-m_T decrease in $\lambda(m_T) \leftrightarrow$ core-halo model, in-medium η' mass?
- Three-particle analysis: chaotic or coherent emission?

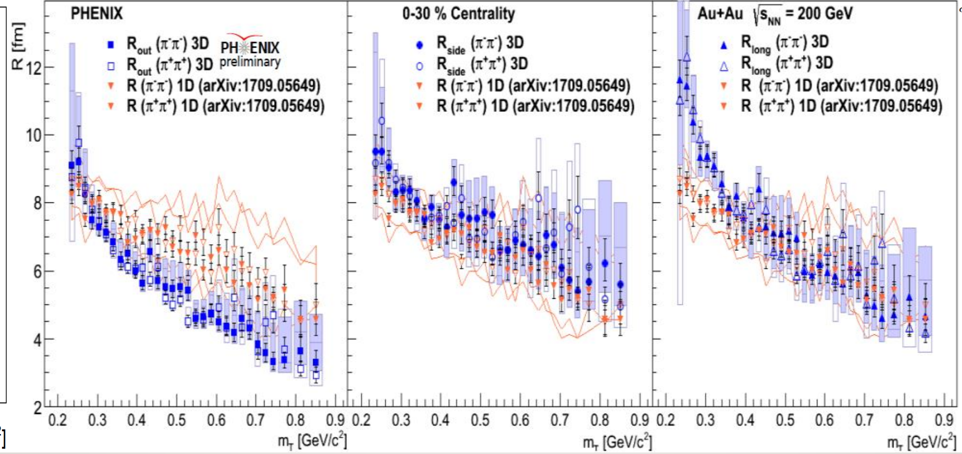
OPEN QUESTIONS

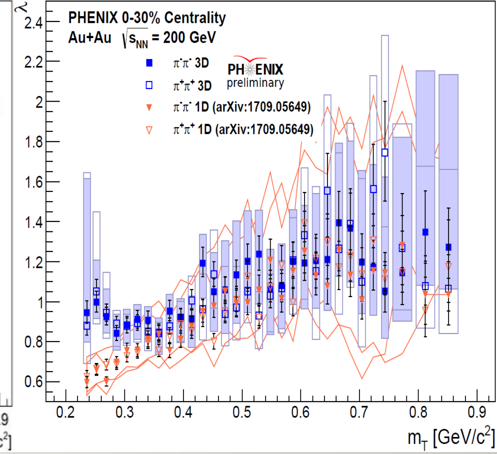
- Collision energy and centrality dependence?
  - Non-monotonicity in $\alpha\left(\sqrt{s_{NN}}\right)$ or $\alpha(\text{centrality})$?
  - Hole in $\lambda(m_T)$ at low $\sqrt{s_{NN}}$? Really due to η'?
  - Lower energies and centrality dependence: see the talk of D. Kincses
- What is the reason for the appearance of Lévy distributions for pions?
  - 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









THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects, come to:

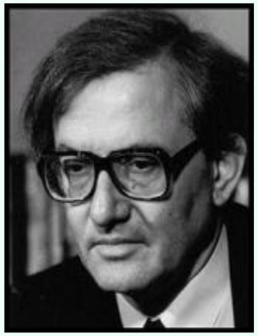
ZIMÁNYI SCHOOL'18


Janos Kass: Falanszter (Phalanstere)

18. Zimányi

WINTER SCHOOL ON HEAVY ION PHYSICS

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


József Zimányi (1931 - 2006)

UNIVERSITAS BUDAPESTINENSIS DE ROLANDO EÖTVÖS NOMINATA 1635

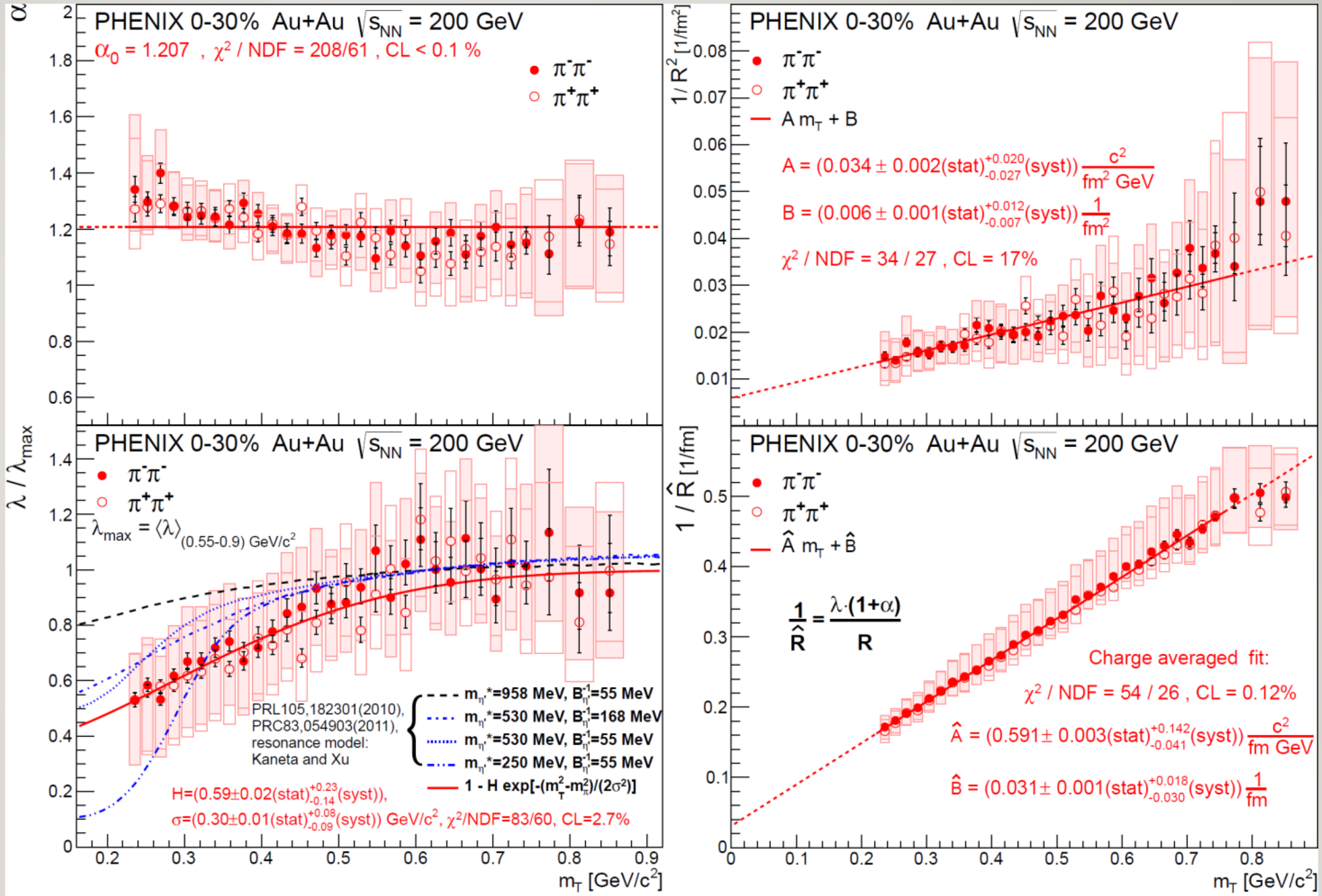
PHENIX

http://zimanyischool.kfki.hu/18

BACKUP

200 GEV 1D ANALYSIS RESULTS RESULTS

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



PRELIMINARY SYSTEMATIC ANALYSIS

- Uncertainty sources for each parameter:
  - PID, matching cuts, pair cuts, fit range, Coulomb-correction, q-binning
- Individual sources: very asymmetric
- Different for small and large mT
- Largest uncertainty: λ

	m_T<500 MeV/c^2										m_T>500 MeV/c^2									
	λ [%]		R_{out} [%]		R_{side} [%]		R_{long} [%]		α [%]		λ [%]		R_{out} [%]		R_{side} [%]		R_{long} [%]		α [%]	
source	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓
PID	2.7	8.4	2.1	2.3	1.9	3.8	4.5	2.7	2.1	1.5	2.9	5.1	1.7	2.6	1.7	2.8	1.8	3.1	1.6	1.1
ID match.	4.1	7.7	2.2	4.8	2.3	4.8	2.2	4.8	2.8	1.9	9.3	18.6	4.9	9.6	4.3	9.6	4.9	10.9	4.8	2.9
paircut	3.3	7.0	2.3	5.0	2.4	5.1	2.1	5.1	3.1	1.7	6.3	14.6	4.5	9.5	4.6	10.2	3.6	9.1	4.6	2.8
fitlim max	0.3	0.1	0.2	0.0	0.2	0.0	0.2	0.0	0.0	0.2	0.2	0.2	0.15	0.1	0.2	0.1	0.2	0.1	0.1	0.1
fitlim min	0.6	0.9	0.4	0.6	0.5	0.7	0.5	0.6	0.5	0.4	1.5	1.5	1.0	1.0	1.2	1.2	1.2	1.2	0.8	0.8
Coul. corr.	0.5	4.1	0.4	2.7	0.4	2.8	0.4	2.7	1.8	0.2	0.5	16.9	0.2	13.3	0.3	13.0	0.4	11.3	6.5	0.2
q-binning	10.5	0.4	0.0	7.2	7.8	0.3	7.4	0.3	0.2	4.1	15.9	0.0	0.3	3.3	12.3	0.0	12.8	0.0	0.0	9.0