Bose-Einstein correlations of charged kaons produced by $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions at the STAR experiment

ELTE
EÖTVÖS LORÁND UNIVERSITY

STAR

XV. WORKSHOP ON PARTICLE CORRELATIONS AND FEMTOSCOPY

DÁNIEL KINCSES FOR THE STAR COLLABORATION

EÖTVÖS UNIVERSITY, BUDAPEST

FACILITY FOR RARE ISOTOPE BEAMS, MICHIGAN STATE UNIVERSITY, JULY 2022

FRIB

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Brookhaven National Laboratory

Part I: Introduction, motivation

- **Basic definitions of femtoscopic correlation functions**
- **What is the shape of the source?**
- **Appearance of Lévy-type sources in heavy-ion collisions**

Basic definitions of femtoscopic correlation functions

phase-space density

Pair wave function, contains FSI

- **Single particle distribution:** $N_1(p) = \int dx\, S(x,p)$
- **Pair momentum distr.:** $N_2(p_1,p_2) = \int dx_1 dx_2 S(x_1,p_1) S(x_2,p_2) |\psi(x_1,x_2)|^2$
- **Correlation function:** $C(p_1,p_2) = \frac{N_2(p_1,p_2)}{N_1(p_1)N_2(p_2)}$

relative coordinate

- **Pair source/spatial correlation:** $D(r,K) = \int d^4\rho S\left(\rho + \frac{r}{2}, K\right) S\left(\rho - \frac{r}{2}, K\right)$

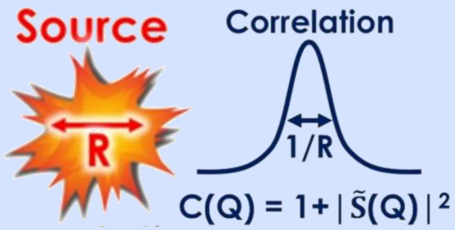
relative pair momentum

average pair momentum

Pair wave func., contains FSI

$$\psi_Q(\boldsymbol{r}) = \frac{1}{\sqrt{2}} \frac{\Gamma(1+i\eta)}{e^{\pi\eta/2}} \{e^{i\boldsymbol{qr}} F(-i\eta, 1, i(kr - \boldsymbol{qr})) + [\boldsymbol{r} \leftrightarrow -\boldsymbol{r}]\}$$

$$C(Q,K) = \frac{\int D(r,K)|\psi_Q(\mathrm{r})|^2 dr}{\int D(r,K) dr}$$



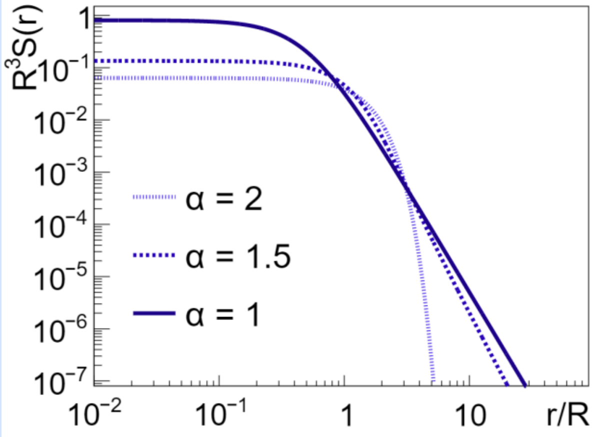
- **Experiments: measuring C(Q) to gain information about D(r)**

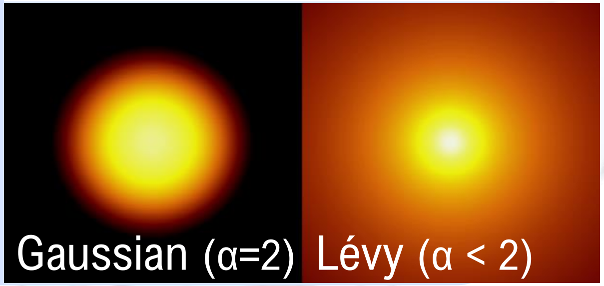
What is the shape of the source?
Gaussian & Lévy distributions in heavy ion physics

$$S(r,K) = \mathcal{L}(\alpha,R;r) = \frac{1}{(2\pi)^3}\int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$$

- **Experimental indications – power-law component in pion pair-source**

$\alpha < 2$
- **STAR** Au+Au@200 GeV — *Phys.Part.Nucl. 51 (2020) 3, 267-269*
- **PHENIX** Au+Au@200 GeV — *Phys.Rev. C97 (2018) no.6, 064911*
- **NA61/SHINE** Be+Be@150A GeV — *Universe 5 (2019) 6, 154*
- **CMS** Pb+Pb@5.02 TeV — *CMS-PAS-HIN-21-011*





- **Symmetric Lévy-stable distribution**
  - From generalized central limit theorem, power-law tail (if $\alpha < 2$) ~ $r^{-(1+\alpha)}$
  - $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy
  - Retains the same α under convolution

$$S(r,K) = \mathcal{L}(\alpha,R;r) \Rightarrow D(r,K) = \mathcal{L}\left(\alpha, 2^{1/\alpha}R; r\right)$$

  - K dependence appear in source parameters

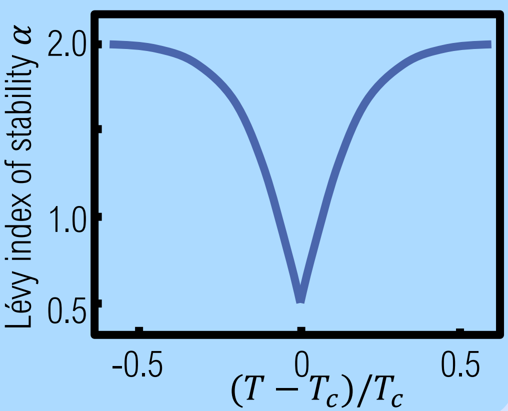
Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67-78;
Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828;
Metzler, Klafter, Physics Reports 339 (2000) 1-77;
Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002;
Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon. B36
Kincses, Stefaniak, Csanád, Entropy 24 (2022) 3, 308
Halasz et al., Phys.Rev.D58 (1998) 096007
Stephanov et al., Phys.Rev.Lett.81 (1998) 4816
Rieger, Phys.Rev.B52 (1995) 6659

Appearance of Lévy-type sources in heavy-ion collisions (Au+Au @ 200 GeV)

- **Possible (competing) reasons for the appearance of Lévy-type sources:**
  1. **Jet fragmentation**
  2. **Proximity of the critical endpoint**
  3. Event averaging (different shapes)?
  4. Resonance decays?
  5. Anomalous diffusion

- **Fractal phenomena in QCD jets**
  - Jets emitting jets, emitting jets, …
  - *Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon. B36*

- **2nd order phase transitions: critical exponents**
  - Spatial correlations $\sim r^{-d+2-\eta}$ at CEP
  - Lévy source: $\sim r^{-(1+\alpha)}$; $\boldsymbol{\alpha \Leftrightarrow \eta}$?
  - QCD ↔ (random field) 3D Ising model
  - $\eta = 0.50 \pm 0.05$
  - *Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828;*



Not relevant for Au+Au @ 200 GeV

Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67-78; Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002;
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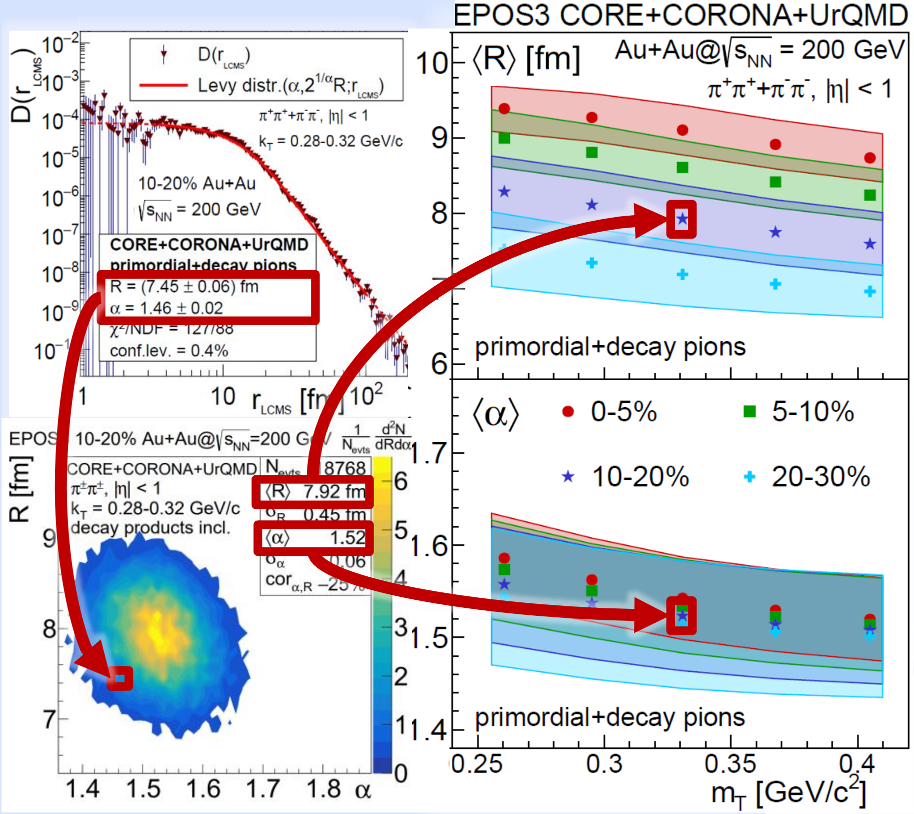
- **EPOS 200 GeV Au+Au collisions: Event-by-event non-Gaussianity!!!**
  - Single-event Lévy fits → good description
  - power-law tail strongly affected by rescattering, decays; $2 > \alpha_{EPOS} > \alpha_{exp}$
  - Lévy shape not from event averaging!

D. Kincses, M. Stefaniak, M. Csanád, Entropy 24 (2022) 3, 308



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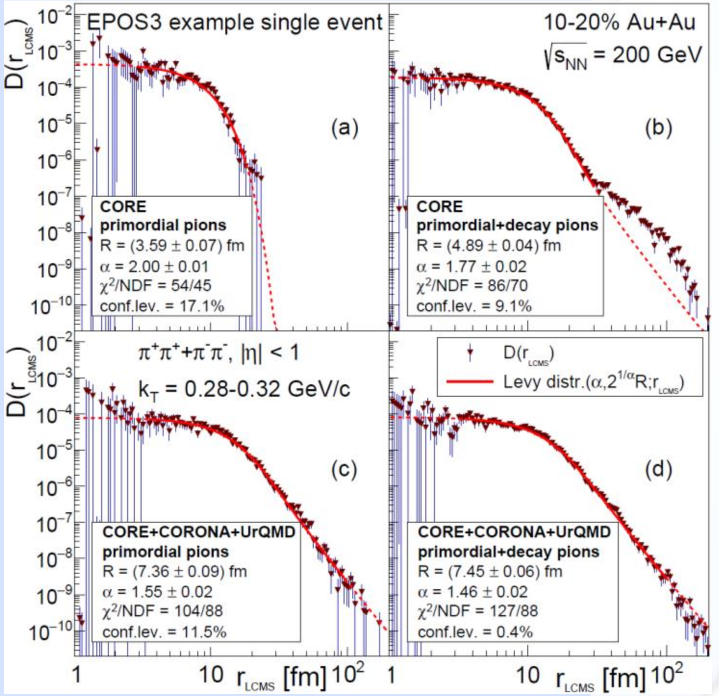
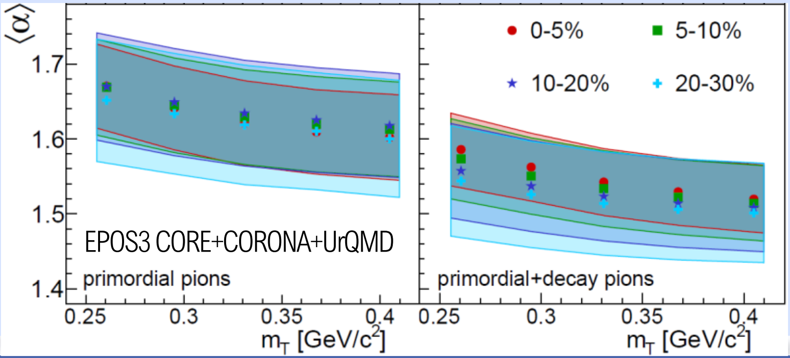
  5. Anomalous diffusion
- **Decay pions create power-law-like structures**
  - Without rescattering not perfectly Lévy
  - With rescattering: **stronger tail with decays included**!





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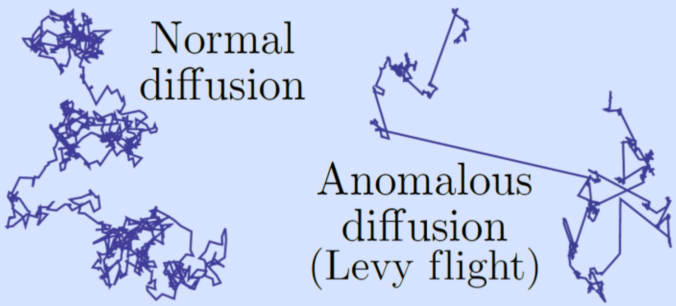


- **Elastic rescattering of hadrons**
  - Expanding hadron gas → time dependent increasing mean free path
  - Hadronic Resonance Cascade (HRC) model
    - α depends on total inelastic cross-section
    - $\alpha_{\pi}^{HRC} > \alpha_{K}^{HRC}$ (smaller c.s. → larger m.f.p.)

Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002;

T. J. Humanic, Int. J. Mod. Phys. E 15, 197 (2006)

- **Kaon vs. pion measurements can test the anom.diff. picture**

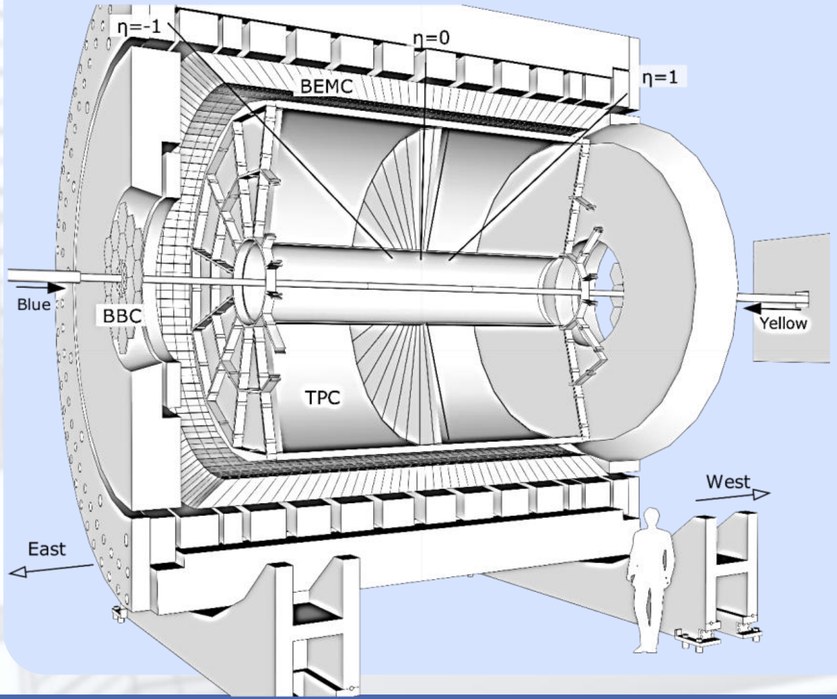
Motivation for Lévy femtoscopy with kaons!

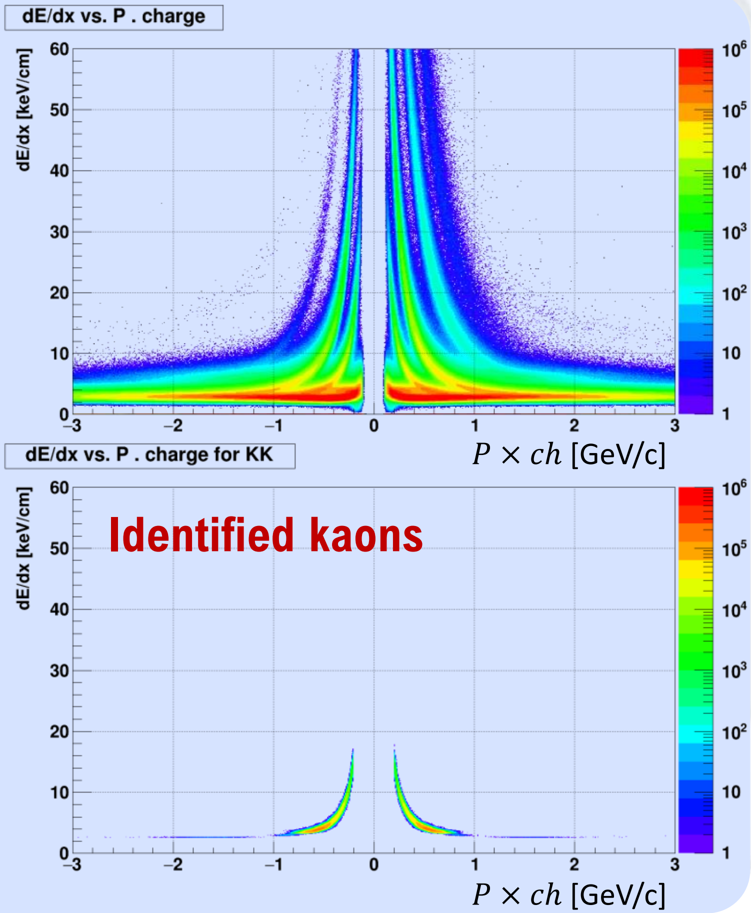
Part II: Measurement and fitting of correlation functions, preliminary results

- The STAR detector
- Measurement of the kaon-kaon correlation functions
- An example fit for 0-30% 200 GeV Au+Au collisions
- Average transverse mass dependence of the Lévy source parameters

The STAR detector

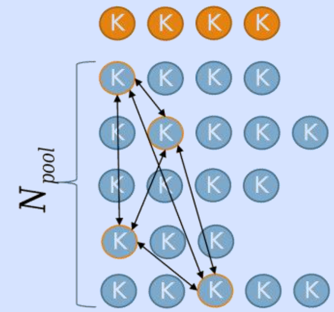
- **Detectors used for the analysis:**
  - **BBC, ZDC, VPD:** centrality, vertex position
  - **TPC:** tracking, dE/dx PID

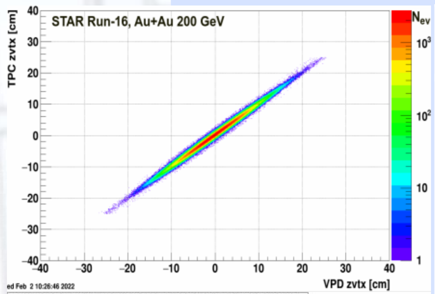


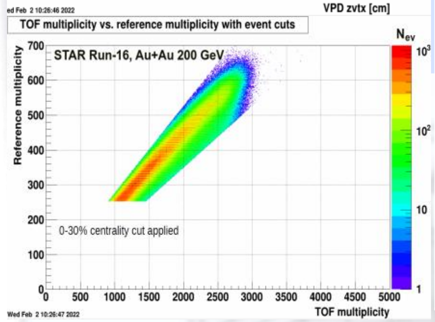


Measurement of the $K^{\pm}K^{\pm}$ correlation functions

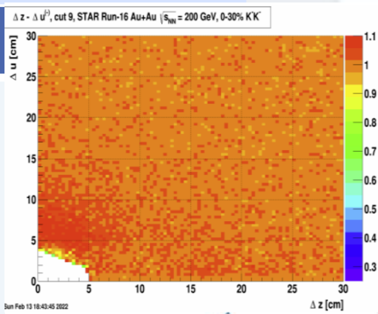
- Analyzing data from **200 GeV Au+Au, Run-16**
- Measurements of **1D two-kaon HBT correlation functions**
- **Event mixing** is done similarly to *Phys.Rev. C97 (2018) no.6, 064911*
  - 2 cm wide z vertex bins, 5% wide centrality bins
  - C(Q) = A(Q) / B(Q)

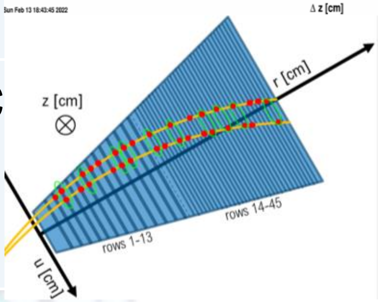






Event cuts	Single track cuts	Pair cuts
Vertex position $\lvert v_z \rvert$ < 30 cm $\lvert v_z^{vpd}$-$v_z^{TPC}\rvert$ < 3 cm v_r < 2 cm	PID $N_\sigma(K)$ < 1, $N_\sigma(\pi,p,e)$ > 3 Number of TPC hits N_{hits} > 18	Splitting level SL < 0.6 Frac. of merged hits FMH < 0.001 *J. Adams et al. (STAR Coll.), Phys. Rev. C 71, 044906 (2005)*
Charged particle multiplicity cuts	0.2 GeV/c < p_T < 4.0 GeV/c	Geometric cuts on TPC local coordinates $\langle\Delta u\rangle^{pad\ rows}$, $\langle\Delta z\rangle^{pad\ rows}$
0-30% centrality	Dist. of Closest Appr. DCA < 3 cm	





Fitting process with Lévy parametrization

- **Lévy parametrization without final state effects:**

$$C^{(0)}(Q) = 1 + \lambda \cdot e^{-|RQ|^{\alpha}}$$

Lévy exponent

LCMS three-momentum difference

$Q = |\boldsymbol{q}_{LCMS}| =$

$= \sqrt{(p_{1x} - p_{2x})^2 + (p_{1y} - p_{2y})^2 + q_{long,LCMS}^2}$

Intercept parameter (correlation strength)

Lévy scale parameter

- **Bowler-Sinyukov procedure:**

$$C(Q) = \left(1 - \lambda + \lambda \cdot \overbrace{K(Q;\alpha,R)}^{\text{Coulomb correction}} \cdot \left(1 + e^{-|RQ|^{\alpha}}\right)\right) \cdot \overbrace{N \cdot (1 + \varepsilon Q)}^{\text{Possible linear background (usually negligible)}}$$

- **Coulomb-correction:**

Two-particle wave function (with Coulomb interaction)

$$K(Q;\alpha,R) = \frac{\int D(r)\left|\psi^{Coul}(r)\right|^2 dr}{\int D(r)\left|\psi^{(0)}(r)\right|^2 dr}$$

→ **calculated numerically**

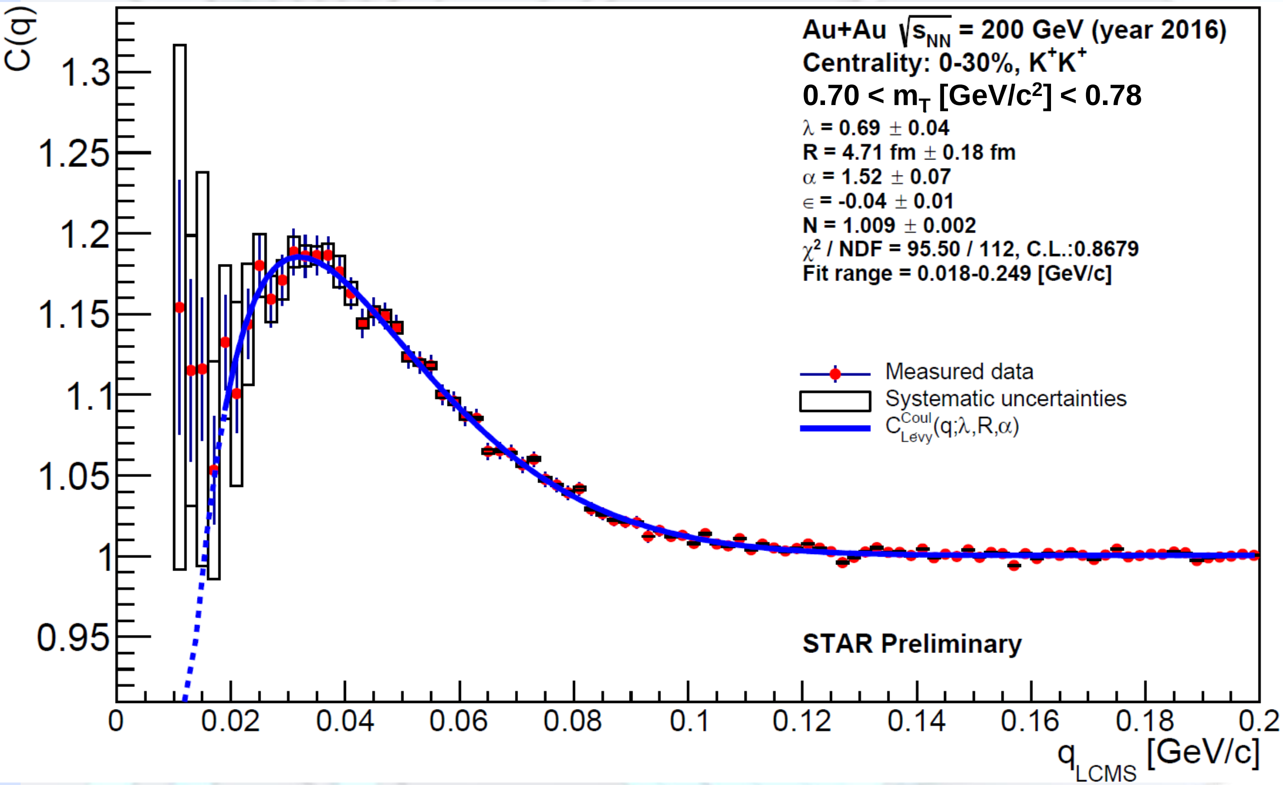
Spatial correlations

Two-particle wave function (plane wave)

An example K^+K^+ Lévy fit

- 0-30% Au+Au @ 200 GeV
- K^+K^+ correlation function
- $k_T = 0.5\sqrt{K_x^2 + K_y^2}$
- $m_T = \sqrt{k_T^2 + m_K^2}$
- 0.5 GeV/c < k_T < 0.6 GeV/c
- 0.70 GeV/c^2 < m_T < 0.78 GeV/c^2
- Confidence level 87%
- Pair cut syst. uncertainties illustrated with boxes (not incl. in fit)

- **Good description over the whole q_{LCMS} range**
- **Lévy exponent α = 1.52, far from Gaussian (α = 2)**



Average tranverse mass dependence of the Lévy source parameters

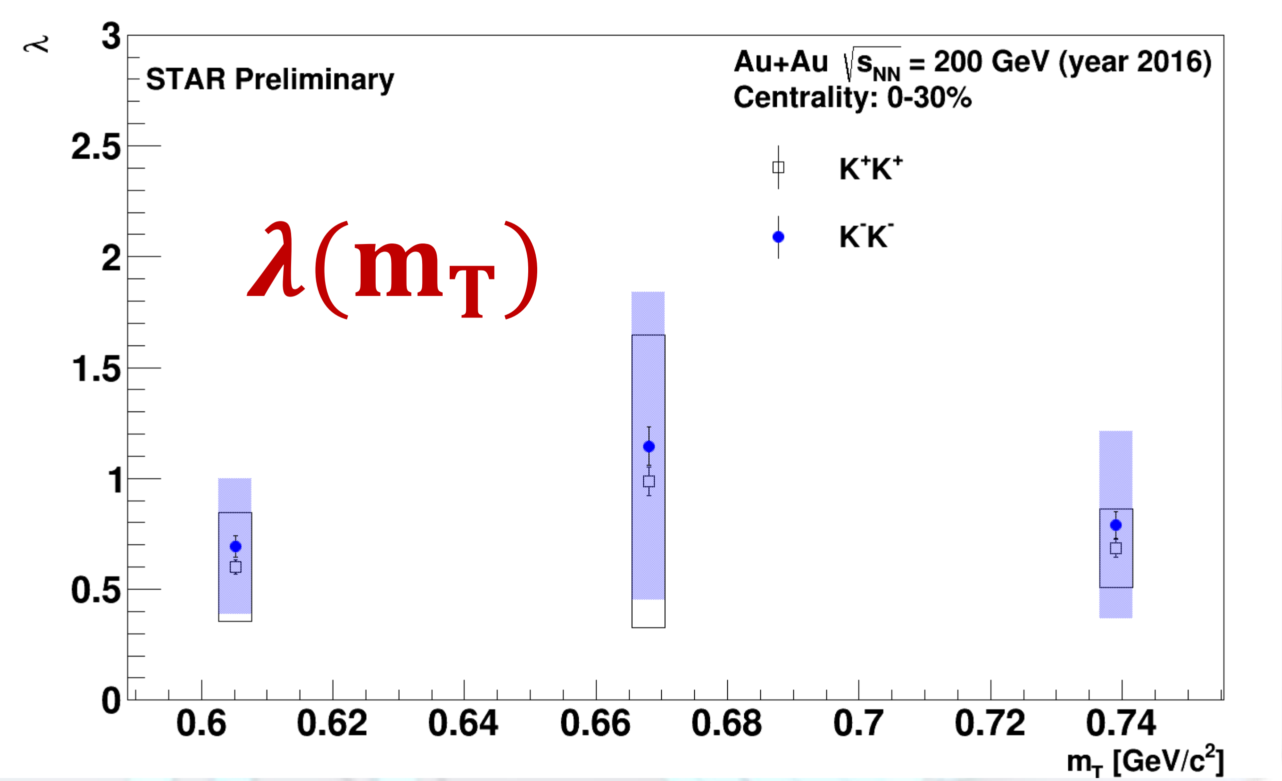
- Weak m_T dependence, large systematic uncertainties
- λ values close to unity (within systematic uncertainties)
- Core-Halo model:

$$\lambda = \frac{N_{Core}}{N_{Core} + N_{Halo}} \approx 1$$

Small frac. of decay kaons

Core – prim. + short-lived decays

Halo – long-lived decays



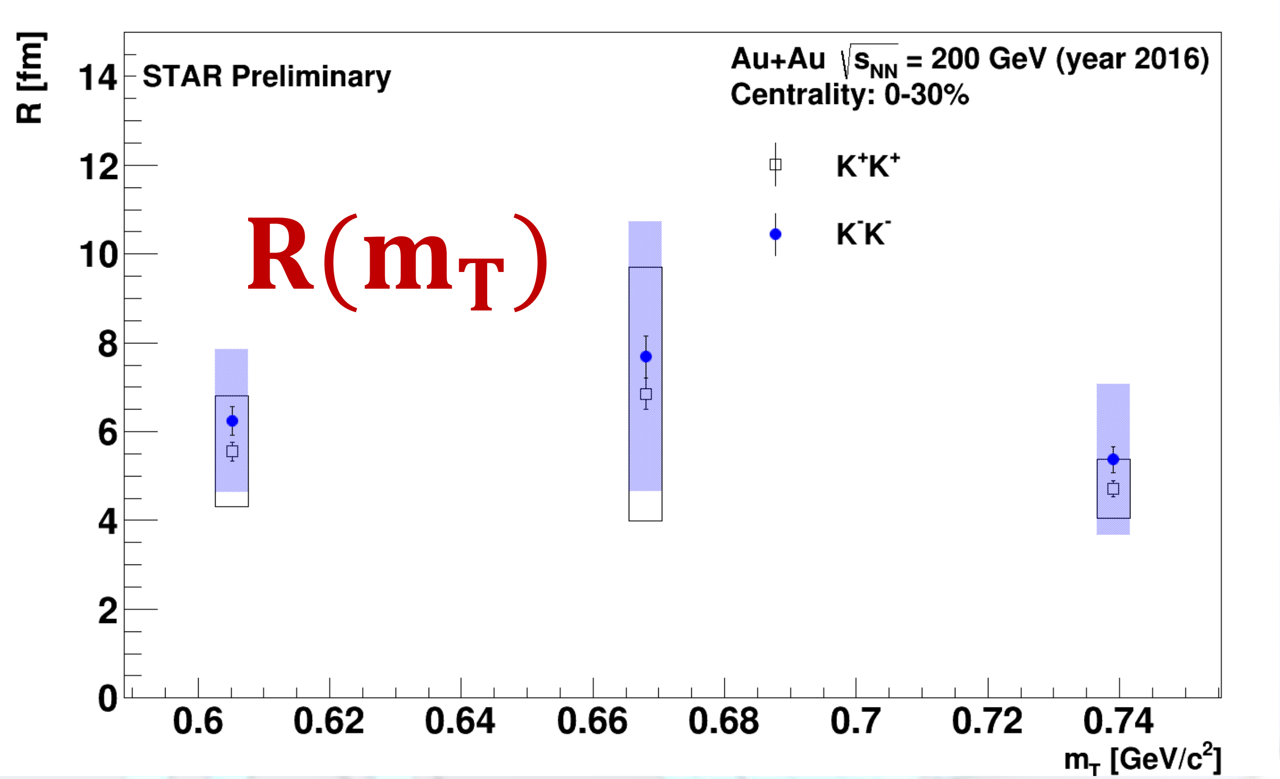
Average tranverse mass dependence of the Lévy source parameters

- Weak m_T dependence, large systematic uncertainties
- R values close to PHENIX pion results

$R_\pi^{exp} \simeq 7\text{ fm} - 5\text{ fm}$
$m_T = 0.6 - 0.7\text{ GeV}/c^2$

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

- Not incompatible with usual decreasing behavior (hydro expansion)

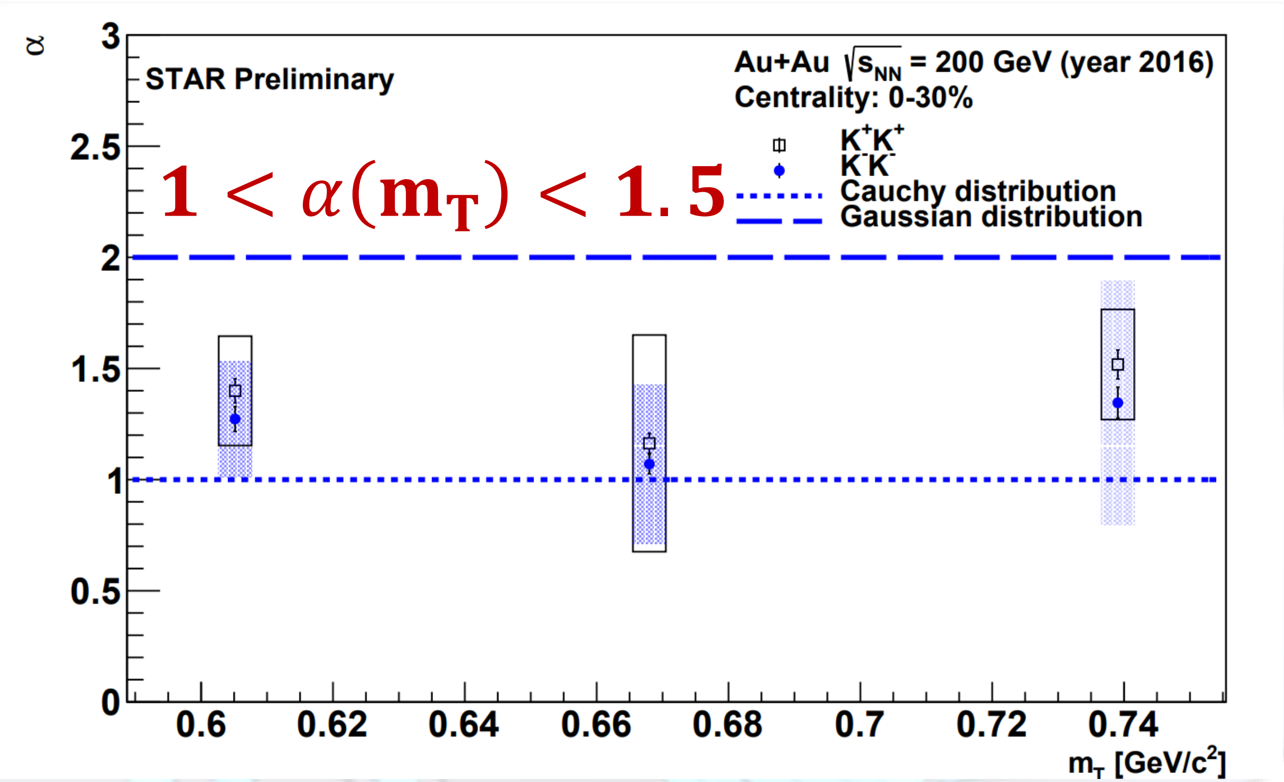


Average tranverse mass dependence of the Lévy source parameters

- Weak m_T dependence, large systematic uncertainties
- α values close to PHENIX pion results
  $\alpha_\pi^{exp} \simeq 1.2$
  (Phys.Rev. C97 (2018) no.6, 064911)

$$\alpha_K^{exp} \simeq \alpha_\pi^{exp} \overset{?}{\Leftrightarrow} \alpha_\pi^{HRC} > \alpha_K^{HRC}$$

- **Preliminary results indicate non-Gaussian kaon pair-source function**



Supported by the ÚNKP-21-4 New National Excellence Program of the Hungarian Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund

Summary, outlook

STAR

Thank you for your attention!

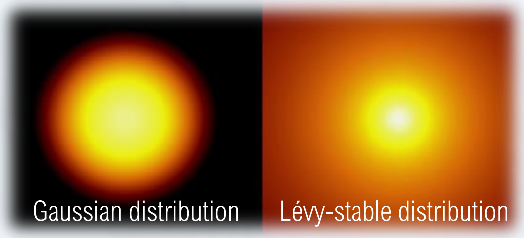
- **Preliminary results for identical charged kaon correlations indicate Lévy sources for central Au+Au collisions @ 200 GeV**
- **Lévy exponent α comparable to pion results** $\alpha_K^{exp} \simeq \alpha_\pi^{exp} \overset{?}{\Leftrightarrow} \alpha_\pi^{HRC} > \alpha_K^{HRC}$
- **Next step: more thorough systematic uncertainty analysis, centrality dependence, $\sqrt{s_{NN}}$ dependence**

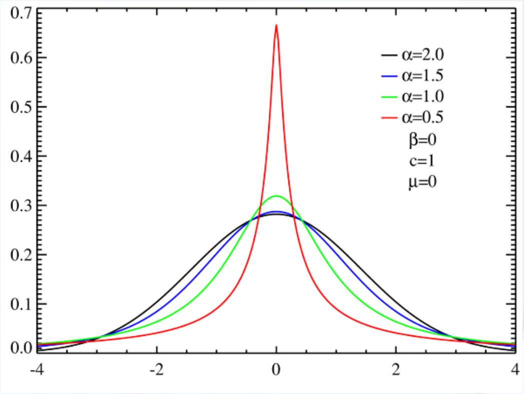
BACKUP – Properties of univariate stable distributions

- **Univariate stable distribution:** $f(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\varphi(q)e^{-ixq}dq$,
  where the characteristic function:

$$\Phi = \begin{cases} \tan\left(\frac{\pi\alpha}{2}\right), \alpha \neq 1 \\ -\frac{2}{\pi}\log|q|, \alpha = 1 \end{cases}$$

- $\varphi(q;\alpha,\beta,R,\mu) = \exp(iq\mu - |qR|^{\alpha}(1 - i\beta\mathrm{sgn}(q)\Phi))$
- α: index of stability
- β: skewness, symmetric if $\beta = 0$
- R: scale parameter
- μ: location, equals the median,
  if $\alpha > 1$: $\mu =$ mean



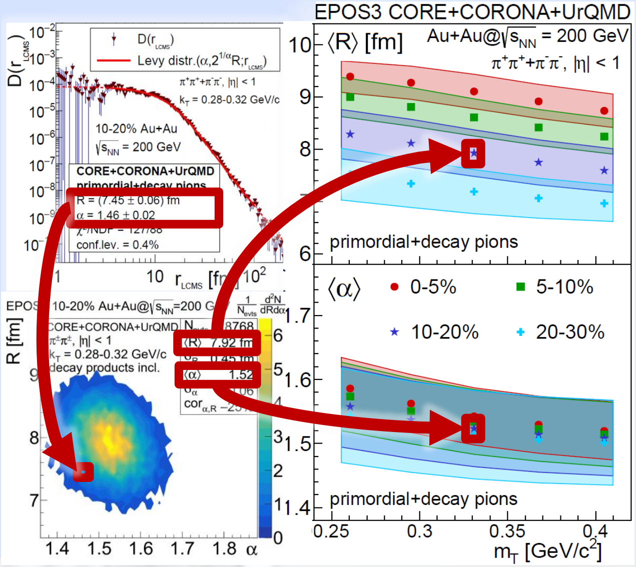


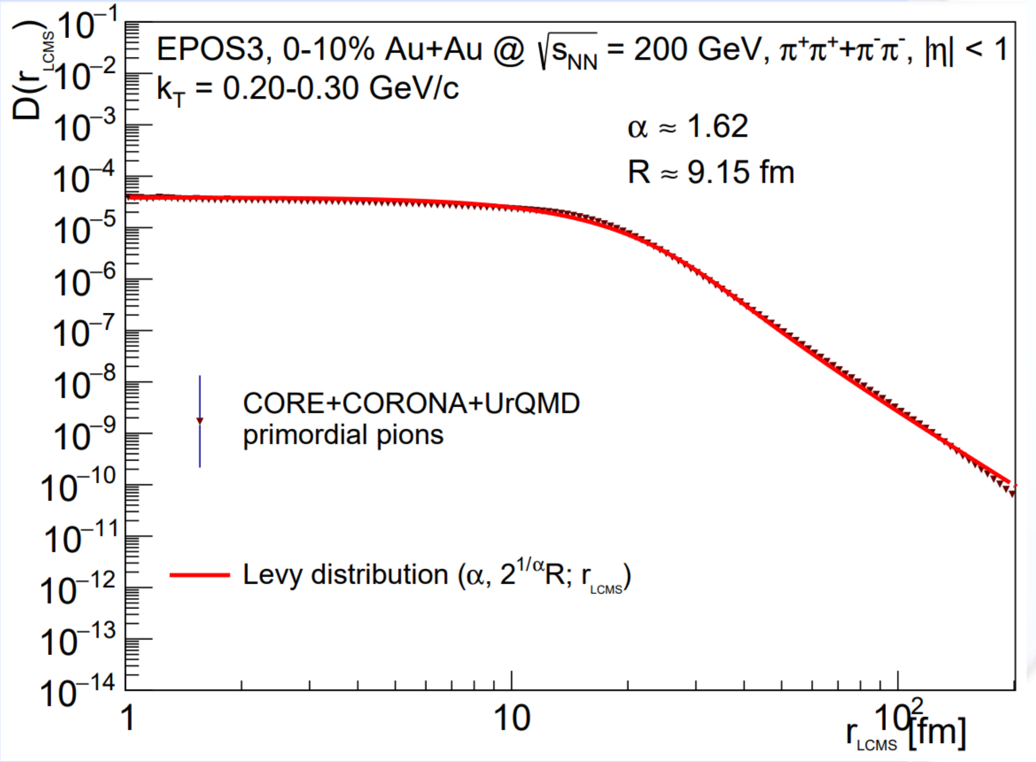
- **Important characteristics of stable distributions:**
  - The distributions retain the same α and β under convolution of random variables
  - Any moment greater than α isn't defined

BACKUP – EPOS event-averaged two-pion source distribution

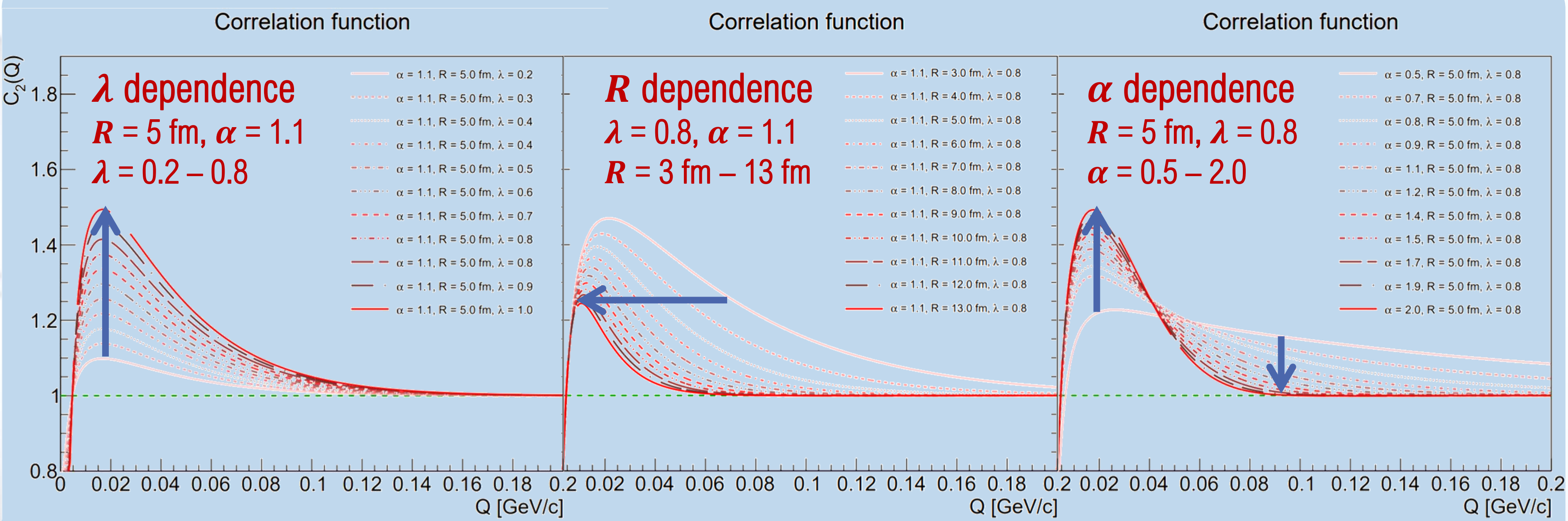
Entropy 24 (2022) 3, 308

- Event-averaged source not perfectly Lévy
- Nevertheless, very similar parameters
- Event averaged: $\alpha \approx 1.62$, $R \approx 9.15$ fm
- Event-by-event: $\alpha \approx 1.66$, $R \approx 8.96$ fm
- More reasonable approach for kaons





BACKUP - Shape of the correlation functions with Coulomb effect included



$$C(Q) = 1 - \lambda + \lambda \cdot K(Q;\alpha,R) \cdot \left(1 + e^{-|RQ|^{\alpha}}\right)$$

BACKUP – Kinematic variables of the correlation function

- Usually used one-dimensional variable (with the Bertsch-Pratt variables in the LCMS frame):

$$\boldsymbol{q_{inv}} = \sqrt{(\boldsymbol{1} - \boldsymbol{\beta_T^2})\boldsymbol{q_{out}^2} + \boldsymbol{q_{side}^2} + \boldsymbol{q_{long}^2}}, \qquad \beta_T = 2k_T/(E_1 + E_2)$$

- If β_T is close to 1 (intermediate-high k_T) q_{inv} can be small even if q_{out} is not
- Radius extracted from q_{inv} dependent two pion HBT correlations (in Au+Au) overestimates the 3D LCMS ($R_{out}, R_{side}, R_{long}$) results (see e.g. the thesis of A. Enokizono) *http://inspirehep.net/record/673843/*
- Another approach: **LCMS three-momentum difference:**

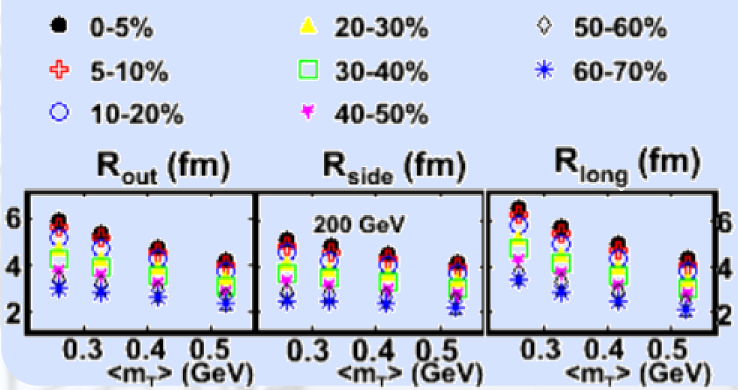
$$Q = |\boldsymbol{q}_{LCMS}| = \sqrt{(p_{1x} - p_{2x})^2 + \left(p_{1y} - p_{2y}\right)^2 + q_{long,LCMS}^2}$$

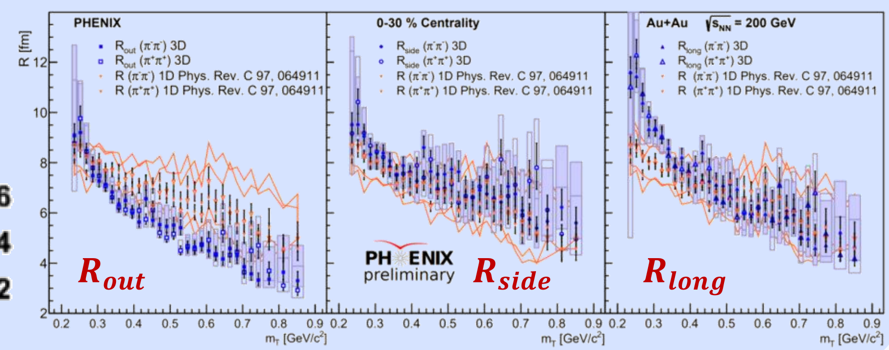
BACKUP – Kinematic variables of the correlation function

- Info from the tracks: E, p_x, p_y, p_z
- $\boldsymbol{q_{inv}} = \sqrt{(E_1 - E_2)^2 - \left((p_{1,x} - p_{2,x})^2 + (p_{1,y} - p_{2,y})^2 + (p_{1,y} - p_{2,y})^2\right)} = \sqrt{\boldsymbol{q_{0,LCMS}^2 - Q_{LCMS}^2}}$
- $q_{0,LCMS} = \frac{(E_1^2 - E_2^2) - (p_{1,z}^2 - p_{2,z}^2)}{\sqrt{(E_1 + E_2)^2 - (p_{1,z} + p_{2,z})^2}}$
- $q_T = \sqrt{(p_{1,x} - p_{2,x})^2 + (p_{1,y} - p_{2,y})^2}$, $q_{z,LCMS} = \frac{2(p_{1,z}E_2 - p_{2,z}E_1)}{\sqrt{(E_1 + E_2)^2 - (p_{1,z} + p_{2,z})^2}}$
- $\boldsymbol{Q_{LCMS}} = \sqrt{\boldsymbol{q_T^2 + q_{z,LCMS}^2}}$

BACKUP – Kinematic variables of the correlation function

- $q_{inv} = |q_{PCMS}|$, in PCMS the source is not spherically symmetric (but in LCMS it is, approximately, see figs.)
- Measurements in Q_{LCMS} gives similar radii magnitude as three dimensional ($q_{out}, q_{side}, q_{long}$) meas.
- To compare λ and R with 3D (LCMS) results, |q| in the same frame (LCMS) should be used

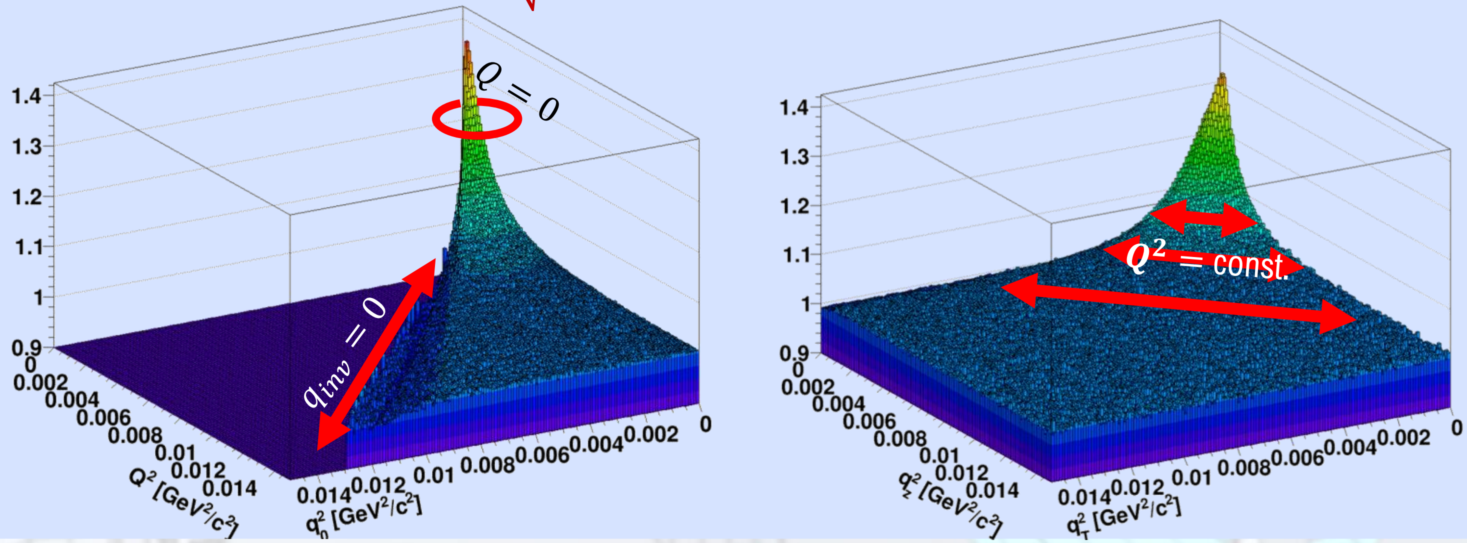




BACKUP – Kinematic variables of the correlation function

- A more appropriate one-dimensional variable: **LCMS three-momentum difference**

$$Q = |\boldsymbol{q}_{LCMS}| = \sqrt{(p_{1x} - p_{2x})^2 + (p_{1y} - p_{2y})^2 + q^2_{long,LCMS}}$$



BACKUP – Kinematic variables of the correlation function

- A more appropriate one-dimensional variable: **LCMS three-momentum difference**

$$Q = |\boldsymbol{q}_{LCMS}| = \sqrt{(p_{1x}-p_{2x})^2 + (p_{1y}-p_{2y})^2 + q_{long,LCMS}^2}$$