Probing the QCD phase diagram with HBT femtoscopy

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Outline

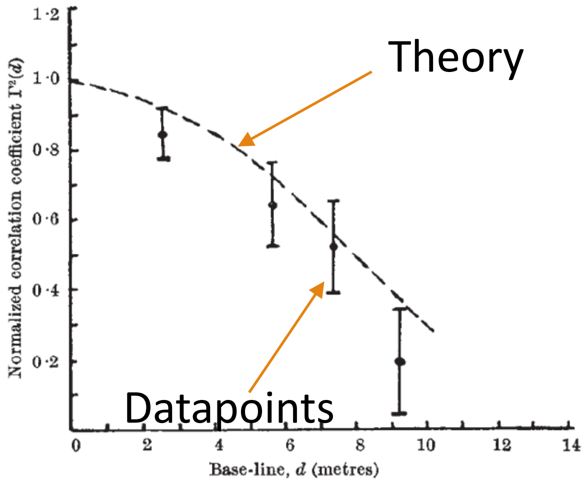
1. HBT interferometry from astrophysics to HEP
2. The Levy parametrization and its possible interpretations
3. Results from RHIC to SPS
4. Conclusion and discussion

Historical remarks

HBT technique originates from radio astronomy

- Hanbury Brown and Twiss observed intensity correlation
- Can be used to measure the angular diameter of stars

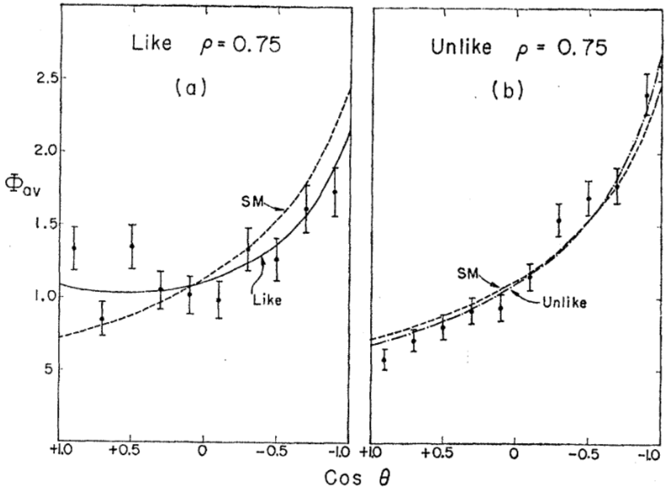
Results for Sirius is consistent with theory



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

Goldhaber, Goldhaber, Lee and Pais searched for the ρ
Found angle correlation of the π mesons (bosons)
Can explain via symmetrization of pair wave function

Birth of femtoscopy in HEP (term coined by Lednicky)
Tool to measure the source size and underlying physical processes



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

Femtoscopy in HEP – general remarks

Technique to access the spatio-temporal structure of the particle emitting source

$$C_2(p_1,p_2) = \frac{N_2(p_1,p_2)}{N_1(p_1)N_1(p_2)}$$

use Yano-Koonin formula to relate the mom. dists. to the source:

$$N_2(p_1,p_2) = \int dx_1 dx_2 S(x_1,p_1) S(x_2,p_2) \left|\Psi_2^{(p_1,p_2)}(x_1,x_2)\right|^2$$

S: source function, Ψ_2: two-particle wavefunction

Femtoscopy – two approaches

$$N_2(p_1, p_2) = \int dx_1 dx_2 S(x_1, p_1) S(x_2, p_2) |\Psi_2(x_1, x_2)|^2$$

Assume the source shape: **$S \sim$ Gaussian**

Measure in a clean environment, e. g. in pp

Learn about the final state interactions hidden in the wave function

Program in ALICE:

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

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

Assume the **wave function**: free planewave

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

Not realistic: Coulomb (and strong) FSI

What is the interacting wave function?

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

$$+\boldsymbol{r} \rightarrow -\boldsymbol{r}$$

(more complicated with strong interaction)

Learn about the source size and shape

Femtoscopy – formulation

Usually pions, kaons, protons are measured

Let's introduce the pair distribution:

$$D_{AB}(x,p) = \int d^3R\ S_A\left(R+\frac{x}{2},p\right) S_B\left(R-\frac{x}{2},p\right)$$

with $K = 0.5(p_1+p_2)$ and $Q = p_1 - p_2$! Also assume that $p_1 \approx p_2$!

The Bowler-Sinyukov formula is given:

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

The simple planewave case (i.e. no FSI):

$$C_2^{(0)}(Q,K) = 1+\lambda\,\frac{\widetilde{D}_c(Q,K)}{\widetilde{D}_c(Q=0,K)}$$

With final state interaction the picture is more complicated (strong, Coulomb, ...)

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

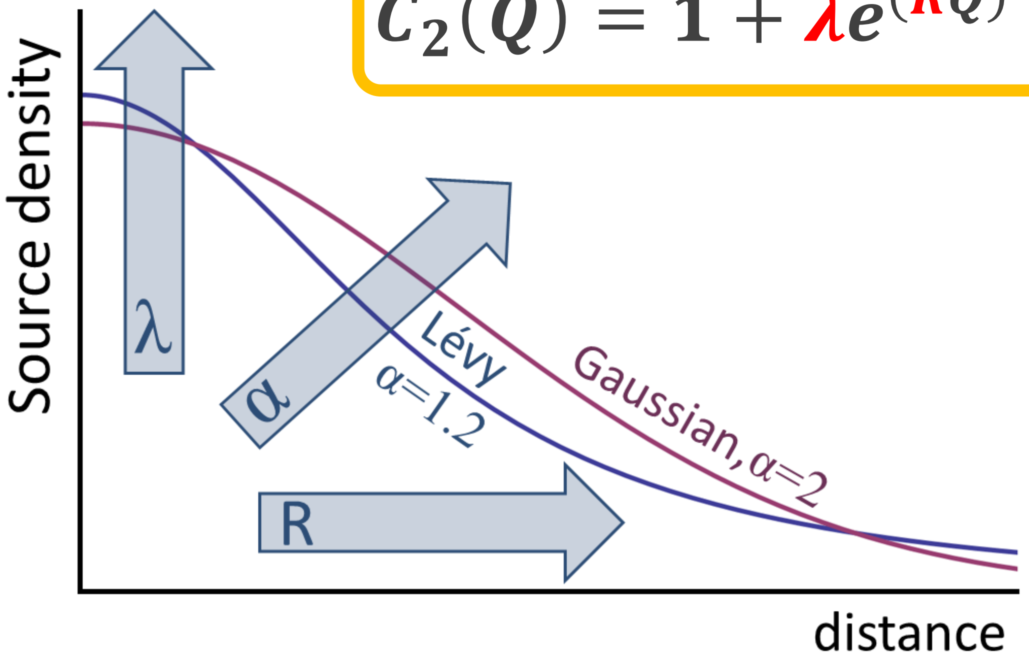
Assume the source to be Levy!

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

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

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

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



Physics in the parameters

Possible interpretations of the λ:

- Specific m_T dependence could be linked to in-medium mass modification effects, partial coherent particle production, final state interactions

Possible interpretation of the R:

- Is it related to the size? Important: $R_{Levy} \neq R_{Gauss}$

Possible interpretation of the α:

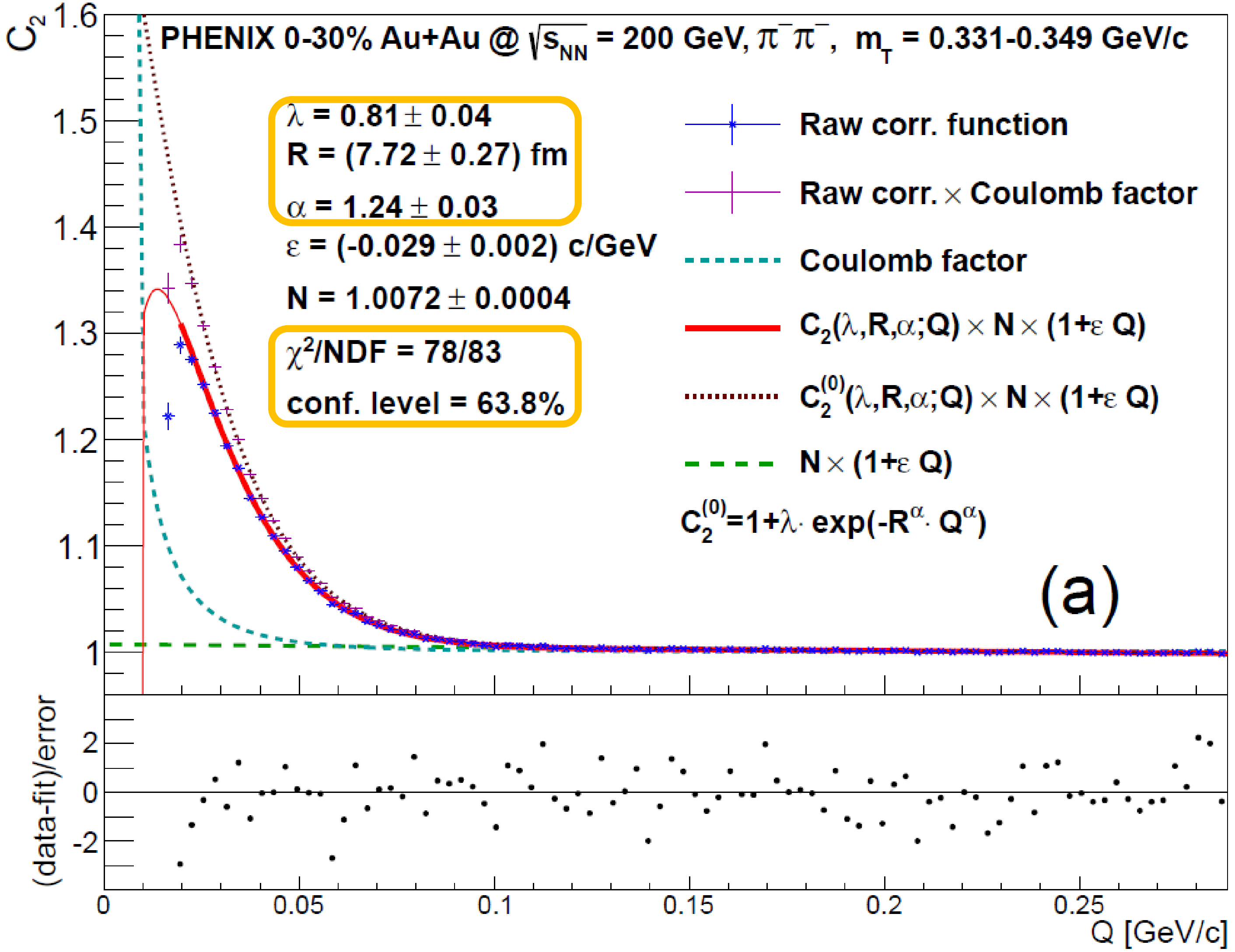
- Surprising similarity with the critical exponent of the spatial correlation in 3D

$$\text{spatial corr.} \sim r^{-1-\eta} \quad \text{???} \quad \text{symm. Levy dist.} \sim r^{-1-\alpha}$$

- Sudden change in α might be a sign for critical behavior
- Could be the sign of anomalous diffusion or jets

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

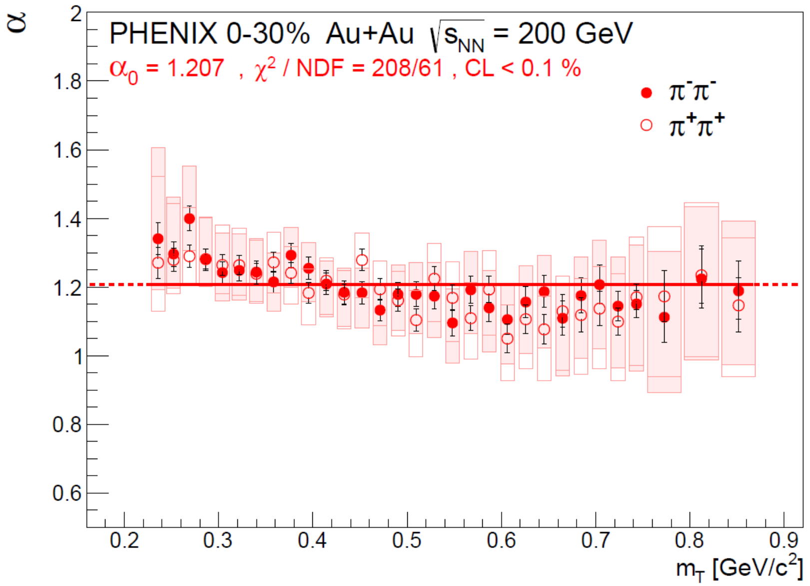
The first results – PHENIX 0-30% Au+Au

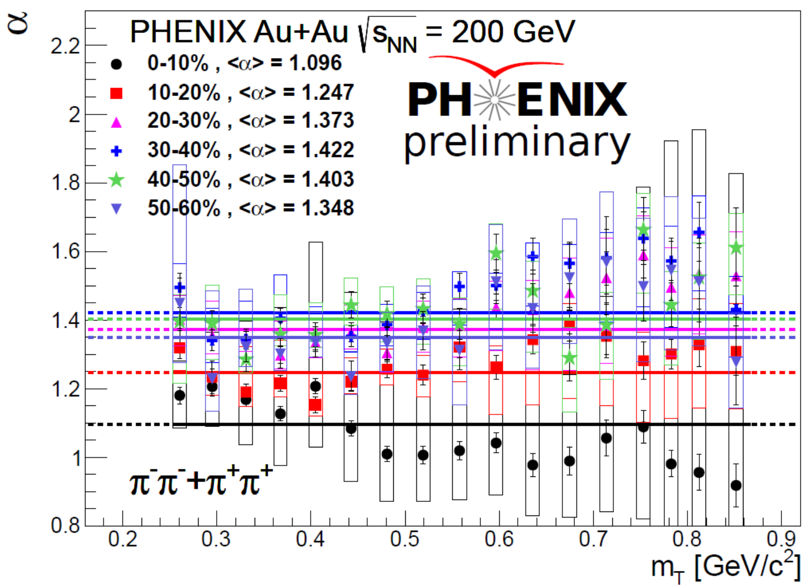


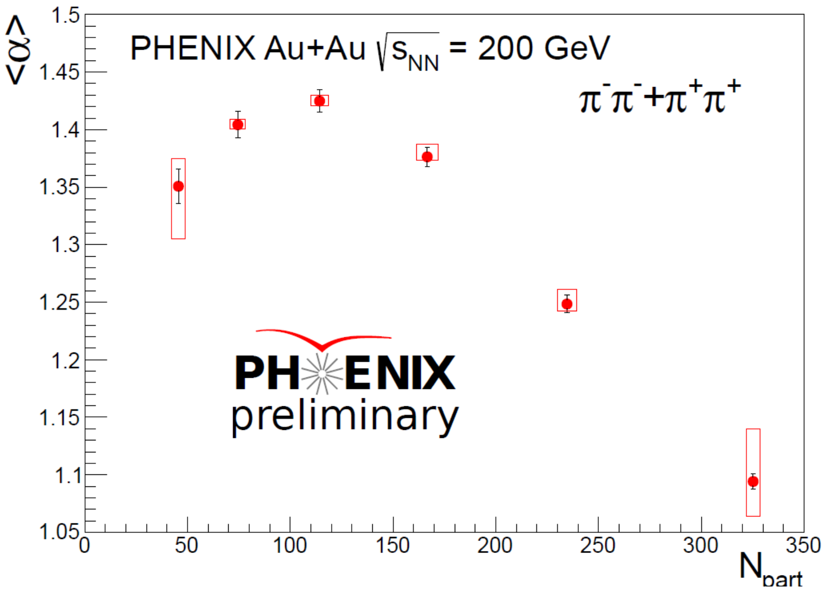
- Measured correlation function in 31 m_T bins with 0-30% cent. selection
- Coulomb correction incorporated into the fit function
- $\alpha \neq 2$ nor $\alpha \neq 1$
- The fits are acceptable in terms of confidence level and χ^2/NDF
- Gaussian parametrization cannot describe the data

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

PHENIX results from Au+Au collision at 200 GeV







- Au+Au from PHENIX
- 0-30% centrality
- Levy is acceptable

- $1 < \alpha < 2\,, \langle\alpha\rangle \approx 1.2$

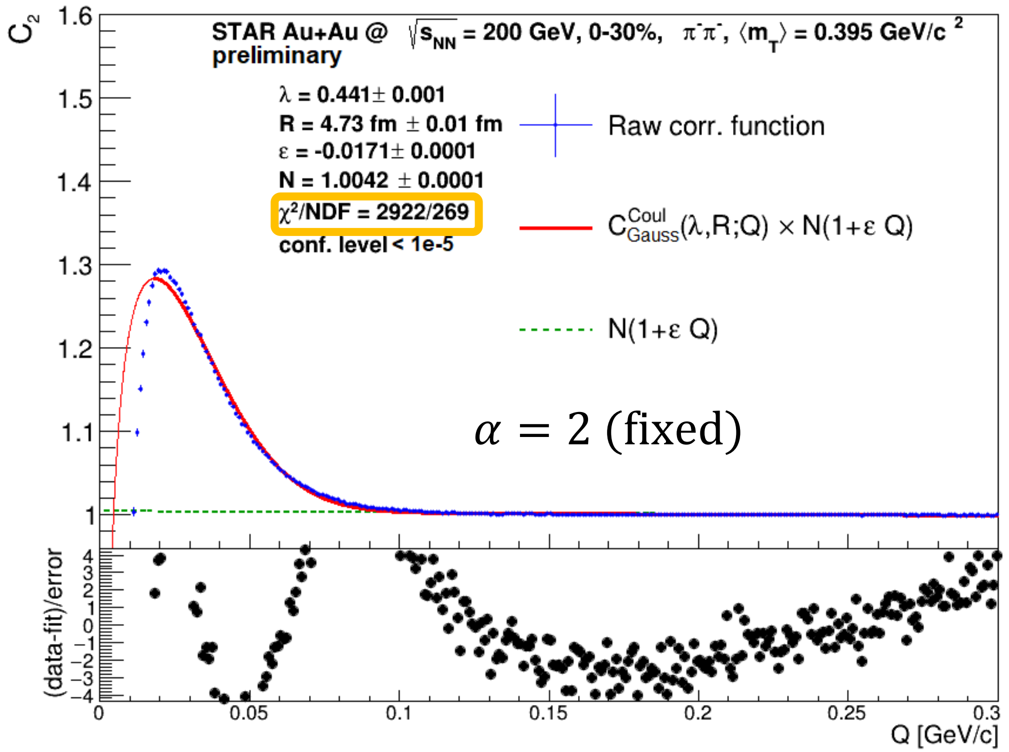
Phys.Rev.C 97 (2018) 6, 064911

- Au+Au from PHENIX
- 10% wide cent. bins: explore mult. dep.
- Levy is acceptable in every bin

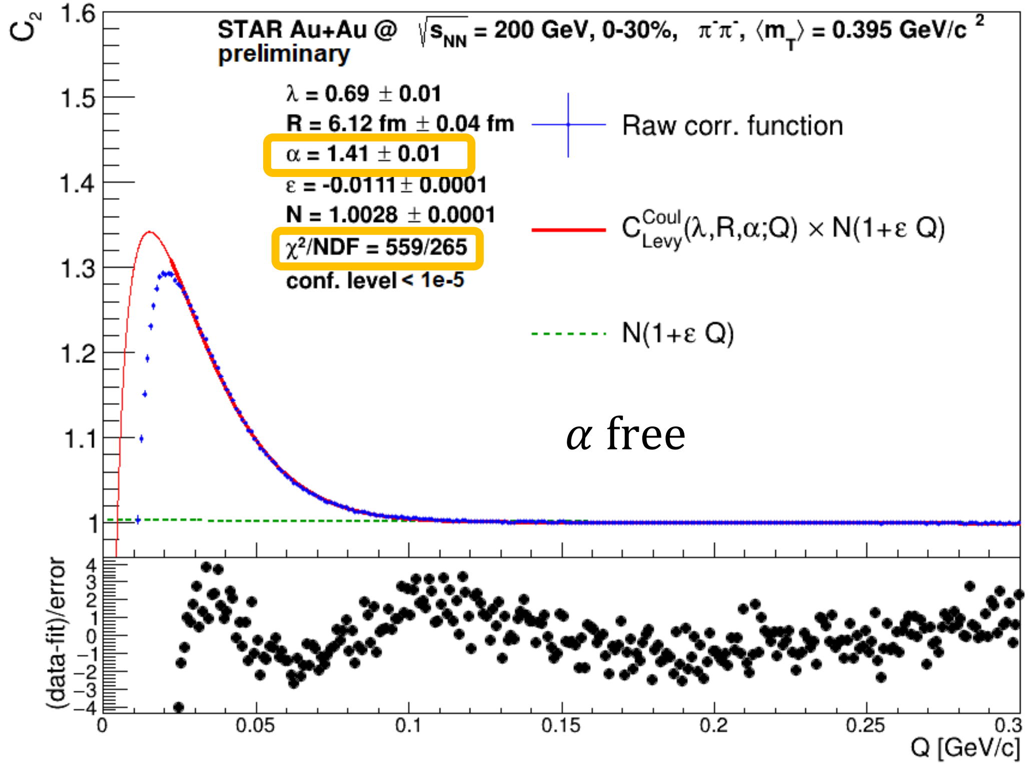
- $1 < \alpha < 2$ and $\alpha(m_T, N_{part}) \approx \alpha(N_{part})$

Universe 4 (2018) 2, 31

STAR 0-30% Au+Au collision at 200 GeV



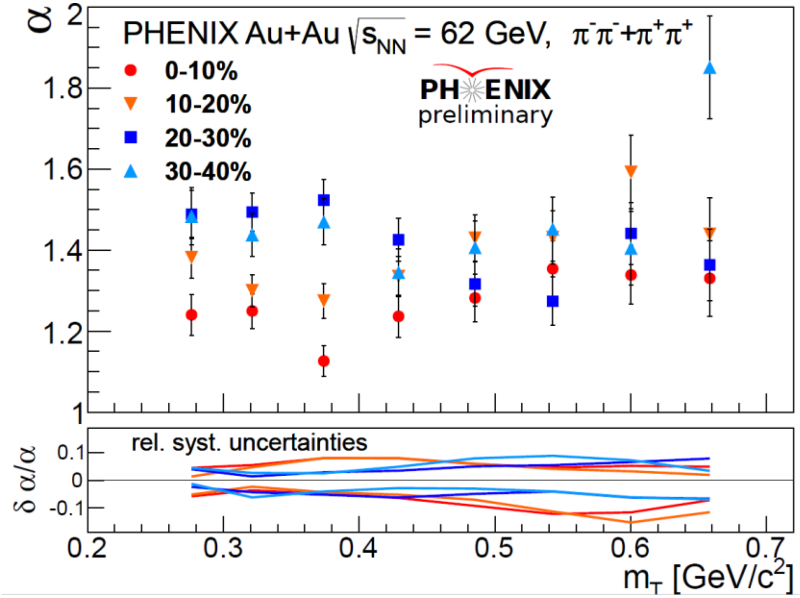
Gaussian

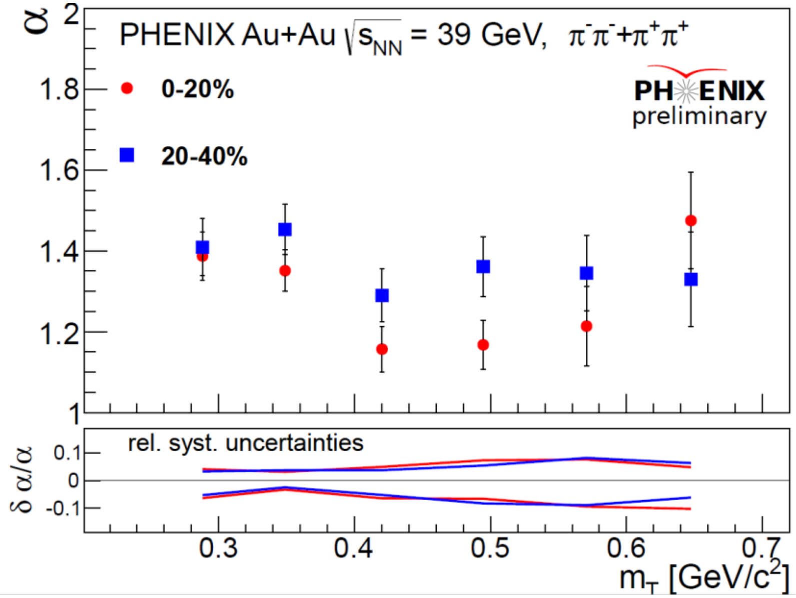


Levy

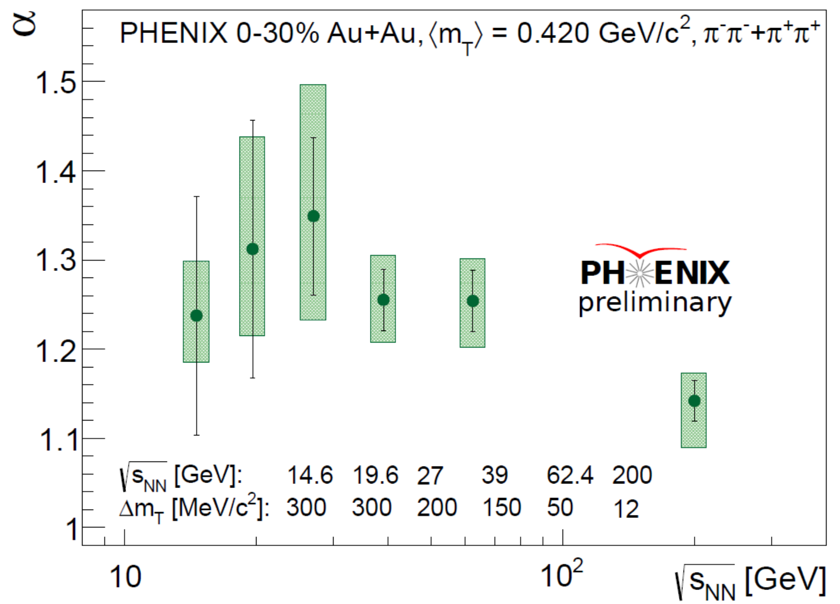
Phys.Part.Nucl. 51 (2020) 3, 267-269

PHENIX Au+Au and NA61 Ar+Sc and Be+Be

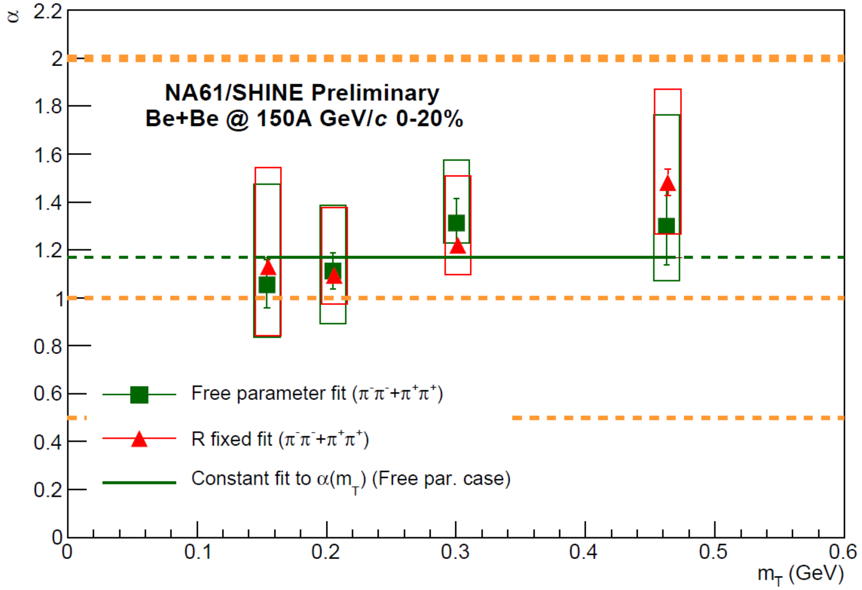




[Universe 4 (2018) 1, 11]



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



- Measured down to $\sqrt{s_{NN}} \sim 15$ GeV
- $1 < \alpha < 2$ and no sudden change observed

[Acta Phys. Pol. B Proc. 12, 451 (2019)]

Summary and outlook

HBT technique is an important tool in high energy physics

Can reveal the source size on the femtometer scale

Precise measurement: Gaussian shape is not sufficient

Assumption of Levy source is statistically acceptable

Results from different experiments, energies, … validate Levy

Levy index might be connected to critical behavior

Explore the high energy part of the phase diagram

THANK YOU FOR YOUR ATTENTION!

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

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

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

Universe 4 (2018) 1, 11

Final state interactions

Like-charged pions → 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