Investigation of the space-time geometry of heavy-ion collisions

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Introduction

- Investigation of the strongly interacting quark gluon plasma (sQGP)
- Now in focus: femtoscopic correlations
- First use: radio astronomy
  R. Hanbury Brown & R.Q. Twiss, 1954-1956: correlation between different photons
- In particle physics: observed correlation between identical pions (p+p+, p-p- pairs) in „high energy” reactions („GGLP effect”, 1960)
- Femtoscopy: in heavy-ion physics we can study the space-time geometry of events happening in the femtometric scale
- For identical boson pairs the correlation is explained as Bose-Einstein correlation

Femtoscopic correlation function

- Investigation of the correlation function of identical boson pairs

$$C_2(q) = \frac{\int d^4x\, D(x,K)\left|\psi_q(x)\right|^2}{\int d^4x\, D(x,K)}$$

- The pair source distribution:

$$D(x,K) = \int d^4X\ S\left(X + \frac{x}{2}, K\right) S\left(X - \frac{x}{2}, K\right)$$

- If final state particles move freely, the wave-function is symmetric
  ⇒ the correlation is the Fourier-transform of the source function

$$C_2(q,K) = 1 + \frac{\widetilde{D}(q,K)}{\widetilde{D}(0,K)}$$

$$\widetilde{D}(q,K) = \int d^4x\, D(x,K) e^{-iqx}$$

- $C(q,K)$ can be measured in experiments
- The $D(x,K)$ function can be reconstructed in event generators

Lévy-type source function

- Experimental (and phenomenological) indications: power-law tail for pions, non-Gaussianity?

T. Csorgo, S. Hegyi and W. A. Zajc, Eur. Phys. J. C 36 (2004), 67-78
A. Adare et al. [PHENIX], Phys. Rev. C 97 (2018) no.6, 064911

- Generalised Gaussian ⇒ Lévy-function
- General form of the function:

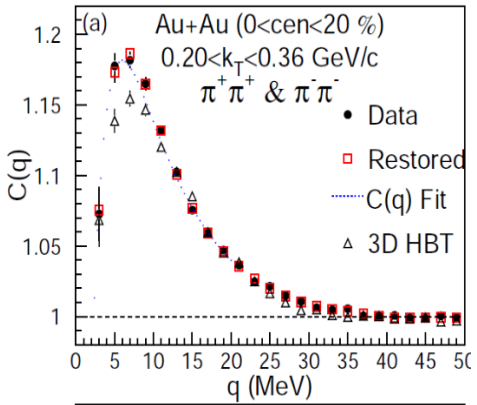
$$\mathcal{L}(r, R_x, R_y, R_z, \alpha) = \frac{1}{(2\pi)^3} \int d^3q\, e^{iqr} e^{-\frac{1}{2}\left|q_x^2 R_x^2 + q_y^2 R_y^2 + q_z^2 R_z^2\right|^{\frac{\alpha}{2}}}$$

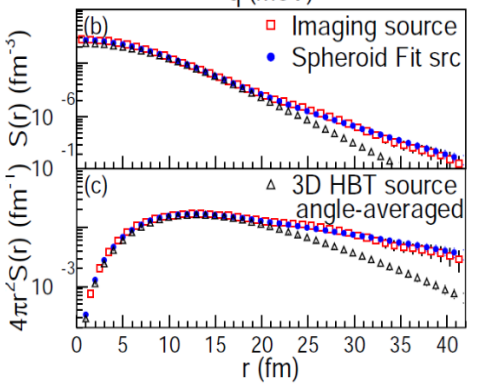
- 1 dimensional case:

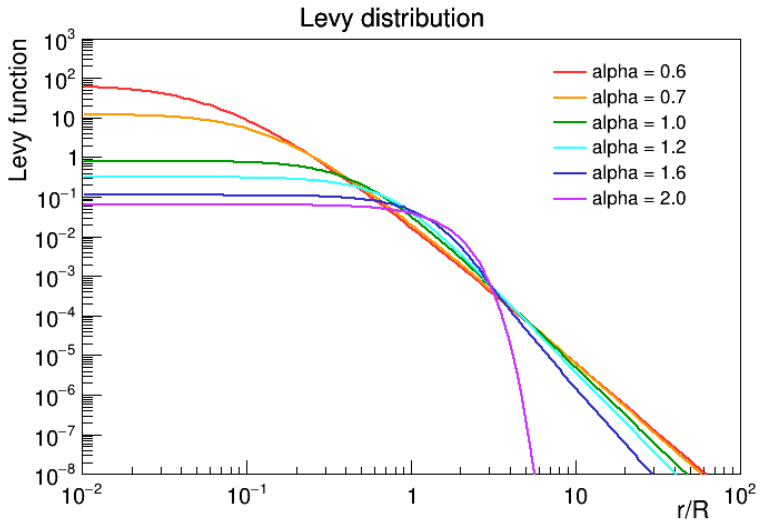
$$\mathcal{L}(r, R, \alpha) = \frac{1}{\pi} \int_0^\infty dq \cos qr\, e^{-\frac{1}{2}qR}$$

- Lévy exponent: $\alpha<2$ power-law, $\alpha=2$ Gaussian
- Lévy-scale: R, geometric properties

$$S(r) = \mathcal{L}(r, R, \alpha) \quad \Rightarrow \mathrm{D}(r) = \mathcal{L}\left(r, 2^{\frac{1}{\alpha}}R, \alpha\right)$$





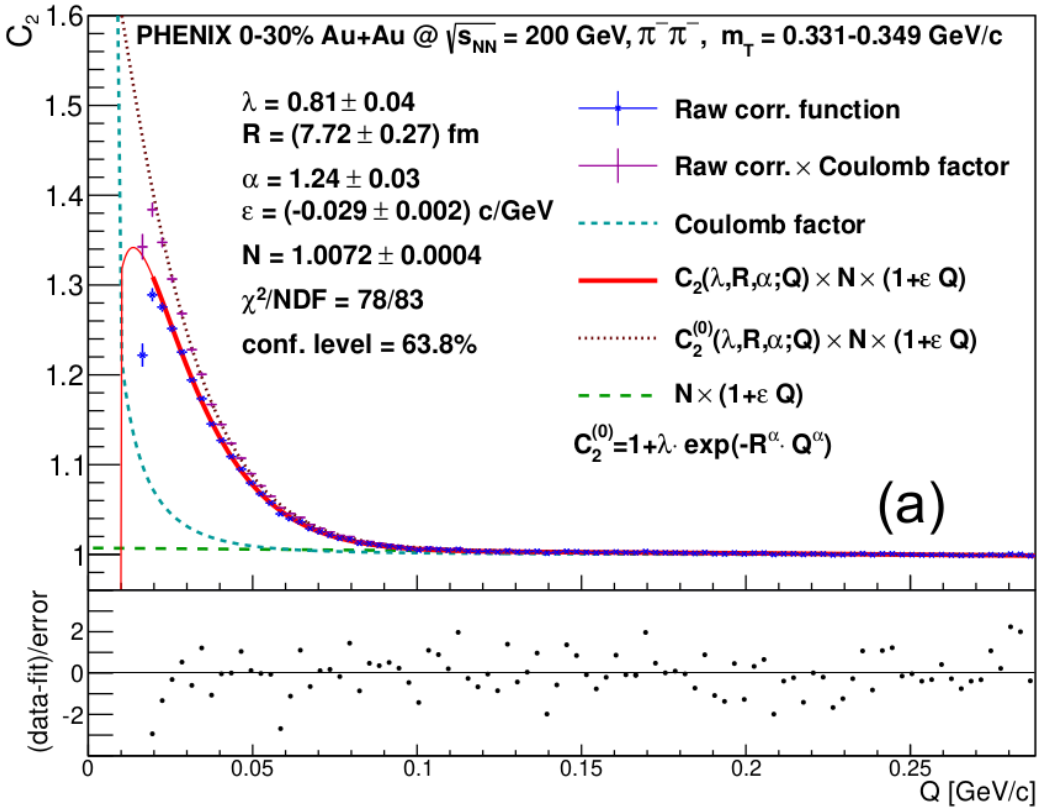


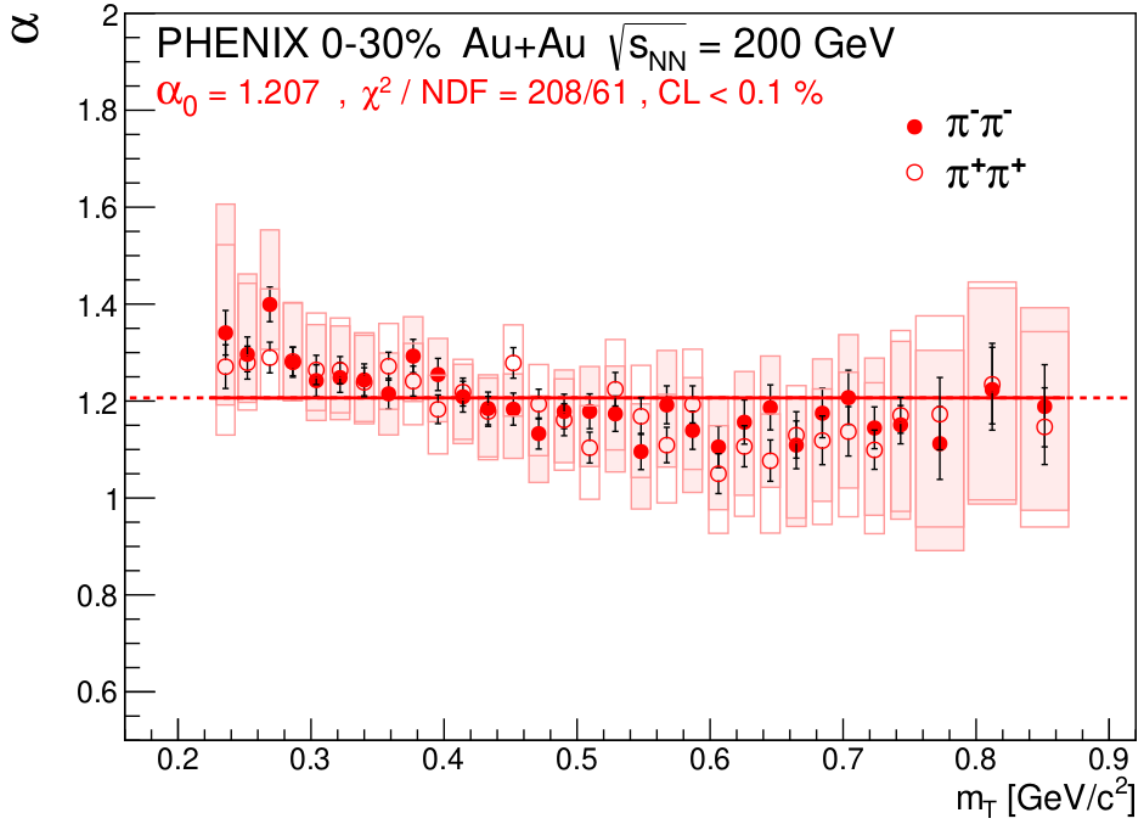
Possible explanations of the Lévy-shape

- Resonance decays Kincses, Stefaniak, Csanád, Entropy24 (2022) 3, 308
- Jet fregmentation Csörgő, Hegyi, Novák, Zajc, Acta Phys. Polon. B 36, 329 (2005)
- Critical behavior Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828
- Anomalous diffusion Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002
- Event-averaging/ direction-averaging Cimerman, Tomasik, Plumberg, Phys.Part.Nucl.51(2020)3,282

Previous results

- Experimental results from PHENIX A. Adare et al. [PHENIX], Phys. Rev. C 97 (2018) no.6, 064911

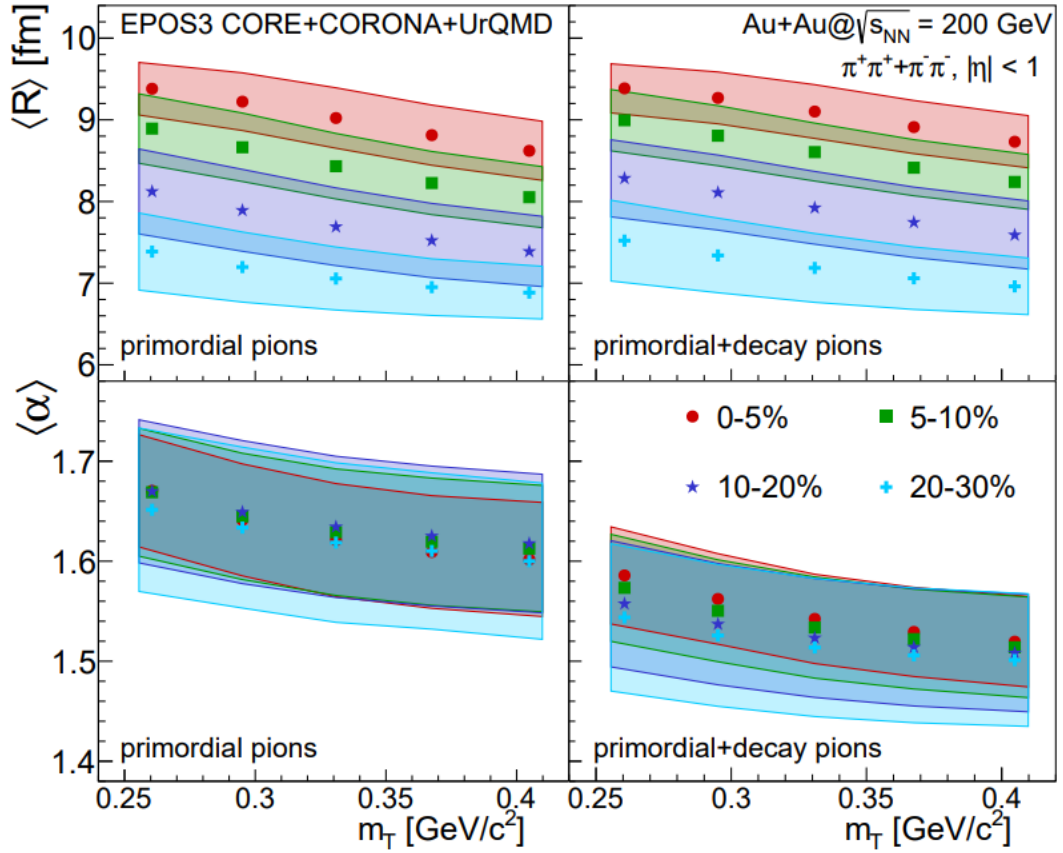




Previous results

- Event-by-event pion pair-source analysis at 200 GeV with EPOS event generator

D. Kincses, M. Stefaniakand M. Csanád, Entropy 24 (2022) no.3, 308



3D analysis

- EPOS: event generator of heavy-ion collisions
- Event-by-event and 3 dimensional investigation to see if the Lévy shape is the result of event-averaging or direction averaging
- Pion pair source function fitted with Lévy distribution

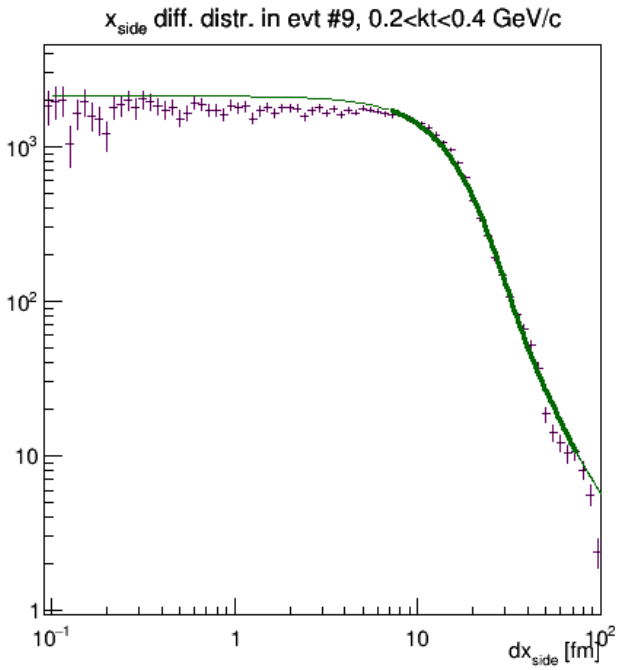
$$\mathrm{D}(r) = \mathcal{L}\left(r, 2^{\frac{1}{\alpha}}R_{out}, 2^{\frac{1}{\alpha}}R_{side}, 2^{\frac{1}{\alpha}}R_{long}, \alpha\right)$$

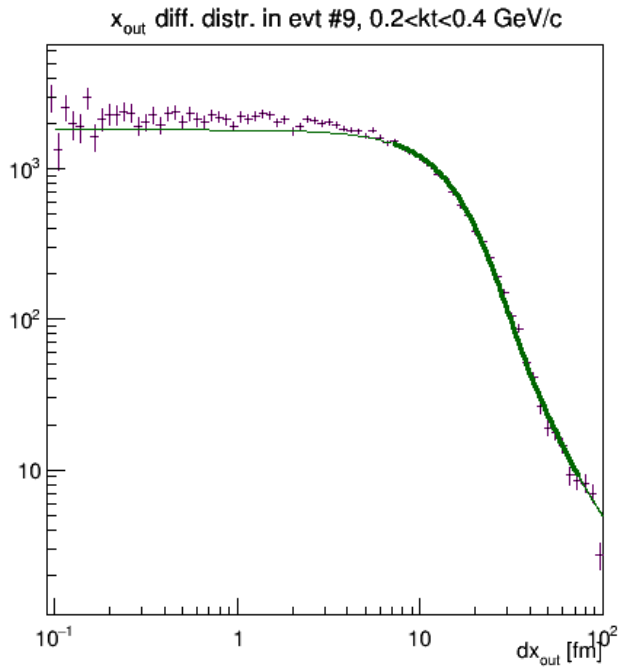
- Event-by-event distributions of pion pairs
- Separated the measurements into centrality and k_T classes
- 3 dimensional pair-distribution ⇒ 1 dimensional projections according Bertsch-Pratt-coordinates
  ⇒ fitting 1 dimensional Lévy-functions to the projections

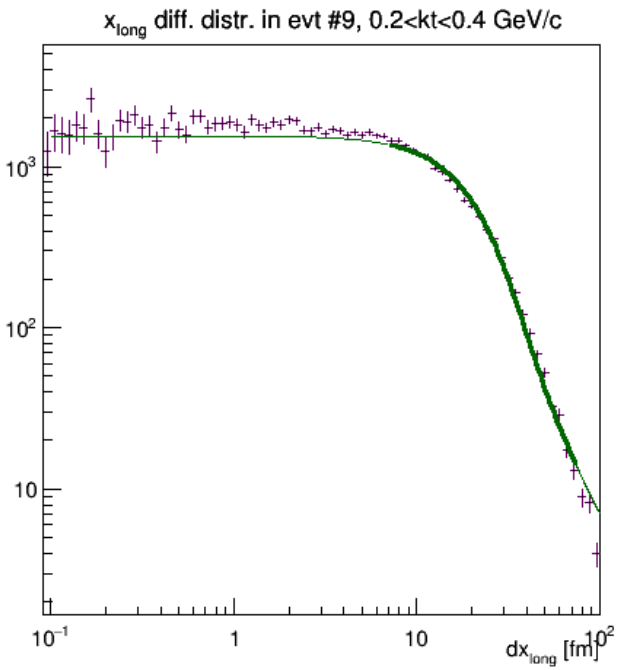
$$\mathcal{L}\left(r, R_{out,side,long}, \alpha\right) = \frac{1}{\pi}\int_0^\infty dq \cos qr \, e^{-\frac{1}{2}qR_{out,side,long}}$$

- For the 3 projection of a 3D distribution: fitting simultaneously with same Lévy exponent but different Lévy scales

3D analysis

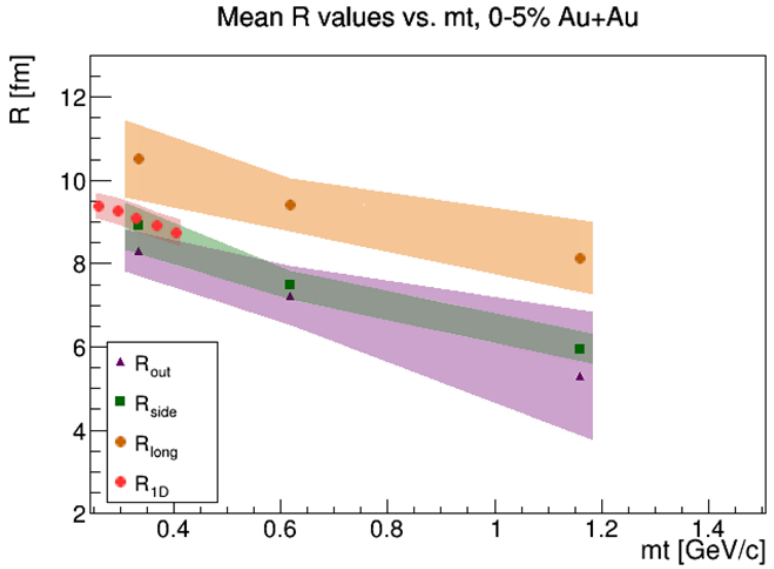

x_{side} diff. distr. in evt #9, 0.2<kt<0.4 GeV/c
10^3
10^2
10
1
10^{-1}
1
10
10^2
dx_{side} [fm]

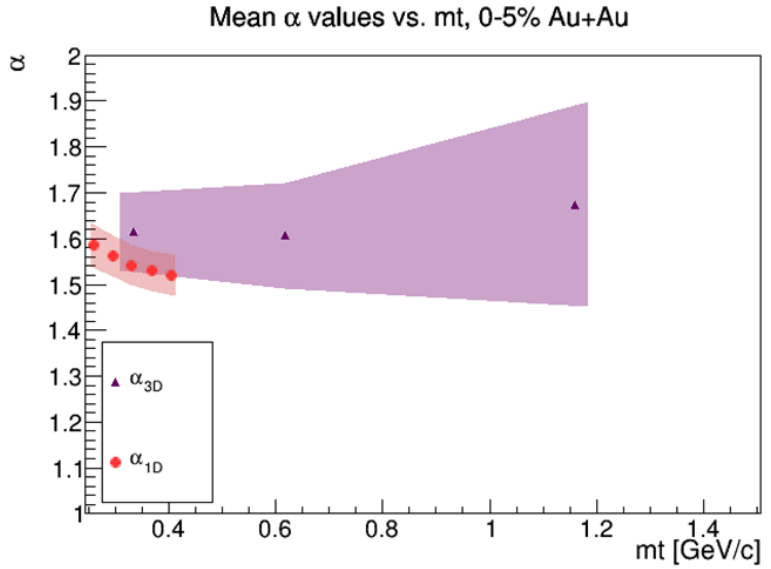

x_{out} diff. distr. in evt #9, 0.2<kt<0.4 GeV/c
10^3
10^2
10
10^{-1}
1
10
10^2
dx_{out} [fm]


x_{long} diff. distr. in evt #9, 0.2<kt<0.4 GeV/c
10^3
10^2
10
10^{-1}
1
10
10^2
dx_{long} [fm]

Results

- Lévy-exponent: $\alpha \approx 1.6 - 1.7$, not Gaussian ($\alpha \neq 2$)
- Lévy-scale: different values for the different projections (with the same α-s)
- Lévy-scale is decreasing with increasing m_t
- Lévy shape is not the result of event-averaging or direction averaging
- Results agree with 1D analysis of Ref. D. Kincses, M. Stefaniak and M. Csanád, Entropy 24 (2022) no.3, 308





Summary

- Investigation of sQGP
- Femtoscopic correlation function
- Lévy source function instead of Gaussian
- Lévy-shape is not a result of event averaging or direction averaging

Thank you for your attention!