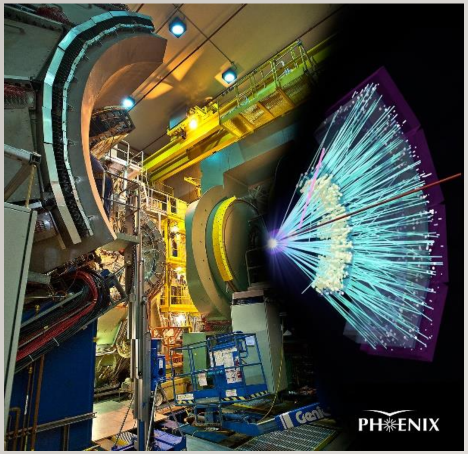

FEMTOSCOPY WITH LEVY SOURCES IN AU+AU COLLISIONS

MÁTÉ CSANÁD (FOR THE PHENIX COLL.) EOTVOS U, BUDAPEST

THE 36TH WINTER WORKSHOP ON NUCLEAR DYNAMICS, 2020

CONTENTS OF THIS TALK

- Basics of femtoscopy and Lévy sources
- PHENIX results on the Lévy exponent
- Results on other Lévy parameters
- Results from other experiments
- Summary and outlook

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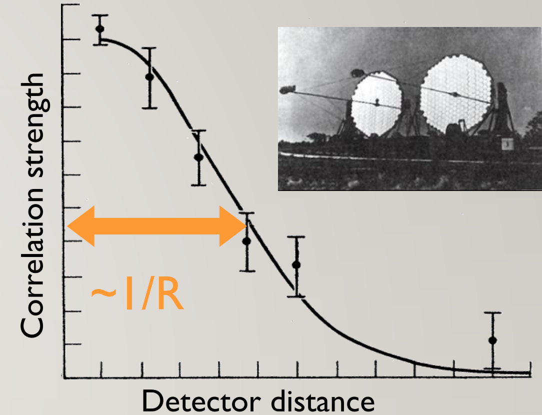
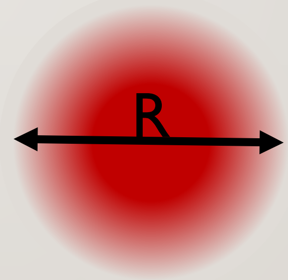
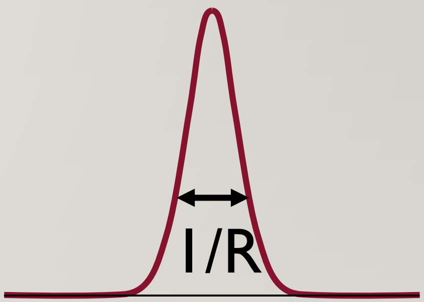
FEMTOSCOPY IN HIGH ENERGY PHYSICS

- 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, …
  Phys. Rev. Lett. 10, 84; Rev. Mod. Phys. 78 1267, …
  - 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)
    or the distance distribution $D(r)$
    $C(q) \cong 1 + \int D(r)e^{iqr}dr$
  - Neglected: pair reco., final state int., N-particle correlations, coherence, …





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

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

5/35 SOURCE OR PAIR DISTRIBUTION?

- Under some circumstances (thermal emission, no interactions, …):

$$C_2(q,K) = \int S\left(r_1, K + \frac{q}{2}\right) S\left(r_2, K - \frac{q}{2}\right) |\Psi_2(r_1,r_2)|^2 dr_1 dr_2$$

$$\cong 1 + \left|\int S(r,K)e^{iqr}dr\right|^2$$

- Let us introduce the spatial pair distribution:

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

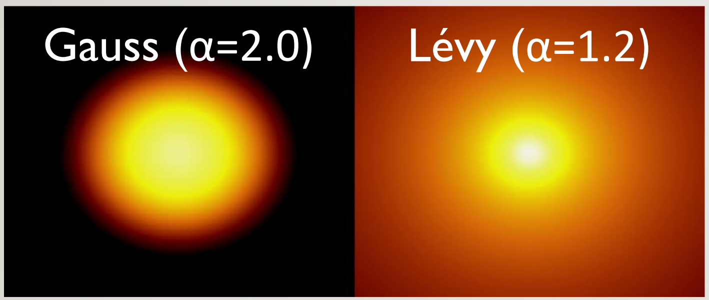
- Then the Bose-Einstein correlation function becomes:

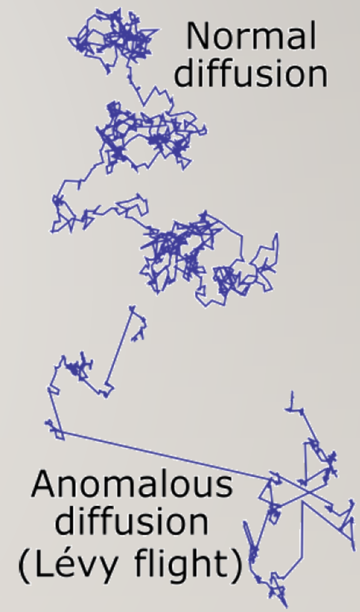
$$C_2(q,K) \cong \int D(r,K)|\Psi_2(r)|^2 dr = 1 + \int D(r,K)e^{iqr}dr$$

- **Bose-Einstein correlations measure spatial pair distributions!**

LÉVY DISTRIBUTIONS IN HEAVY ION PHYSICS

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

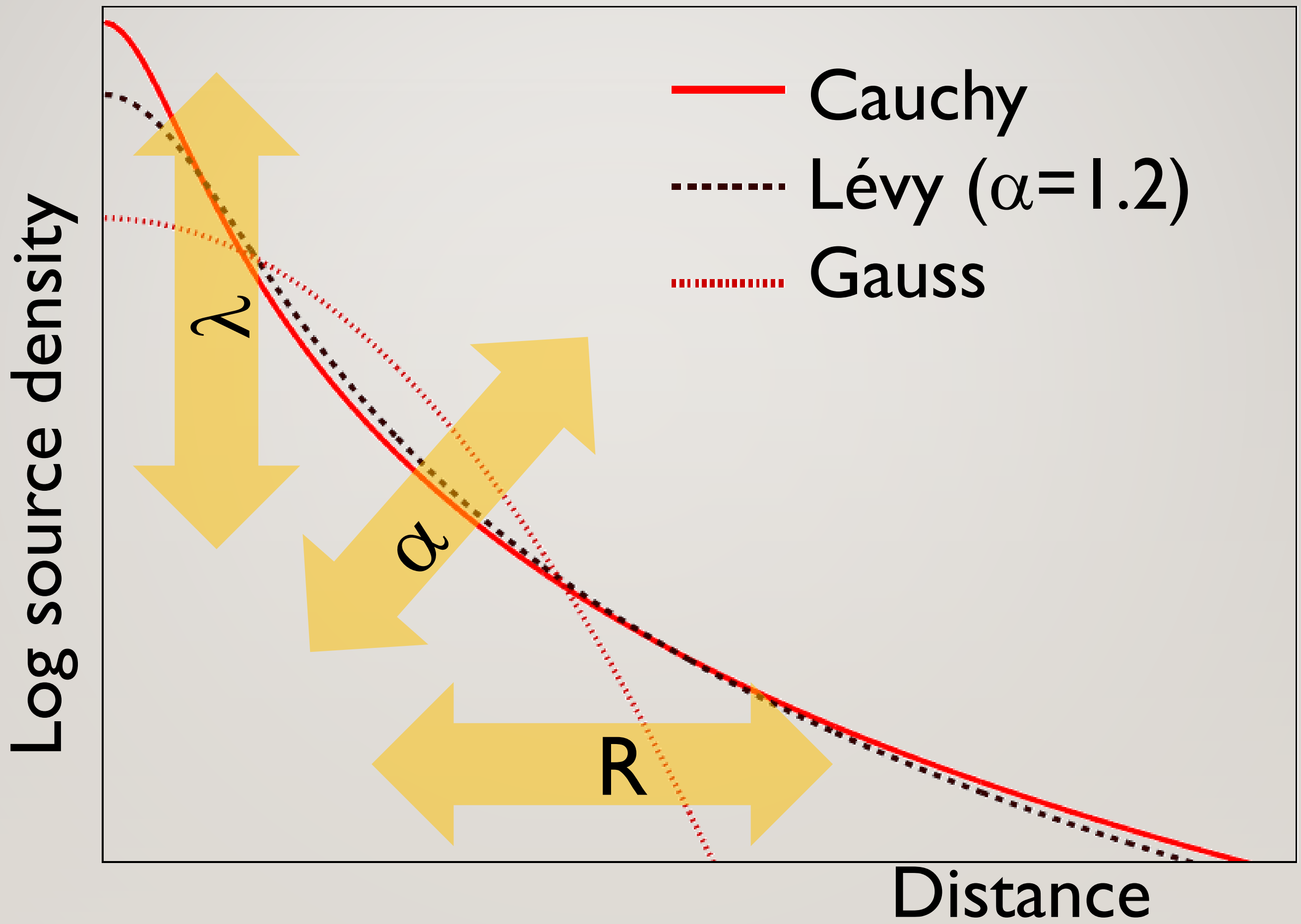




- Shape of the correlation functions with Levy source:
  - $C_2(q) = 1 + \lambda \cdot e^{-|qR|^\alpha}$; $\alpha = 2$: Gaussian; $\alpha = 1$: exponential
    Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67-78
- Reasons for Levy source:
  - Critical phenomena; QCD jets; Anomalous diffusion; what else?
    Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828 (2006) no.1, 525-532;
    Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon. B36 (2005) 329-337
    Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002; Metzler, Klafter, Physics Reports 339 (2000) 1-77

7 /35 LÉVY VERSUS GAUSS VERSUS EXPONENTIAL

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



8/35 LÉVY INDEX AS A CRITICAL EXPONENT?

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

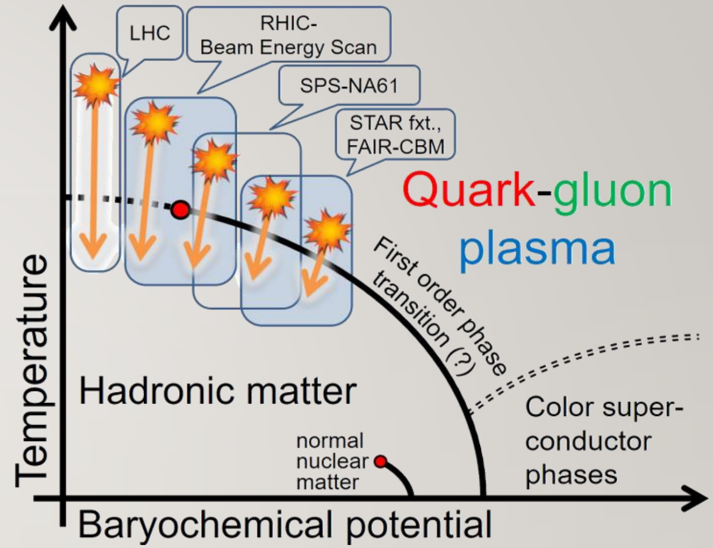
  Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67,

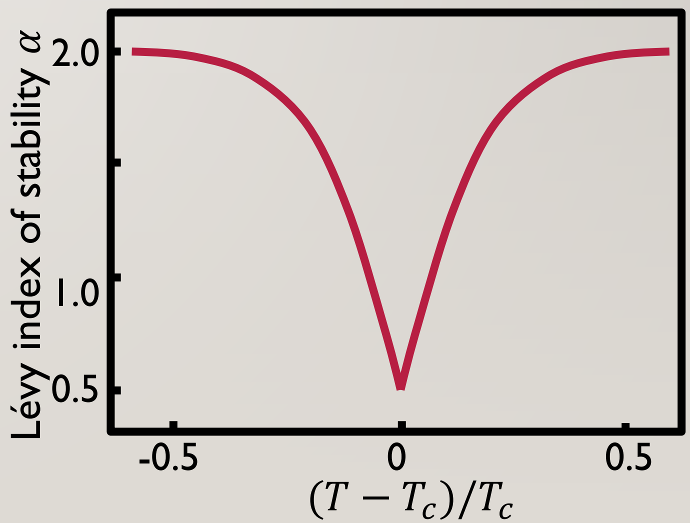
- QCD universality class ↔ 3D Ising

  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?
- Finite size/time & non-equilibrium effects → what does power law mean?





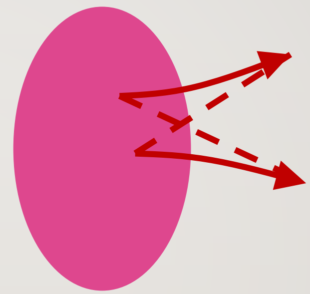
9/35 INTERACTIONS: THE COULOMB-EFFECT

- 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 there is interaction:

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



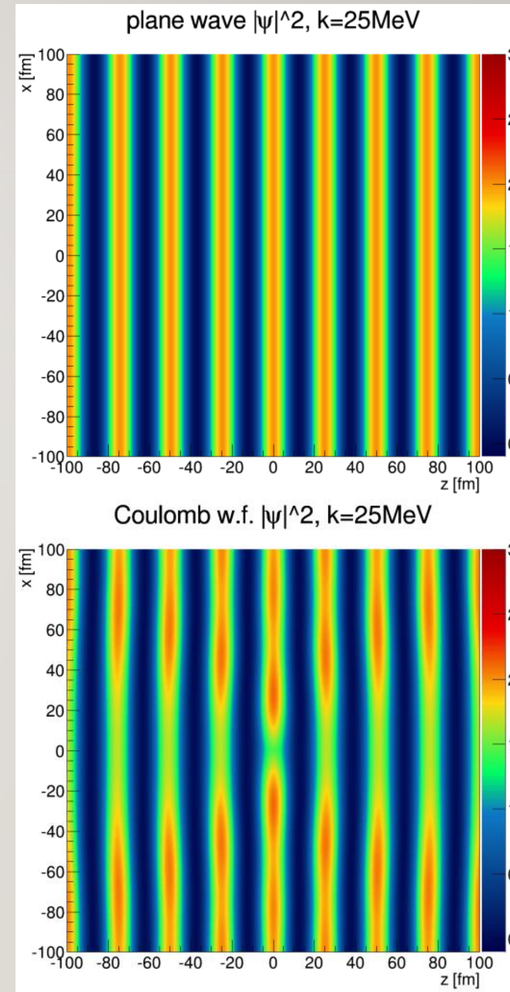
- For Coulomb:

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

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

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

- Complication: need for integrating power-law tails
- In this analyis: assuming spherical source
- Parametrization possible, see e.g. arXiv:1910.02231 or 1905.09714

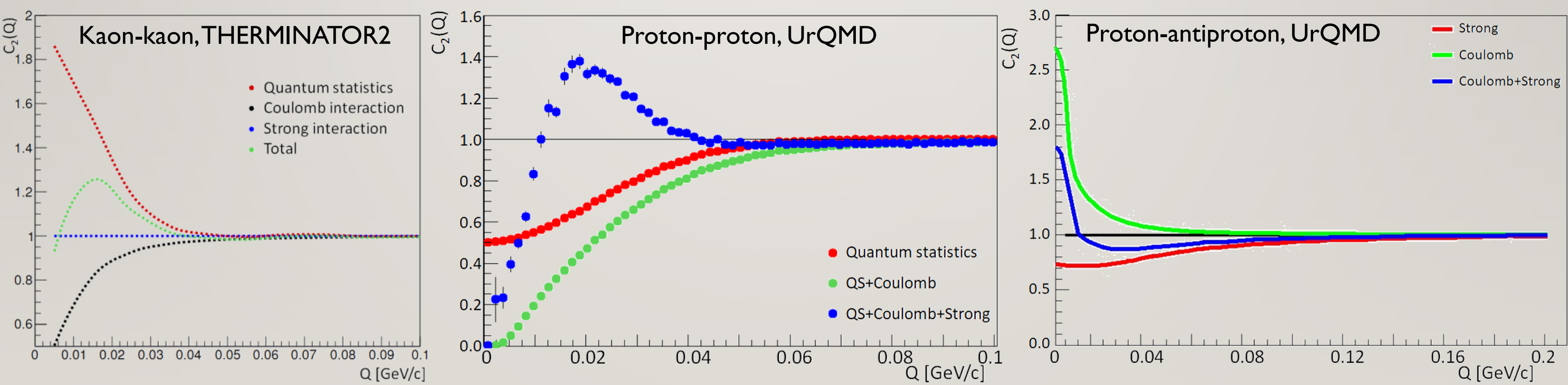


ROLE OF THE STRONG INTERACTION

- In case of other interactions or not identical bosons, the formula still works:

$$C_2(q,K) \cong \int D(r,K)|\Psi_2(r)|^2 dr$$

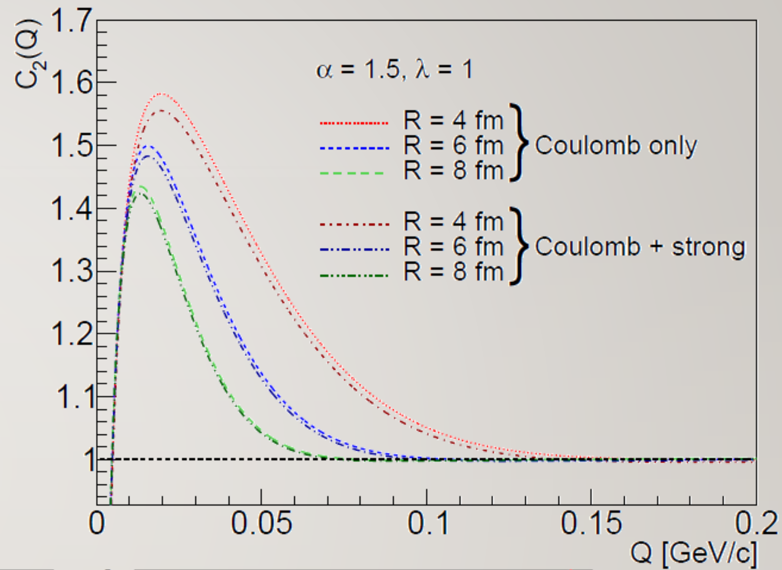
- Pair wave function determines $D \leftrightarrow C_2$ connection
- Mesons, baryons: strong interaction; fermions: anticorrelation
- Non-identical pairs: interaction modifies wave function

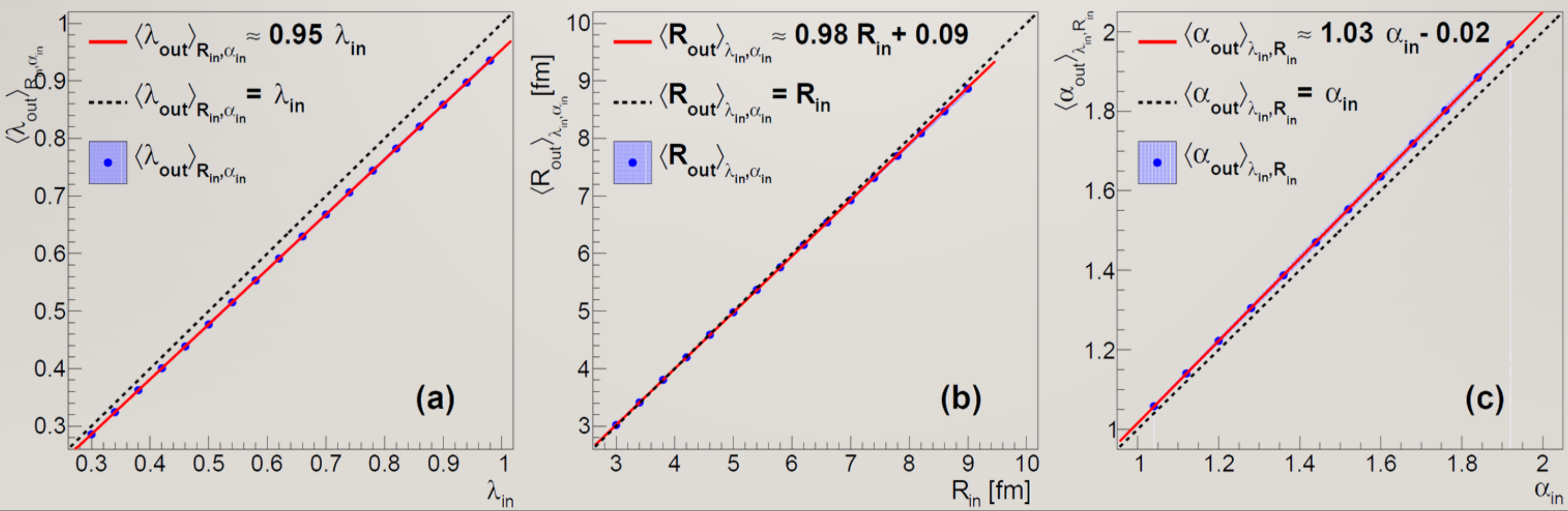


From e.g. H. Zbroszczyk's talk at Zimányi School 2019

STRONG INTERACTION FOR PION PAIRS

- Additional potential appearing
- Possible handling: strong phase shift, Modify s-wave component in wave func.
  R. Lednicky, Phys. Part. Nucl.40, 307 (2009)
- Small difference in case of pions
- Few percent modification in λ, α
  D. Kincses, M. I. Nagy, M. Cs. arXiv:1912.01381





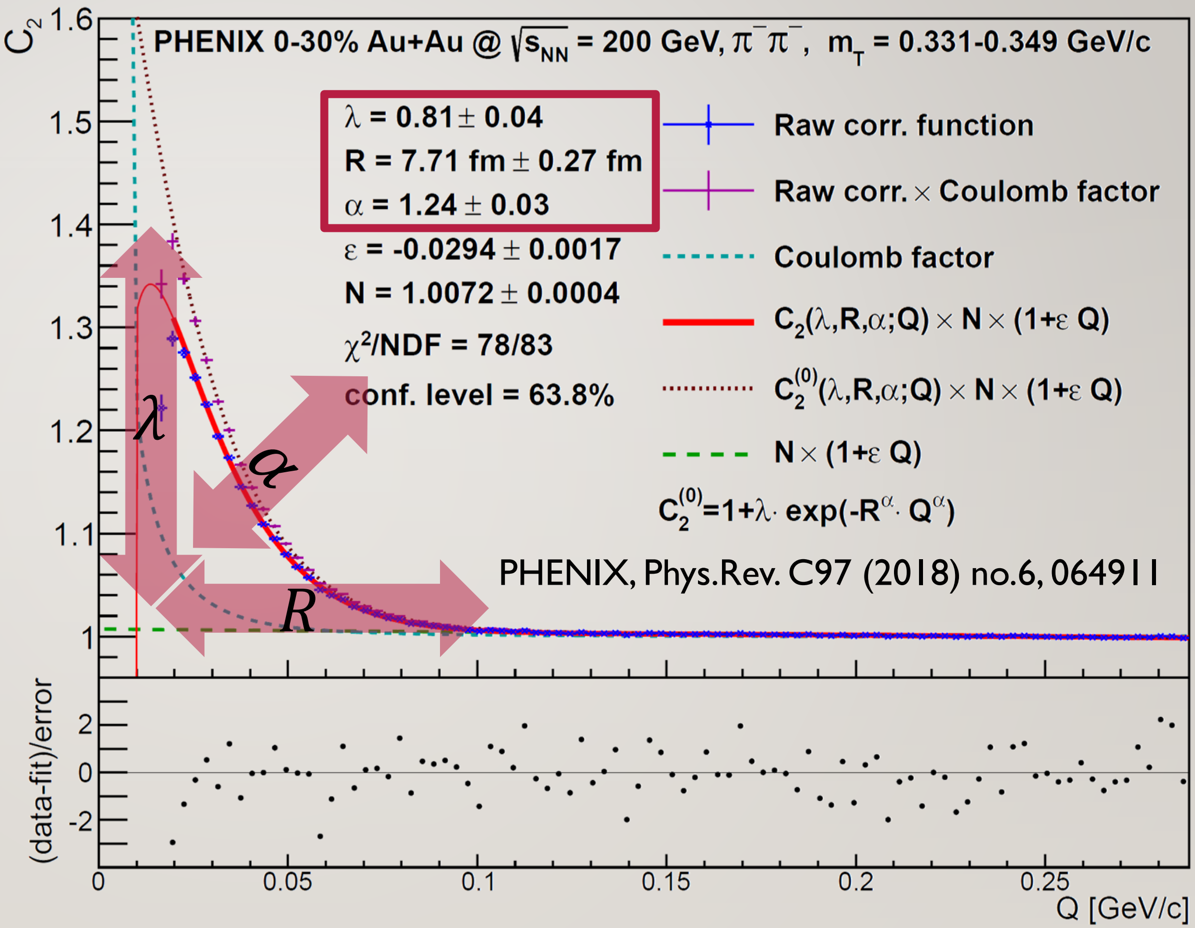
CONTENTS OF THIS TALK

PHENIX LEVY HBT ANALYSES

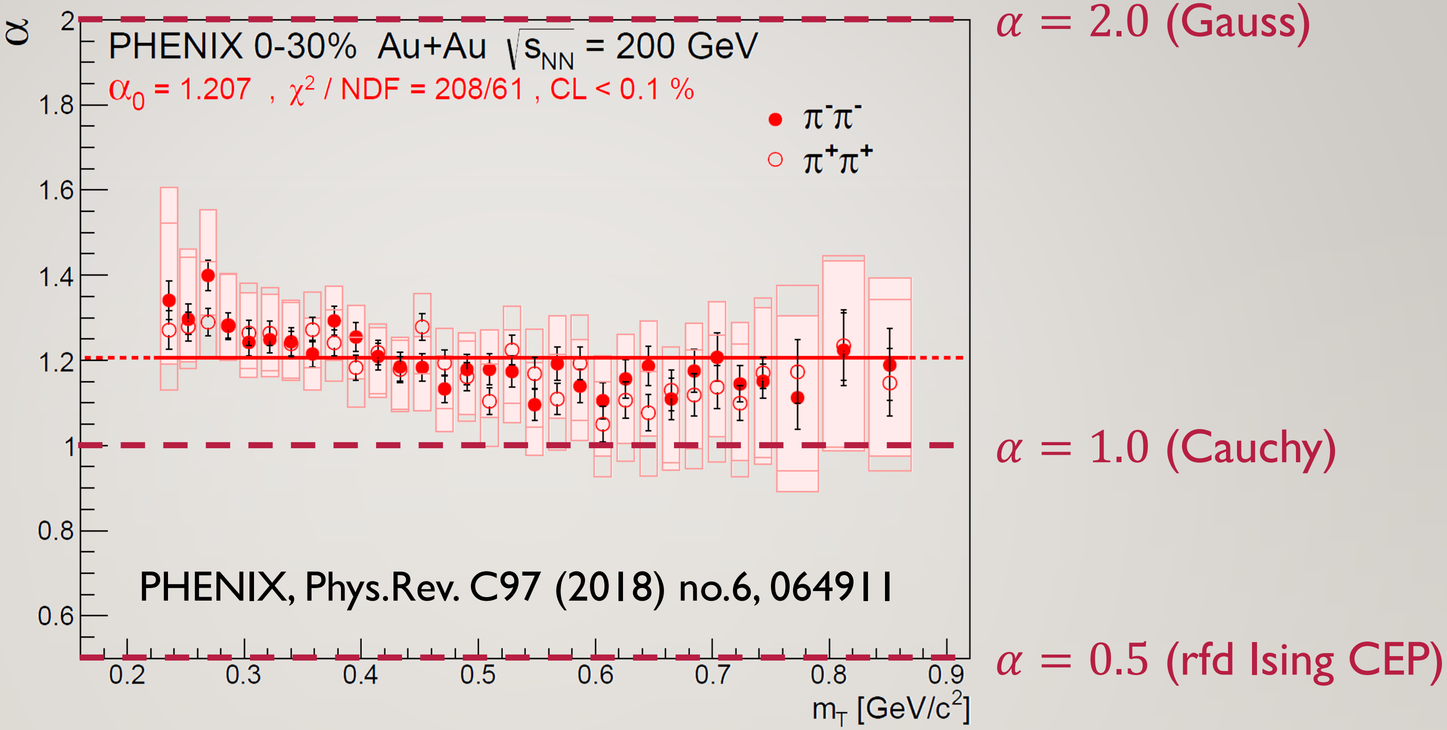
- Dataset used for these analyses:
  - Events: Au+Au, $\sqrt{s_{NN}}$ = 14.6-200 GeV (~2 billion events at 200 GeV)
  - Particle identification:
    - time-of-flight data from PbSc East/West, TOF East/West, momentum, flight length
    - 2σ cuts on m^2 distribution
  - Single track cuts: 2 σ matching 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
- 1D & 3D corr. func. as a function of Q_{LCMS} and $\vec{q}_{\mathrm{LCMS}}$ in various m_T bins
  - $\vec{q}_{\mathrm{LCMS}}$ is momentum difference longitudinal co-moving frame, $Q_{LCMS} = |\vec{q}_{\mathrm{LCMS}}|$
  - 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

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, good confidence levels
- χ values scatter around 0 properly
- Physical parameters: R, λ, α measured versus pair m_T
- Recall α: Lévy index, 0.5 at CEP

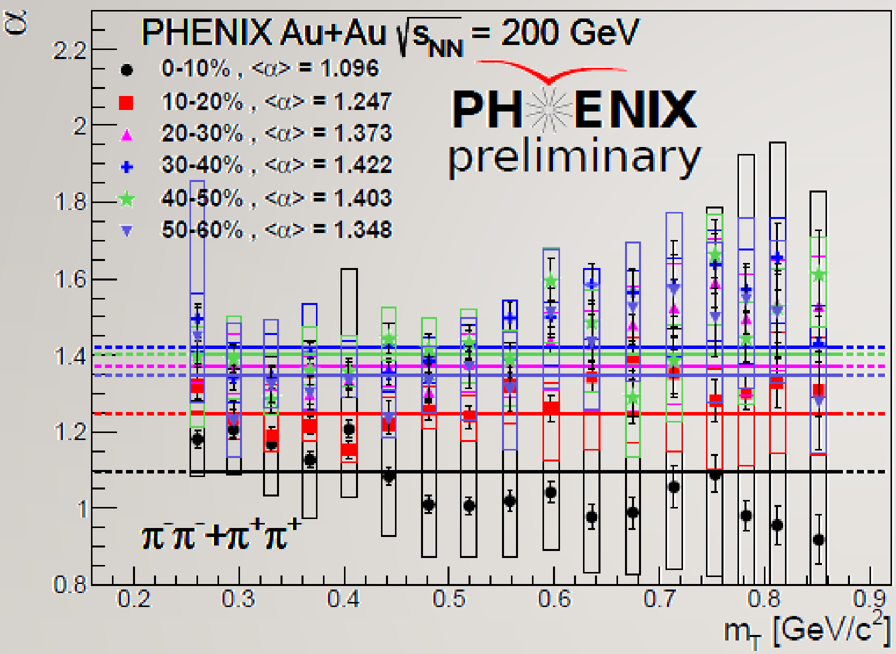


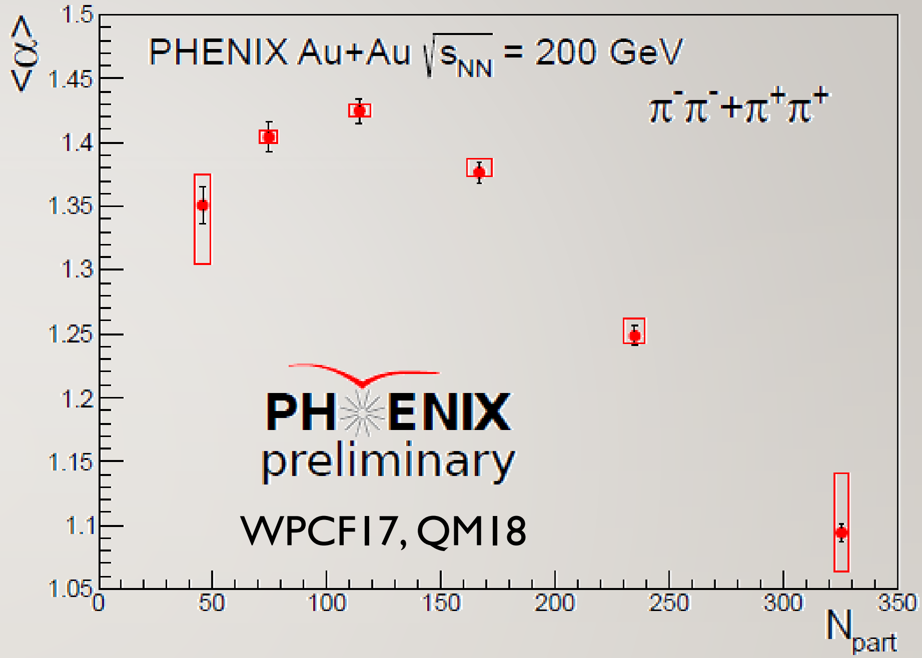
15/35 LÉVY EXPONENT (SHAPE PARAMETER) α



- 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?

ANALYZING THE CETRALITY DEPENDENCE

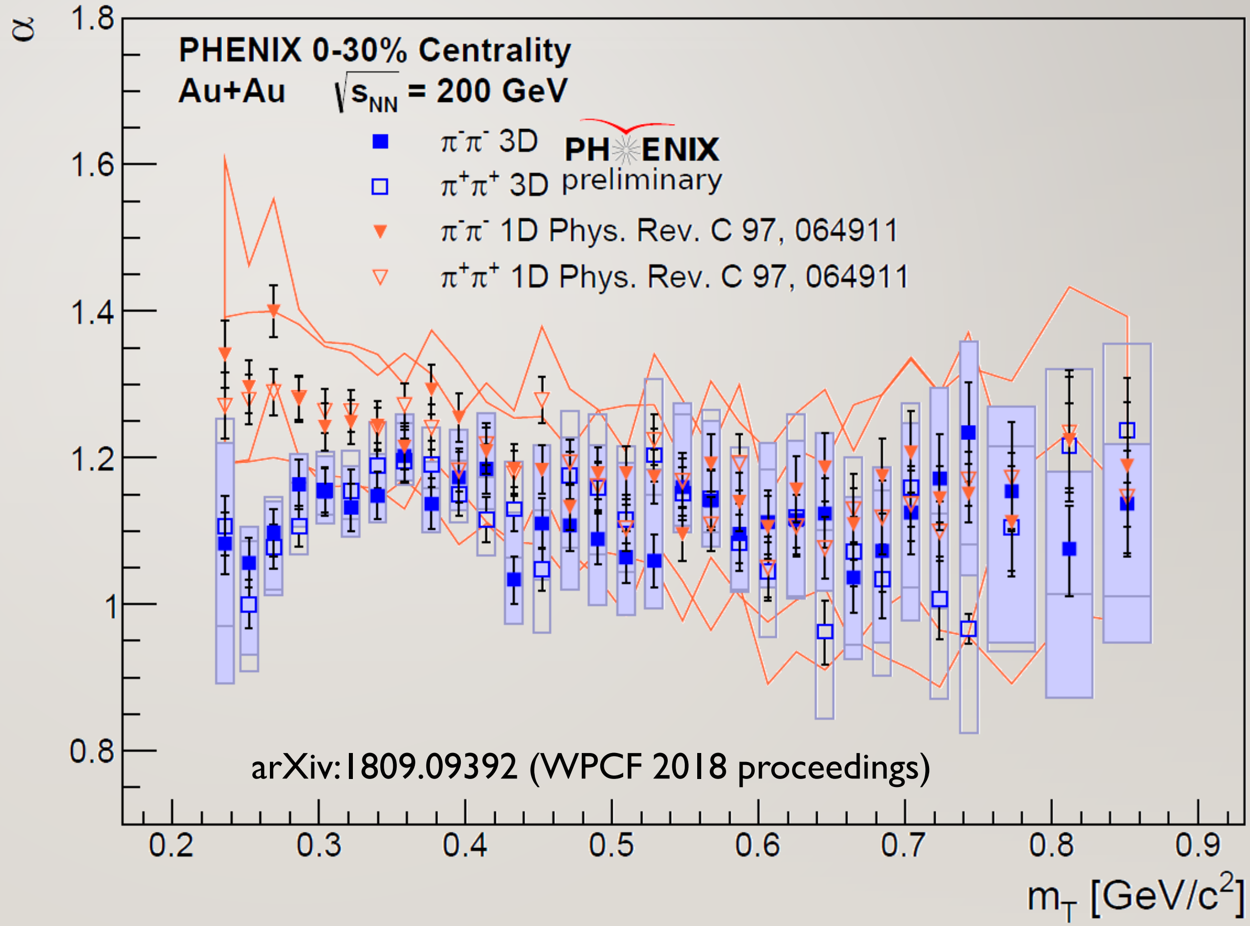




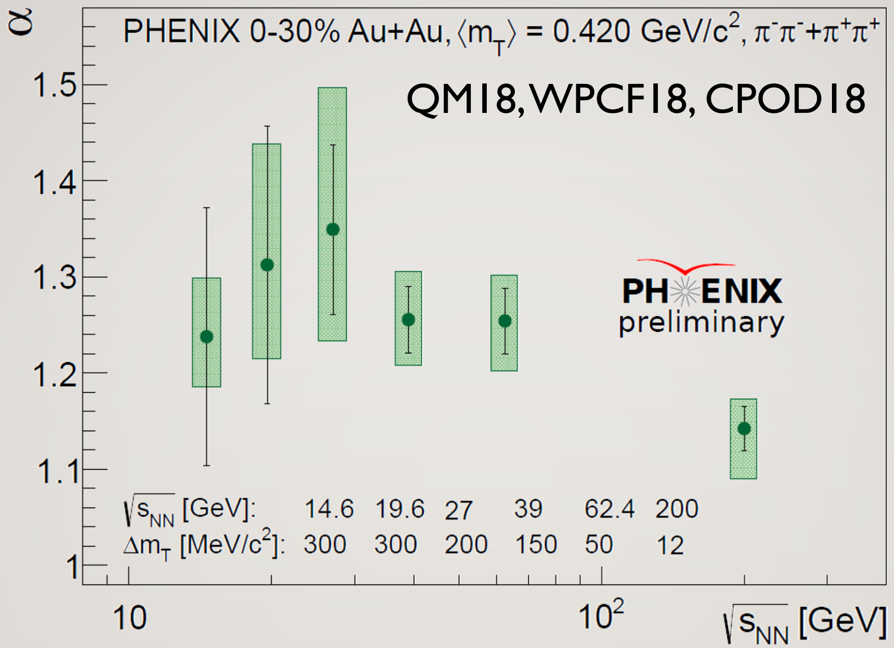
- Slightly non-monotonic behavior as a function of m_T
- Average $\langle\alpha\rangle$ non-monotonic behavior versus N_{part}
- No clear interpretation or understanding of this trend
- Important w.r.t. shape averaging interpretation of $\alpha \neq 2$

17/35 CROSS-CHECK WITH A 3D ANALYSIS

- Lévy exponent α in 3D analysis similar to 1D result
- On average still far from 2
- Observable differences at low m_T
- Maybe due to lack of spherical symmetry?
- Need to calculate Coulomb effect for non-spherical sources
- Working on final results…



18/35 COLLISION ENERGY DEPENDENCE

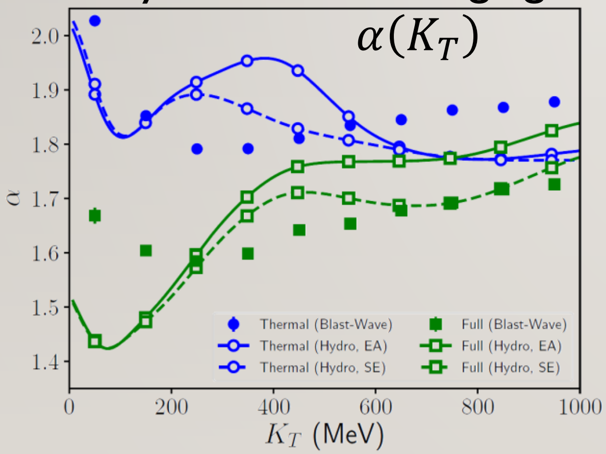


- Average $\langle\alpha\rangle$ not fully monotonic versus $\sqrt{s_{NN}}$
  - No clear interpretation or understanding of this trend
  - Important w.r.t. shape averaging interpretation of $\alpha \neq 2$
- Lévy exponent α still far from conjectured CEP limit of 0.5
  - Very much mT bin width dependent, working on final results…

19/35 WHAT IS THE REASON FOR POWER-LAW TAILS?

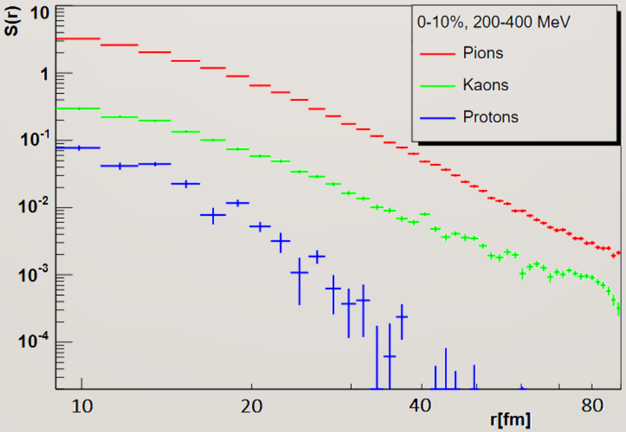
- Simple hydro/thermo picture: exponential cutoff from $\exp\left(-\frac{p^\mu u_\mu}{T}\right)$
- Non-Gaussianity from averaging over different shapes (centr., azimuth angle)
- Power-law tails from rescattering in hadronic phase?
- Power-law tails already present before hadronic phase?

Hydro, event averaging



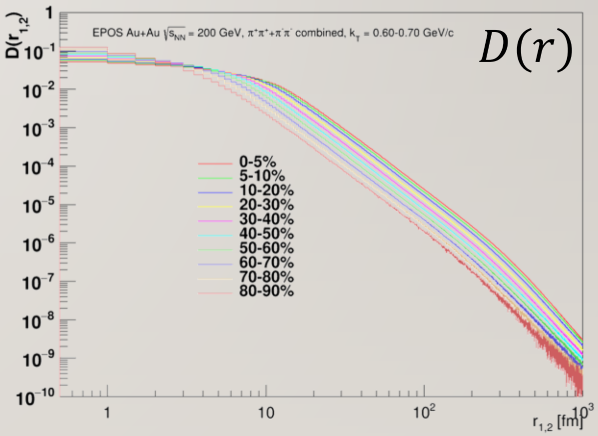
J. Cimerman, C. Plumberg, B. Tomášik
arXiv:1909.07998

HRC simulation, $S(r)$



MCs, T. Csörgő, M. Nagy, Braz.J.Phys. 37 (2007)

Preliminary EPOS result



Courtesy of D. Kincses and M. Stefaniak

CONTENTS OF THIS TALK

- Basics of femtoscopy and Lévy sources
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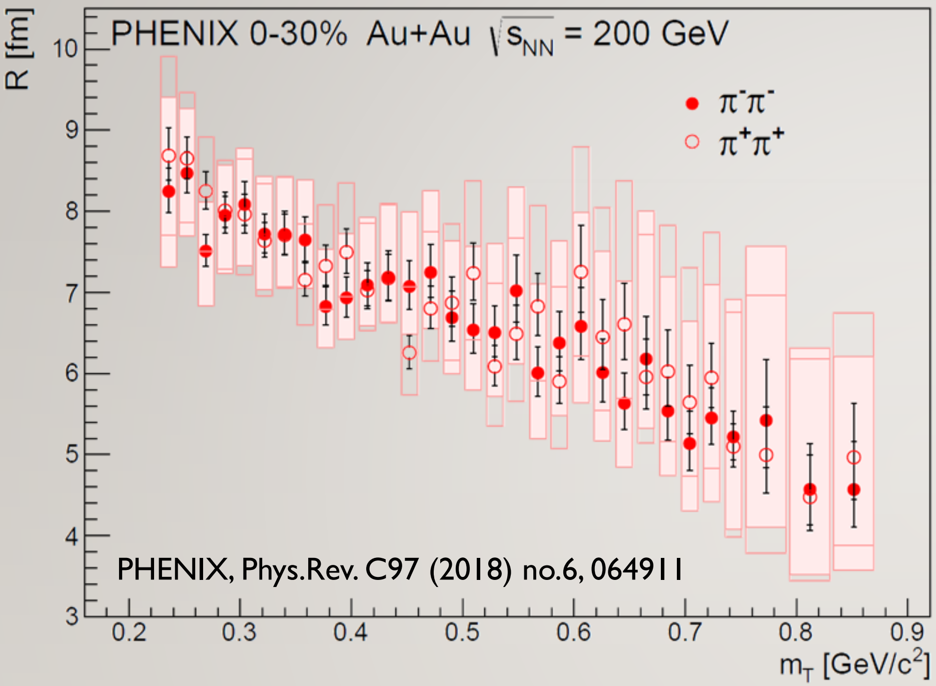
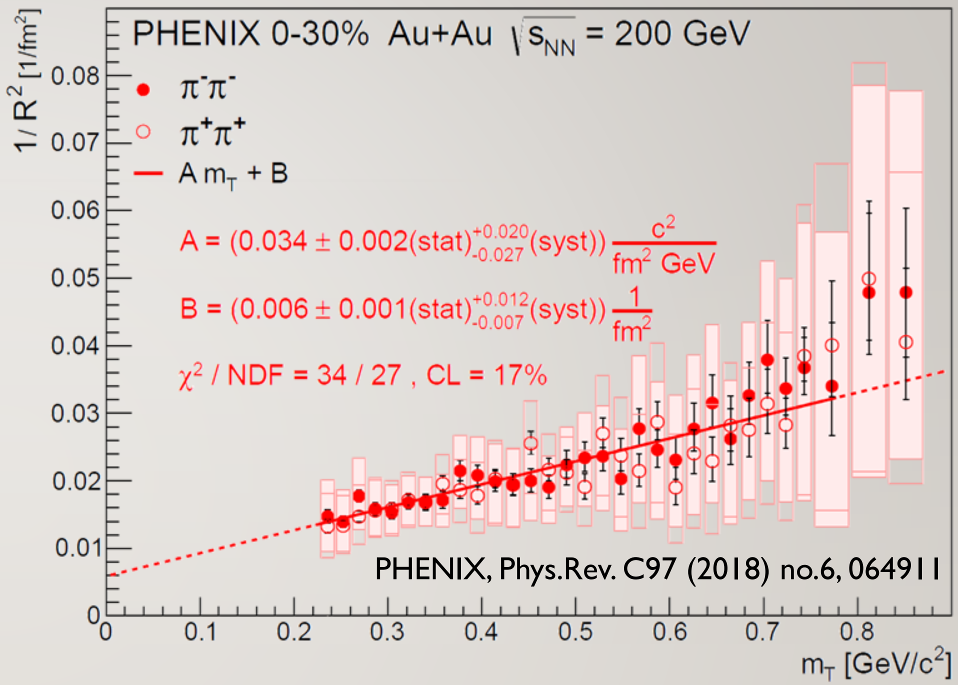
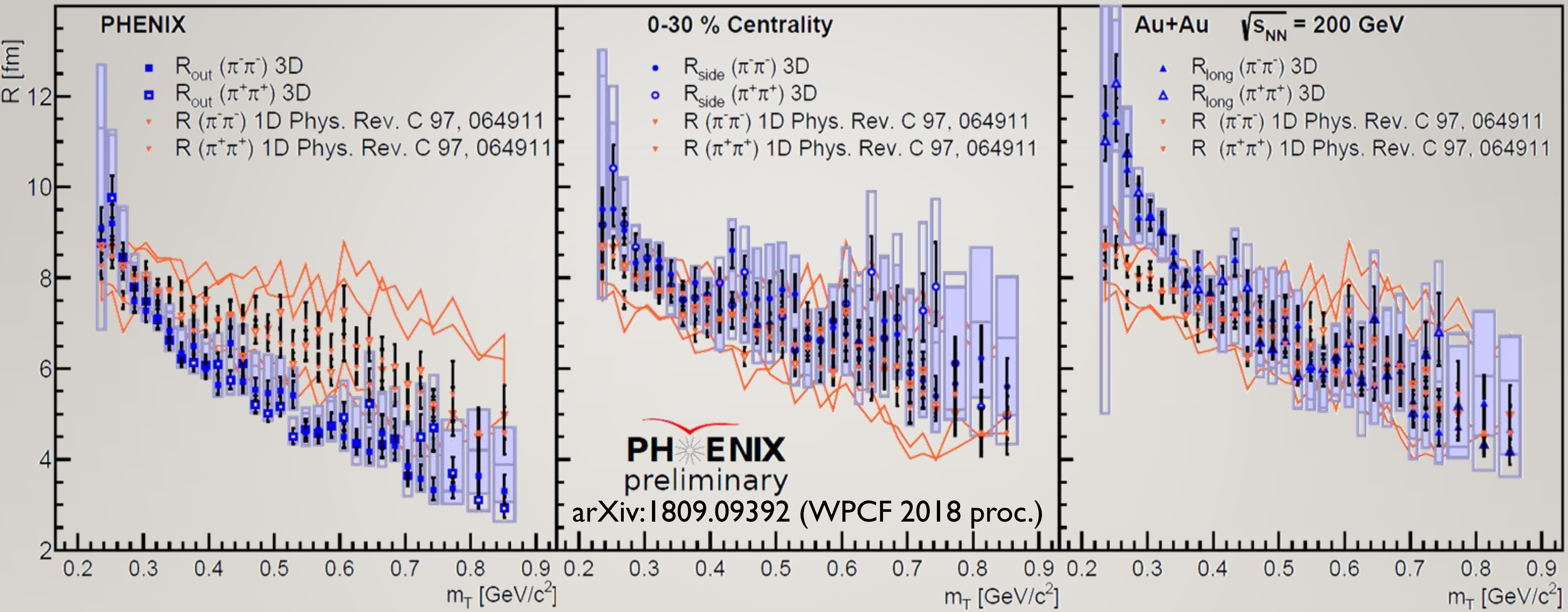
21 /35 LÉVY SCALE PARAMETER R





- Similar decreasing trend as Gaussian HBT radii, but it is not an RMS!
- What do model calculations, simulations say about this?
- Hydro behavior (predicted for Gaussian case) not invalid
- The linear scaling of $1/R^2$, breaks for high m_T?

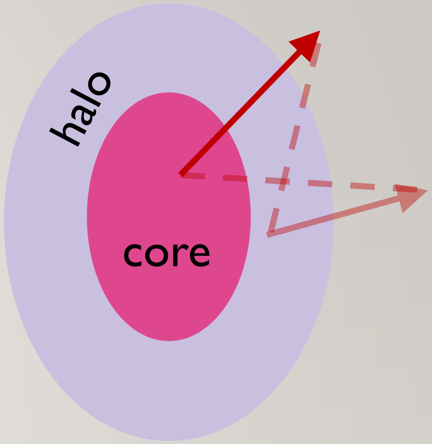
22/35 LÉVY SCALES IN 3D



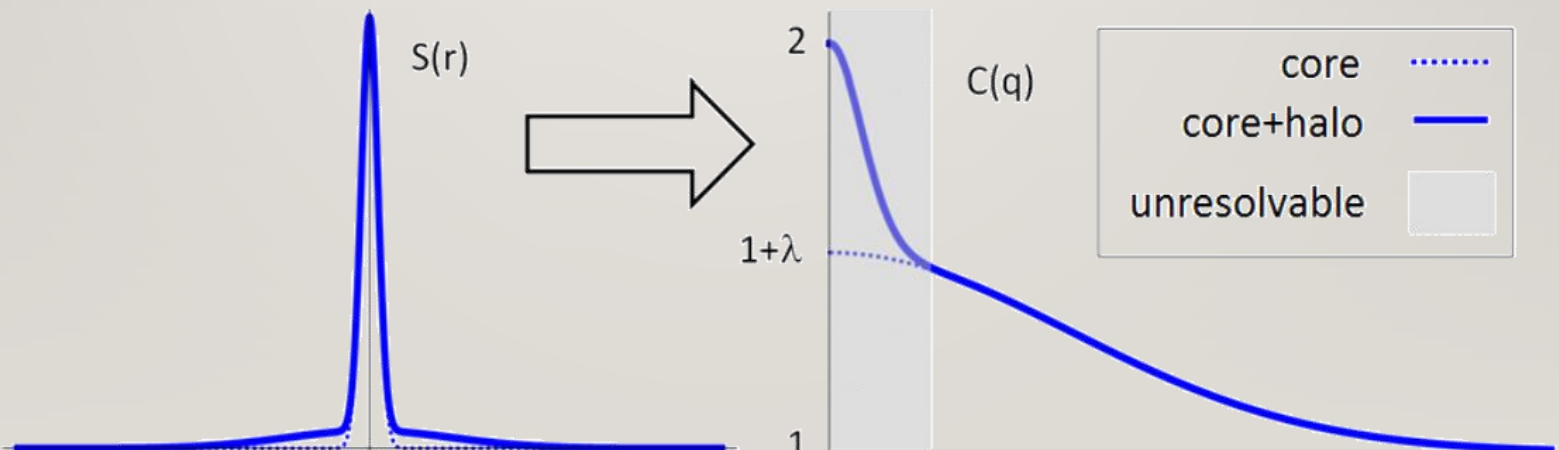
- Compatibility with 1D Lévy analysis
- Similar decreasing trend as Gaussian HBT radii, but it is not an RMS radius!
  - There is no 2nd moment (variance or root mean square) for Lévy distributions with α<2!
- Asymmetric source for small m_T, validity of Coulomb-approximation?

23/35 CORRELATION STRENGTH λ: CORE/HALO

- Two-component core+halo source
  - Core: hydrodynamically expanding, thermal medium
  - Halo: long lived resonances (≳ 10 fm/c, ω,η,η′,K_0^S,...)
  - Unresolvable experimentally
  - Define $f_C = N_{\mathrm{core}}/N_{\mathrm{total}}$
- True $q \to 0$ limit: $C(0) = 2$
- Apparently $C(q \to 0) \to 1 + \lambda$
- $\lambda(m_{\mathrm{T}}) = f_C^2(m_{\mathrm{T}})$



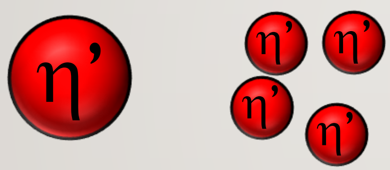
Bolz et al, Phys.Rev. D47 (1993) 3860-3870; Csörgő, Lörstad, Zimányi, Z.Phys. C71 (1996) 491-497



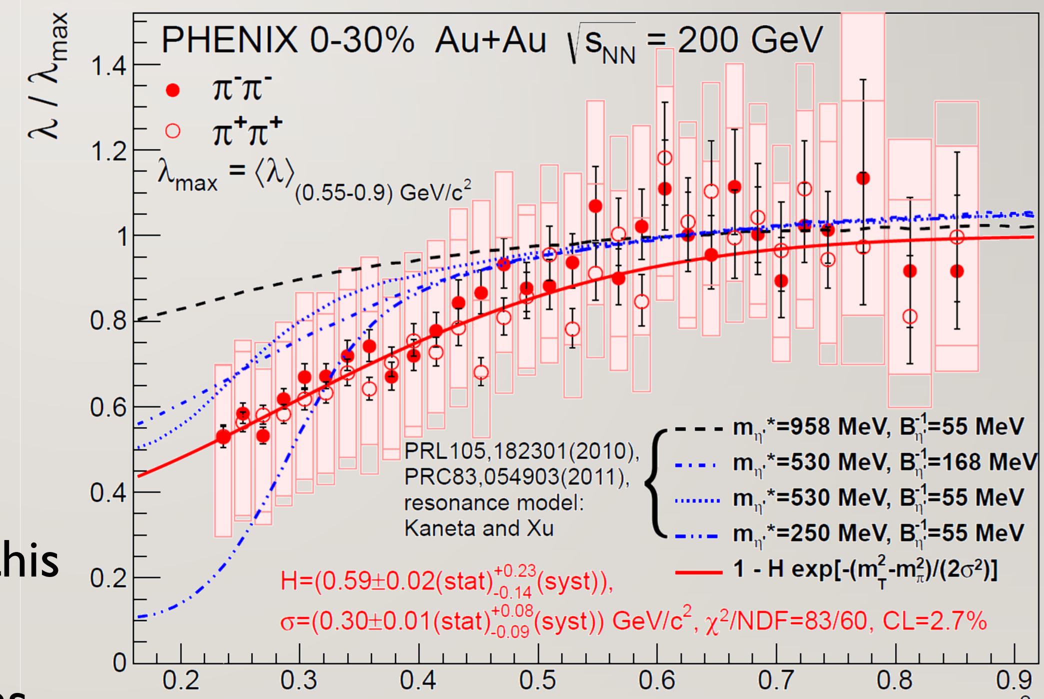
CORRELATION STRENGTH λ: IN-MEDIUM MASS?

- 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



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

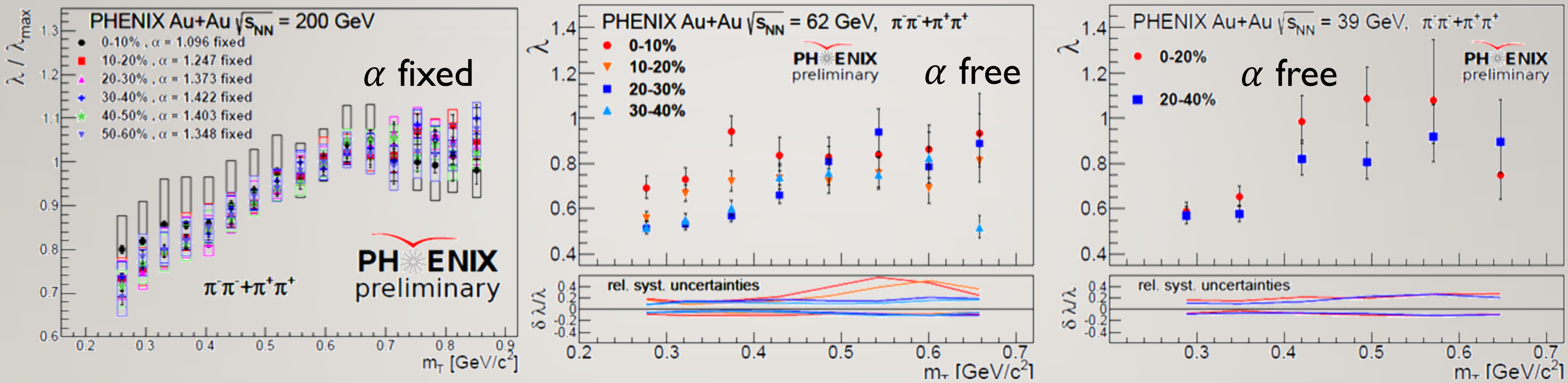


PHENIX, Phys.Rev. C97 (2018) no.6, 064911

- Results not incompatible with this
- 3D results similar to 1D
- Need direct check with photons

25/35 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.
- Statistics prevents more conclusive statement

A CROSS-CHECK: THREE-PION LÉVY HBT

- Recall: two particle correlation strength $\lambda = f_C^2$ where $f_C = N_{\rm core}/N_{\rm total}$
- 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):

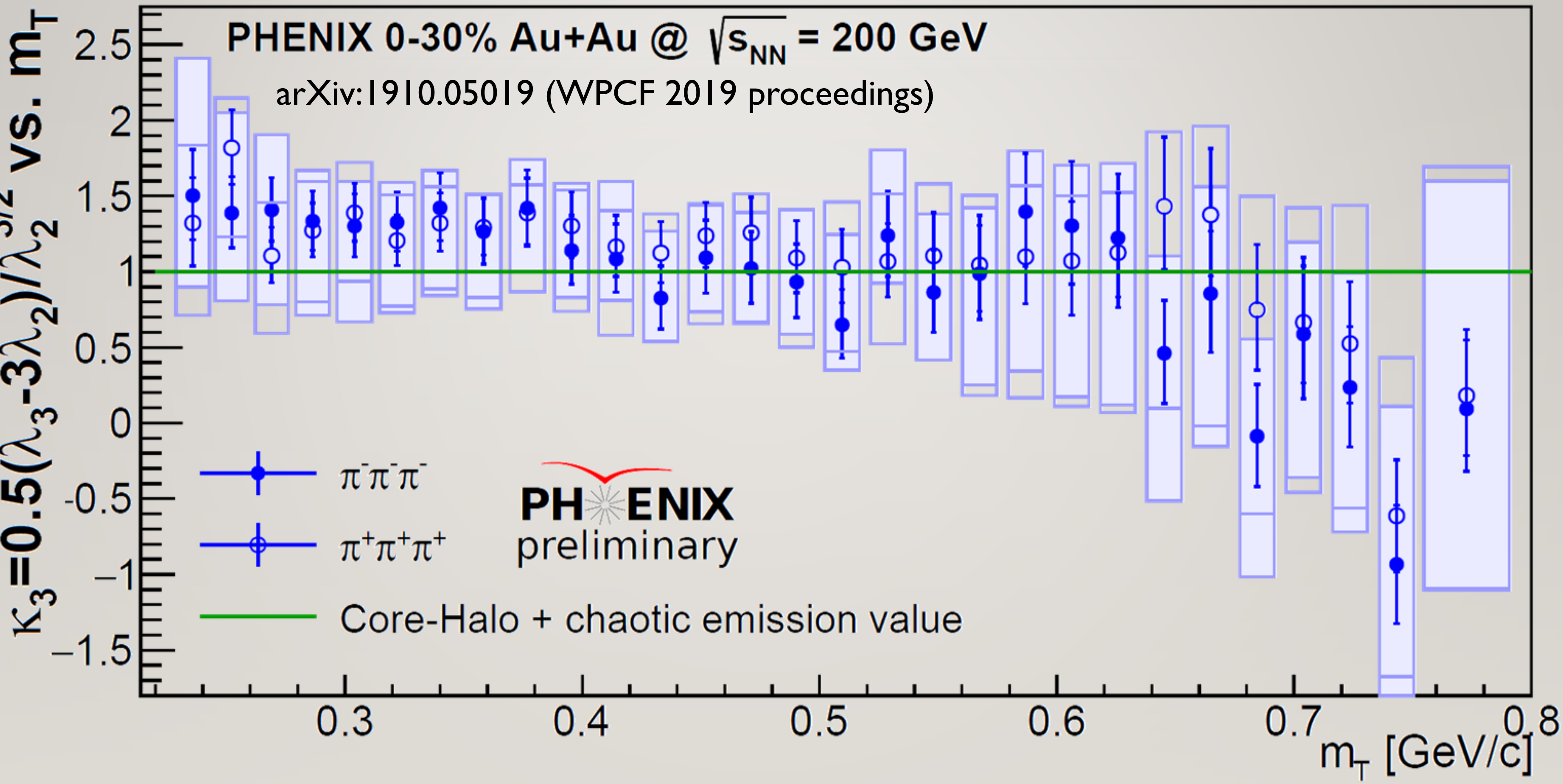
$$\lambda_2 = f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$
$$\lambda_3 = 2f_C^3[(1-p_C)^3 + 3p_C(1-p_C)^2] + 3f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$

- 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?

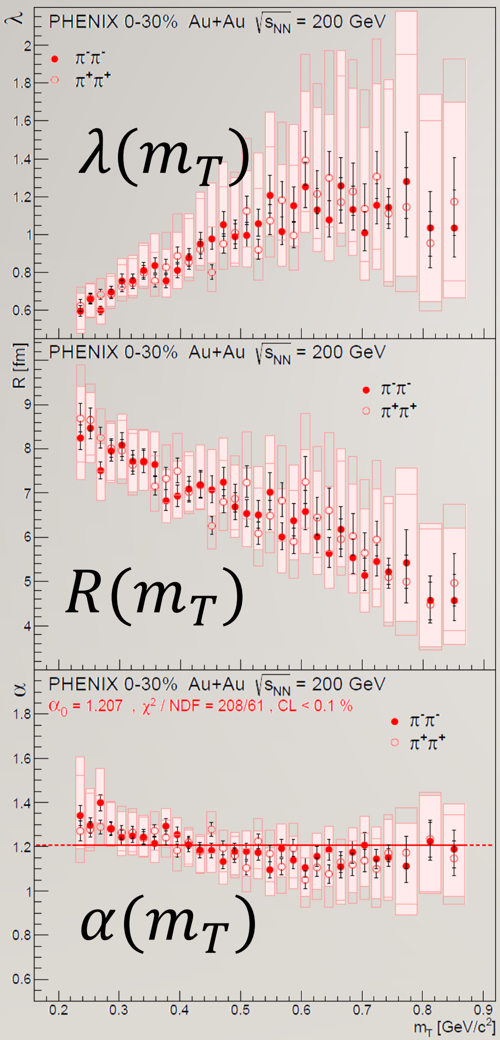
  Gavrilik, SIGMA 2 (2006) 074 [hep-ph/0512357]
- Phase shift (a la Aharonov-Bohm) in hadron gas?
  - Random fields create random phase shift, on average distorts Bose-Einstein correlations

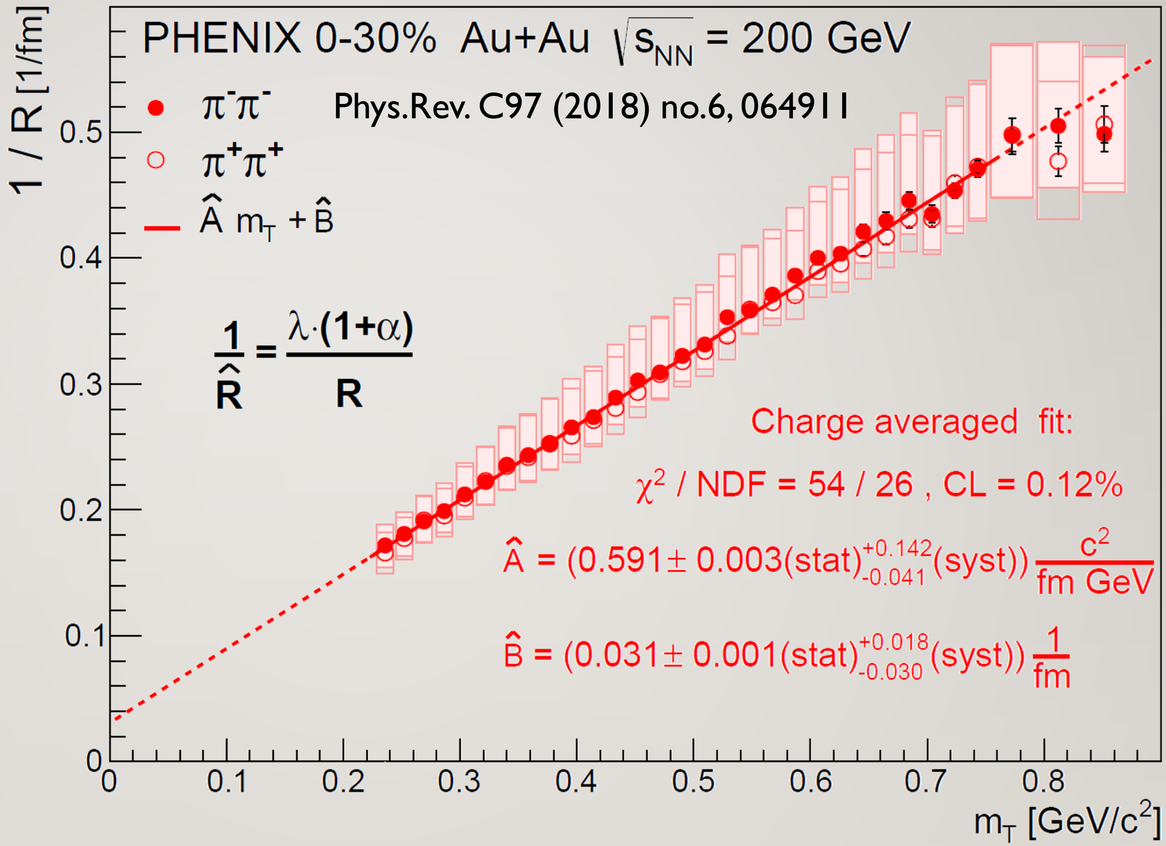
TEST OF CORE-HALO MODEL / COHERENCE

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



28/35 A SCALING PARAMETER: $\hat{R}$





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

CONTENTS OF THIS TALK

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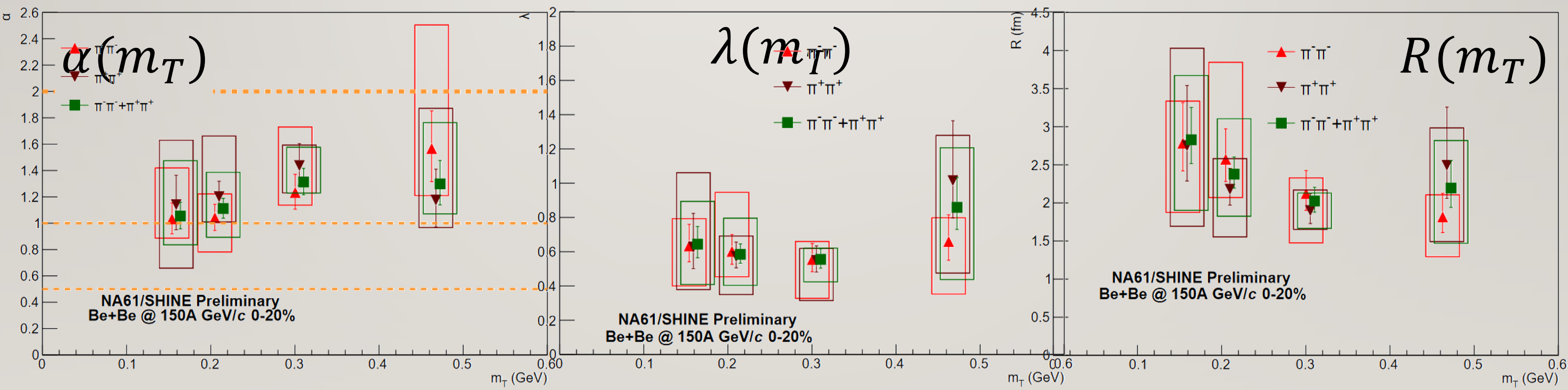
RESULTS AT NA61/SHINE

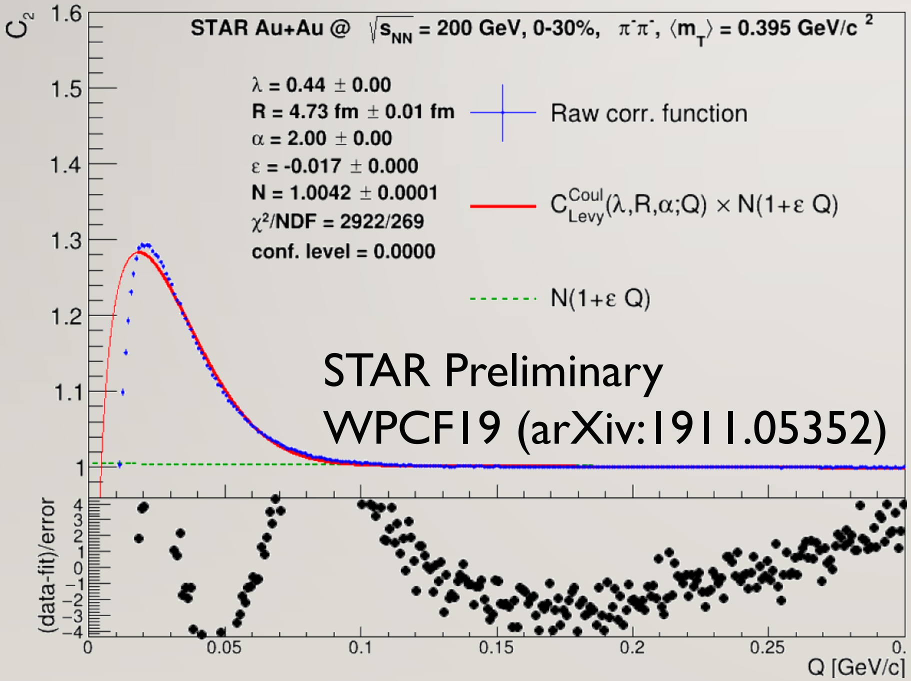
- Be+Be collisions at 150 AGeV beam momentum (17.3 AGeV in c.m.s.)
- Lévy fits describe correlation functions
  - Shape parameter α: far from Gaussian and CEP conjecture
  - Strength parameter λ: nearly constant as previous SPS results, unlike RHIC
  - Spatial scale R: weakly decreasing trend → hydro
- Plans: particle identification, Ar+Sc analysis, different energies

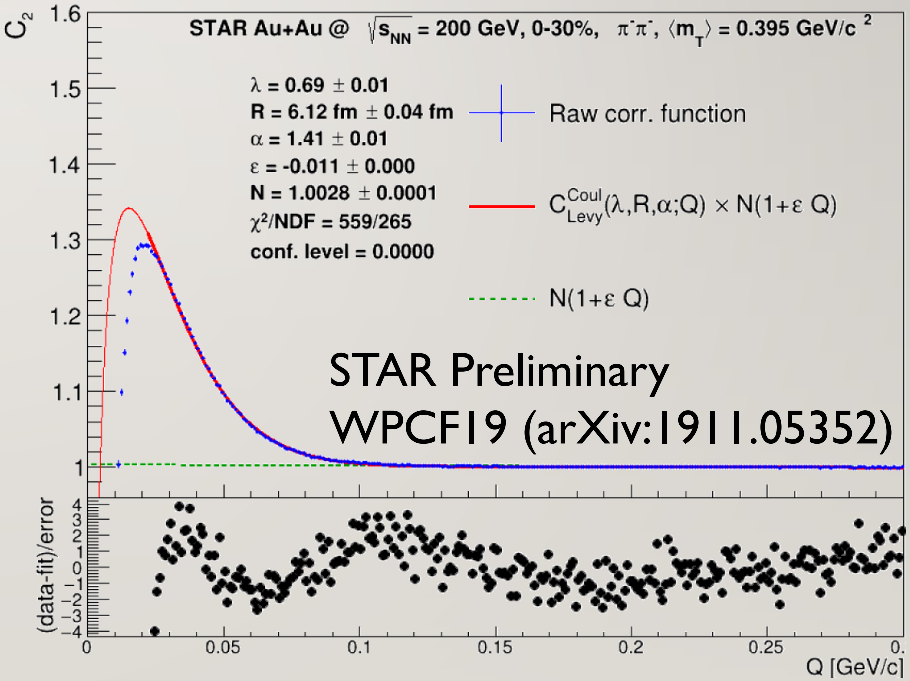


B. Porfy [NA61] WPCF19 & PoS CORFU2018 (2019) 184

RESULTS AT STAR

- Gaussian fit: unacceptable description
- Levy fit somewhat better, but still additional effects present
- Low Q behavior not captured by any of the two





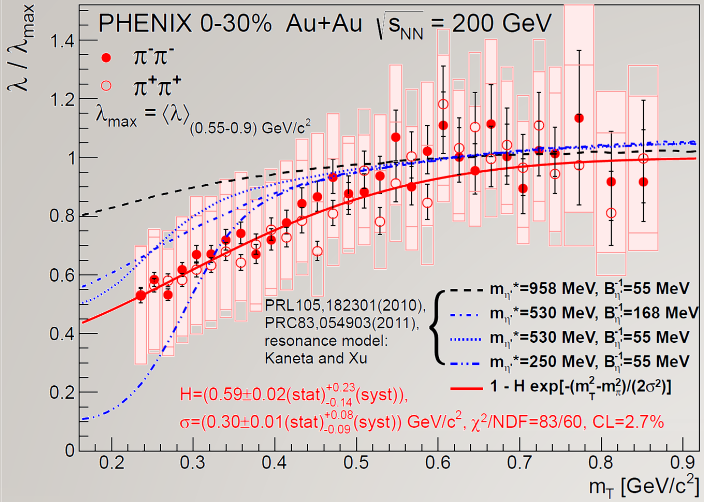
CONTENTS OF THIS TALK

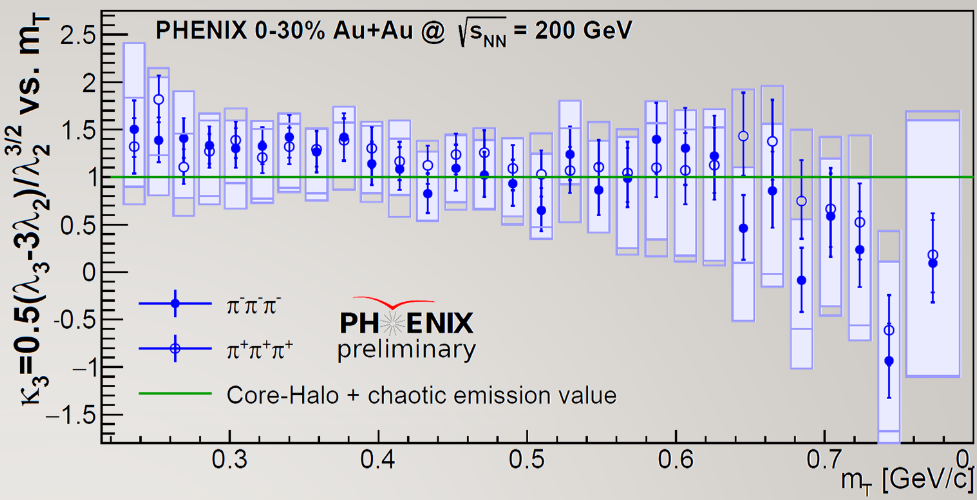
LÉVY HBT STATUS AT PHENIX

- Bose-Einstein correlations measured from 10 GeV to 200 GeV
- Levy fits yield statistically acceptable description
- Levy parameters R, λ, α measured in various collisions
  - Stability parameter $\alpha<2 \leftrightarrow$ anom. diffusion, critical point, QCD jets?
  - 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 of Lévy parameters?
  - 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'?
- 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)





35 THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects:

http://zimanyischool.kfki.hu/20

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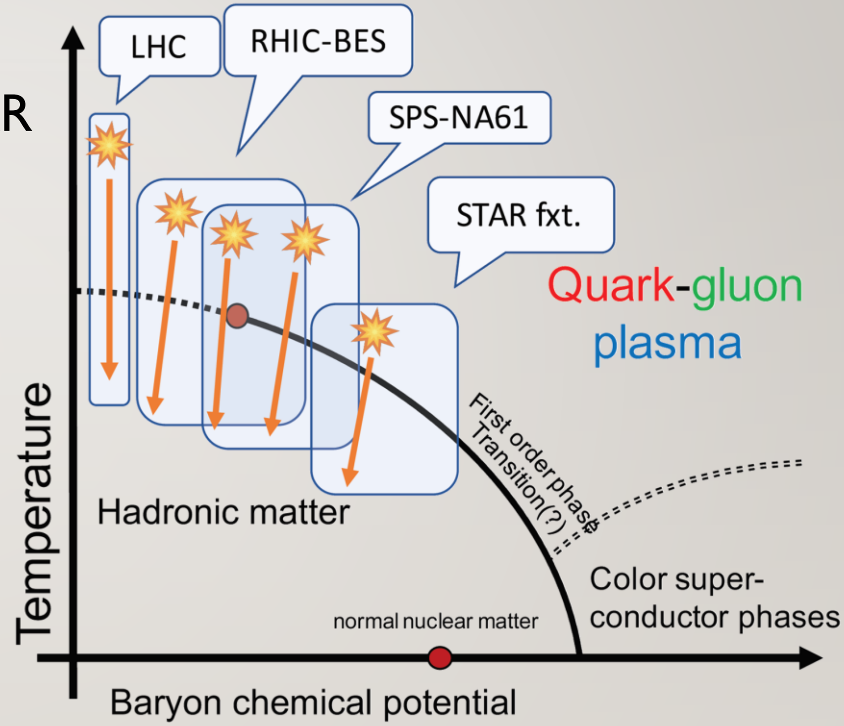
BACKUP

HBT MEASUREMENTS AND THE PHASE DIAGRAM

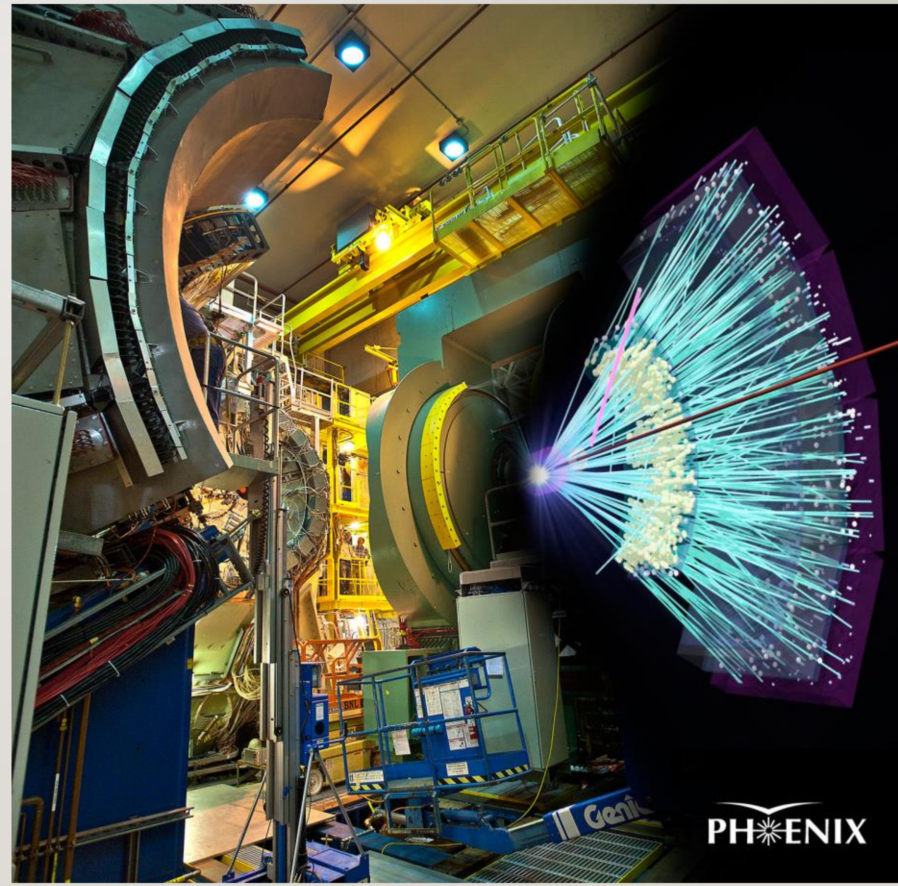
- LHC: measurement at CMS
  - 2-5 ATeV energy, p+p & Pb+Pb
- RHIC: measurement at PHENIX+STAR
  - 10-200 AGeV energy, Au+Au
- SPS: measurement at NA61
  - 17 AGeV energy, Be+Be
- Phase diagram can be investigated



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								✓	



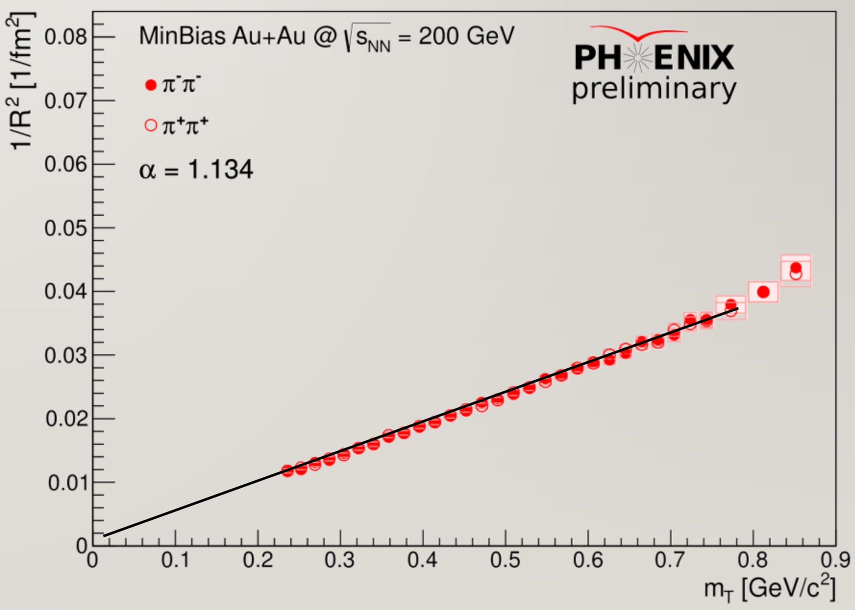
A REALISTIC SOURCE FUNCTION

- Let the source be $S(r) \sim \exp -\frac{r_x^2}{2X^2} - \frac{r_y^2}{2Y^2} - \frac{r_z^2}{2Z^2}$, from there
  $C(k) = 1 + \exp -k_x^2 R_x^2 - k_y^2 R_y^2 - k_z^2 R_z^2$
- In general, $v(r)$ velocity field, $T(r)$ temperature, $n(r)$ density: $S(r) \sim n(r) \exp -\frac{(mv(r)-p)^2}{2mT(r)}$
- Let $v = \left(\frac{\dot{X}}{X} r_x, \frac{\dot{Y}}{Y} r_y, \frac{\dot{Z}}{Z} r_z\right), n = n_0 e^{-\frac{r_x^2}{2X^2} - \frac{r_y^2}{2Y^2} - \frac{r_z^2}{2Z^2}}, T = T_0 \left(\frac{X_0 Y_0 Z_0}{XYZ}\right)^{1/\kappa}$
- Then $R_x^2 = X^2 \left(1 + \frac{m}{T_0} \dot{X}^2\right)^{-1}$
- Not geometrical size!
- Relativistically expanding fireball:

$R_{\rm HBT}^2 = R_{\rm geom}^2 \left(1 + \frac{m_T}{T_0} \dot{R}_{\rm geom}^2\right)^{-1}$ or

$R_{\rm HBT}^{-2} \sim m_T + \rm const$

[Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390]



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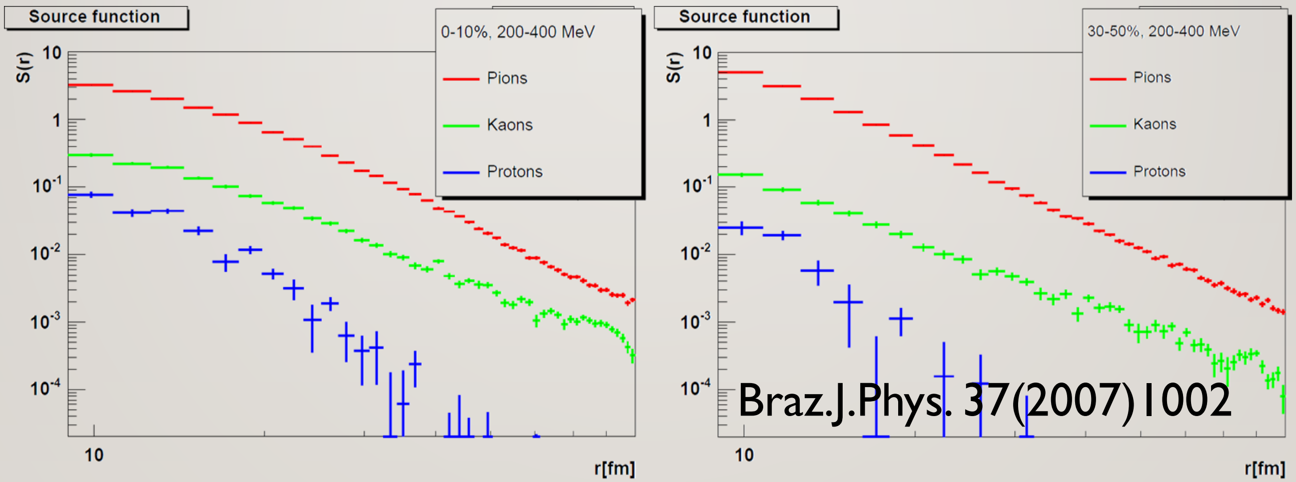
THE IMPORTANCE OF A KAON ANALYSIS

- 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]

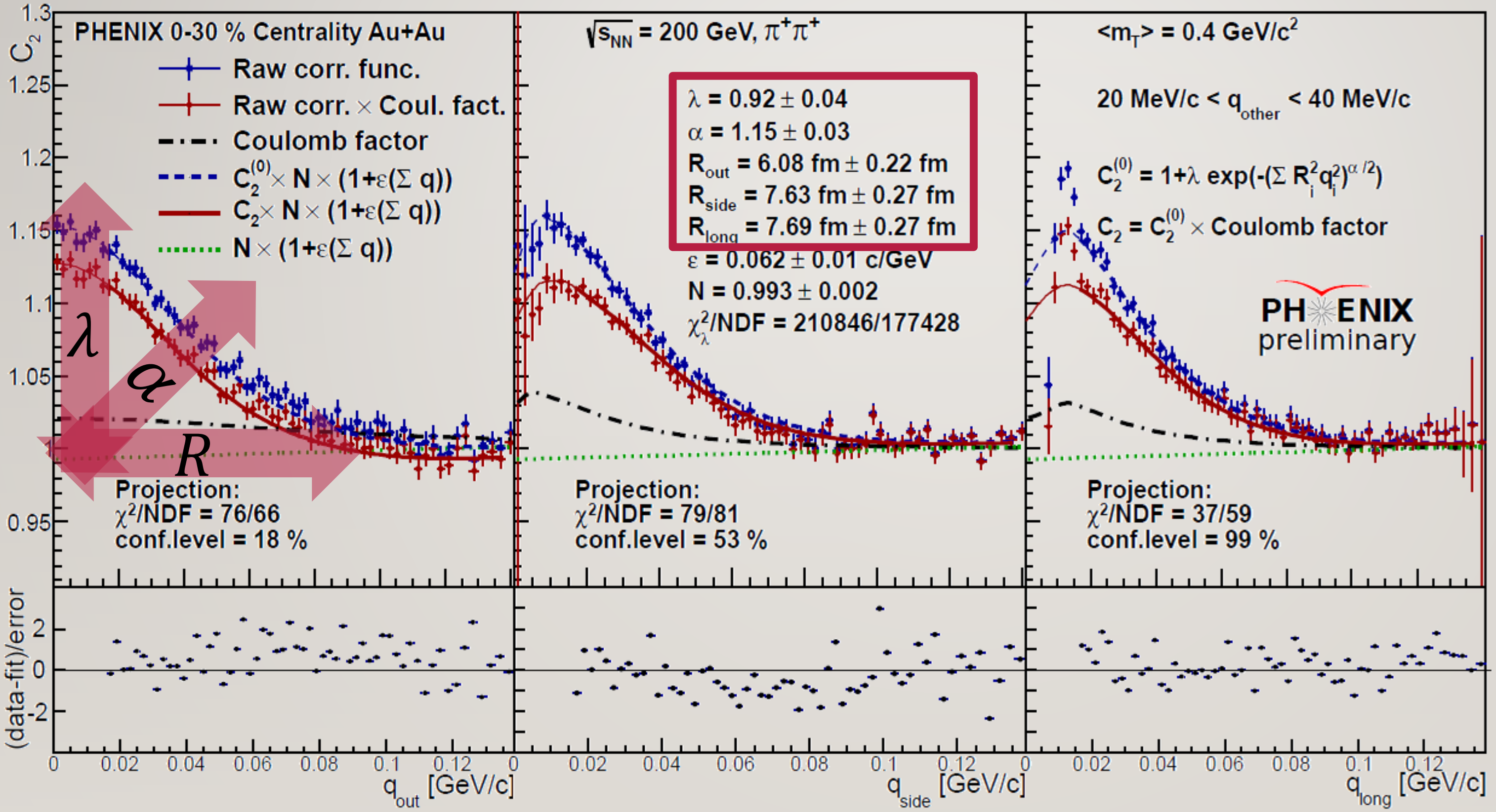
  Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002 [hep-ph/0702032]

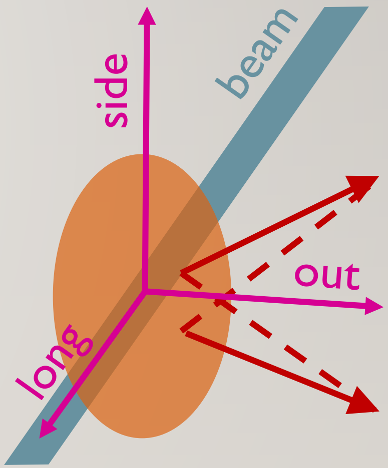


- R_{HBT}(Kaon) mT-scaling or its violation for Lévy scale R?

A CROSS-CHECK: 3D LÉVY FEMTOSCOPY

- Femtoscopy done in 3D: Bertsch-Pratt pair frame (out/side/long coordinates)
- Physical parameters: $R_{out/side/long}$ λ, α measured versus pair m_T
- Fit in this case: modified log-likelihood (small statistics in peak range)





3D VERSUS 1D: STRENGTH λ AND SHAPE α

- Compatible with 1D (Q_{LCMS}) measurement of PRC97(2018)064911
- Small discrepancy at small mT: due to large Rlong at small mT?