Femtoscopy with Lévy sources

Initial Stages 2023 – Copenhagen, Denmark

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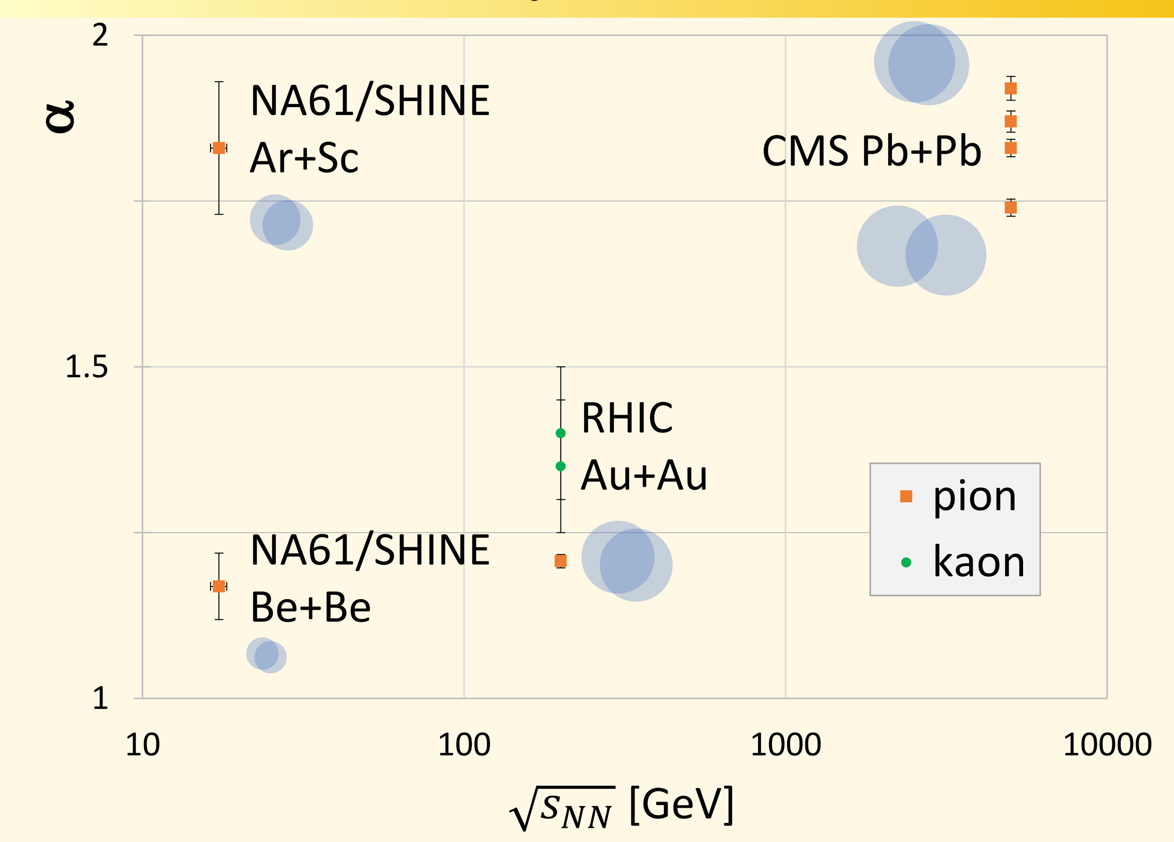
Executive summary



- Measurements at $\sqrt{s_{NN}} = 17 - 5020$ GeV [1–8]
  - Lévy-parameters R, α, λ extracted
  - Interesting energy dependence of α
  - Can have large effect on R vs $\sqrt{s_{NN}}$
  - Kaon versus pion α: origin of Lévy sources?
- EPOS analysis: Lévy shapes event-by-event [16]
  - Event average and fluctuation estimated
- Source size measures investigated: HWHI, HWHM

Bose-Einstein correlations map out the femtometer source

- $N_1(p), N_2(p_1,p_2)$ - invariant momentum distributions, the definition of the correlation function:

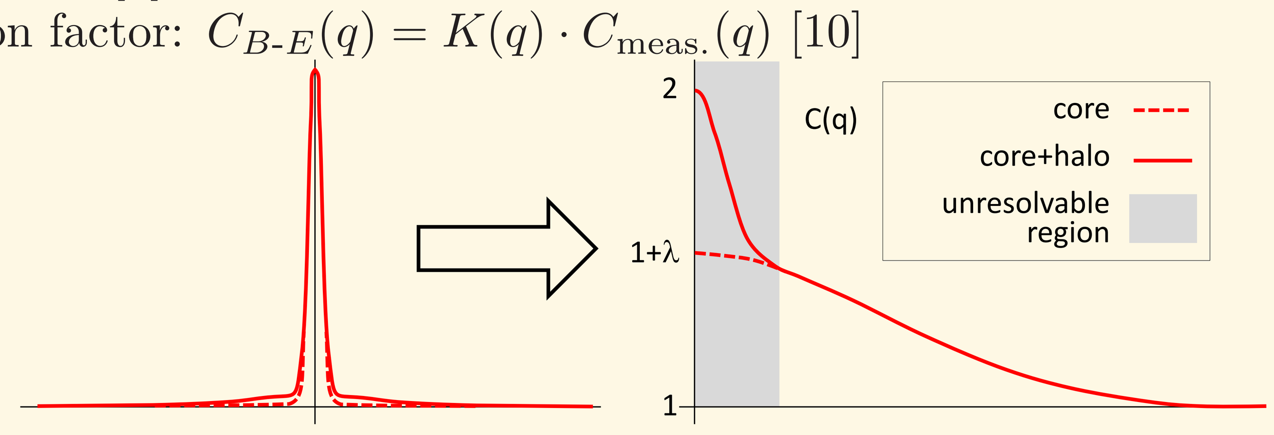
$$C_2(p_1,p_2) = \frac{N_2(p_1,p_2)}{N_1(p_1)N_1(p_2)}, \text{ where } N_2(p_1,p_2) = \int S(x_1,p_1)S(x_2,p_2)|\Psi^{\text{symm}}_{p_1,p_2}(x_1,x_2)|^2 d^4x_1 d^4x_2$$

- $S(x,p)$ source function (usually assumed to be Gaussian – Lévy if more general, c.f. anomalous diffusion)
- $\Psi^{\text{symm}}_{p_1,p_2}$ two-particle symmetrized wave function – interaction free case: $|\Psi^{\text{symm}}_{q=p_1-p_2}(x{=}x_1{-}x_2)|^2 = 1+\cos(qx)$
- Leads to $\widetilde{S}$, the Fourier-transformed of S; if S normalized:

$$C_2(q,K) \simeq 1 + \left|\widetilde{S}(q,K)\right|^2, \quad \widetilde{S}(q,K) = \int S(x,K)e^{iqx}d^4x, \quad q = p_1 - p_2, \; K = (p_1+p_2)/2, \; q \ll K$$

Final state interactions, resonances to take into account

- Identical charged pions: final state interaction distort the simple picture
- Small role of strong interaction for pions with Lévy source [9]
- Different methods of handling, e.g. Coulomb-correction factor: $C_{B\text{-}E}(q) = K(q)\cdot C_{\text{meas.}}(q)$ [10]
- Two-component pion source: $S = S_{\text{core}} + S_{\text{halo}}$
  - Primordial pions: core $\lesssim 10$ fm
  - Resonance pions - from very far regions: halo
  - Observed $C_2(q\to 0) = 1+\lambda \neq 2$
  - Measure: $\sqrt{\lambda} = f_c = $ core/(core+halo)
  - Resonances reduce correlation function [11]



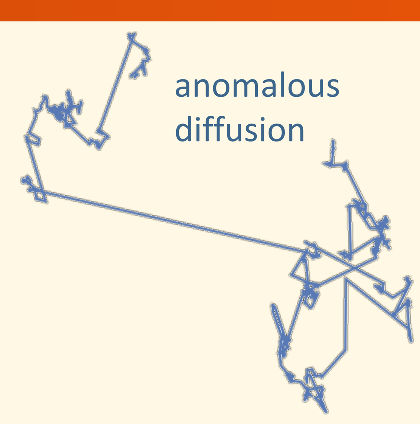
Appearance of Lévy-distributed sources in heavy-ion collisions

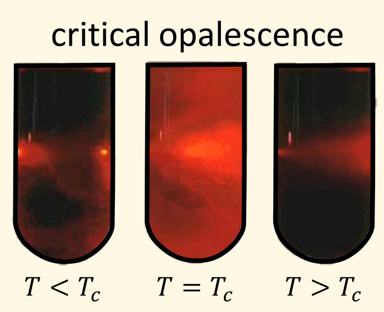
- Generalized central limit theorem → Lévy-distribution

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

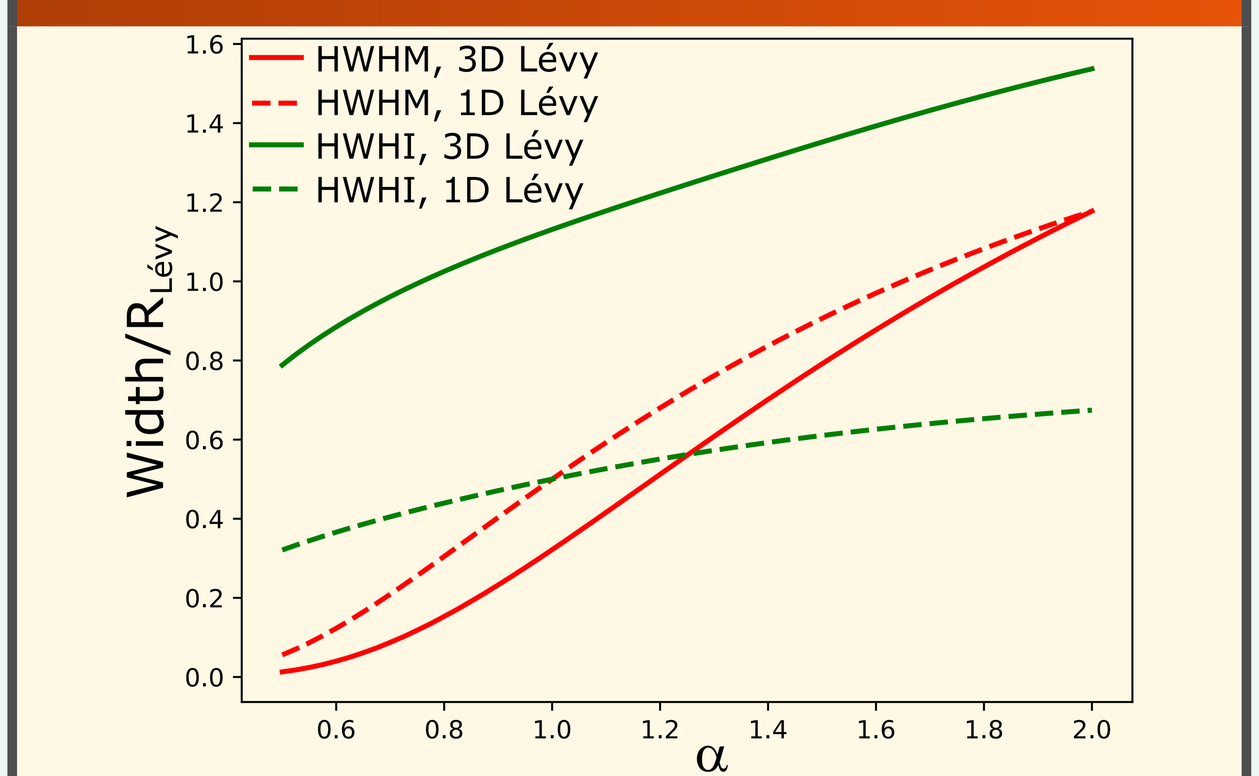
- Shape of the correlation function [12]: $C_2(|q|) = 1+\lambda\cdot e^{-(R|q|)^\alpha}$
- Note: 1D & 3D α results compatible [1,2], validates 1D approach
- **One possible reason: anomalous diffusion**
  - Expanding medium, increasing mean free path → anomalous diffusion, Lévy-flight
- **Another possible reason: critical behavior**
  - Spatial correlations at CEP $\propto r^{-(d-2+\eta)}$ → defines critical exponent η
  - Symmetric Lévy-stable distributions lead to source $\propto r^{-1-\alpha}$

  $\Big\}\ \alpha \equiv \eta$
  - QCD universality class: 3D Ising [13] $\begin{cases}\eta(\text{CEP}) = 0.03631(3) \text{ (3D Ising) [14]}\\ \eta(\text{CEP}) = 0.5\pm 0.05 \text{ (rand. field 3D Ising) [15]}\end{cases}$



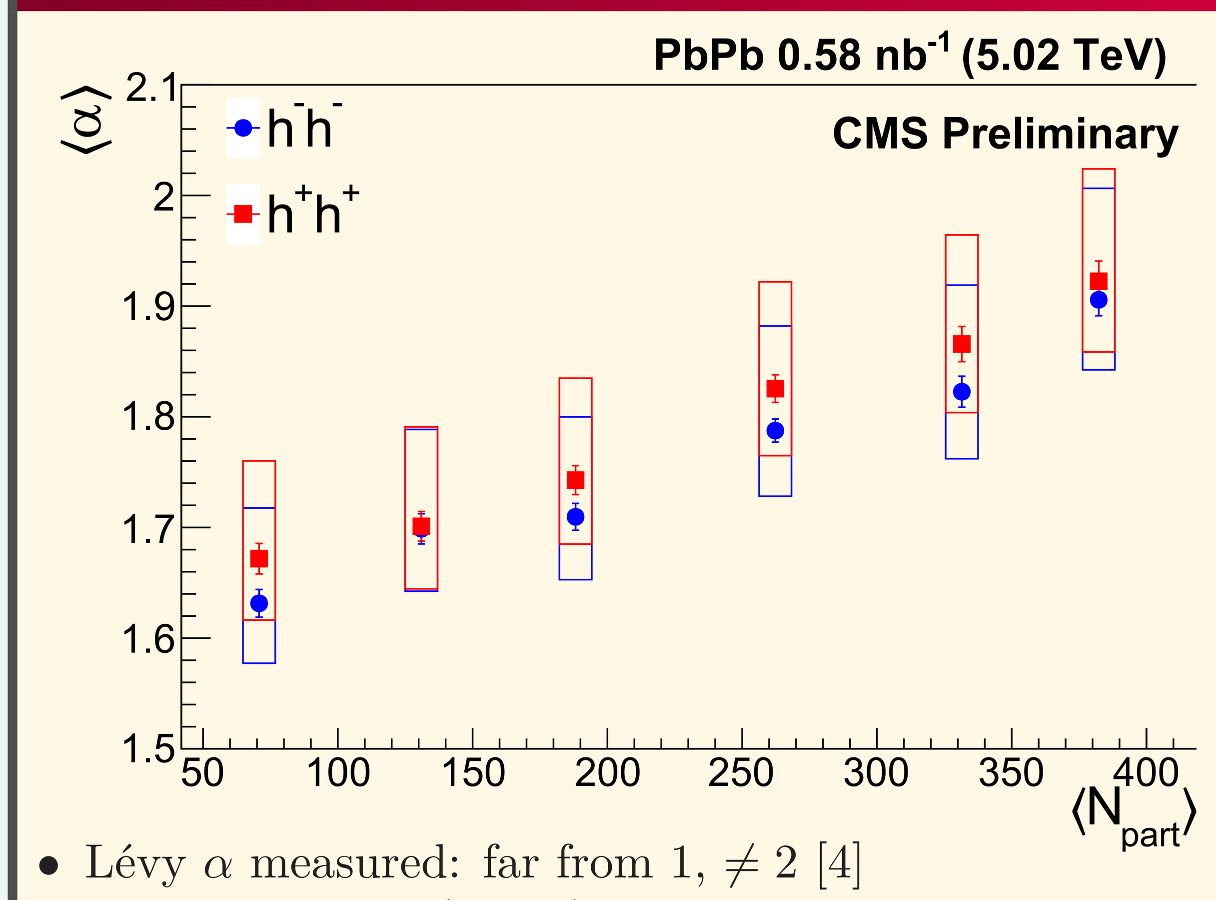


What is the true source size?



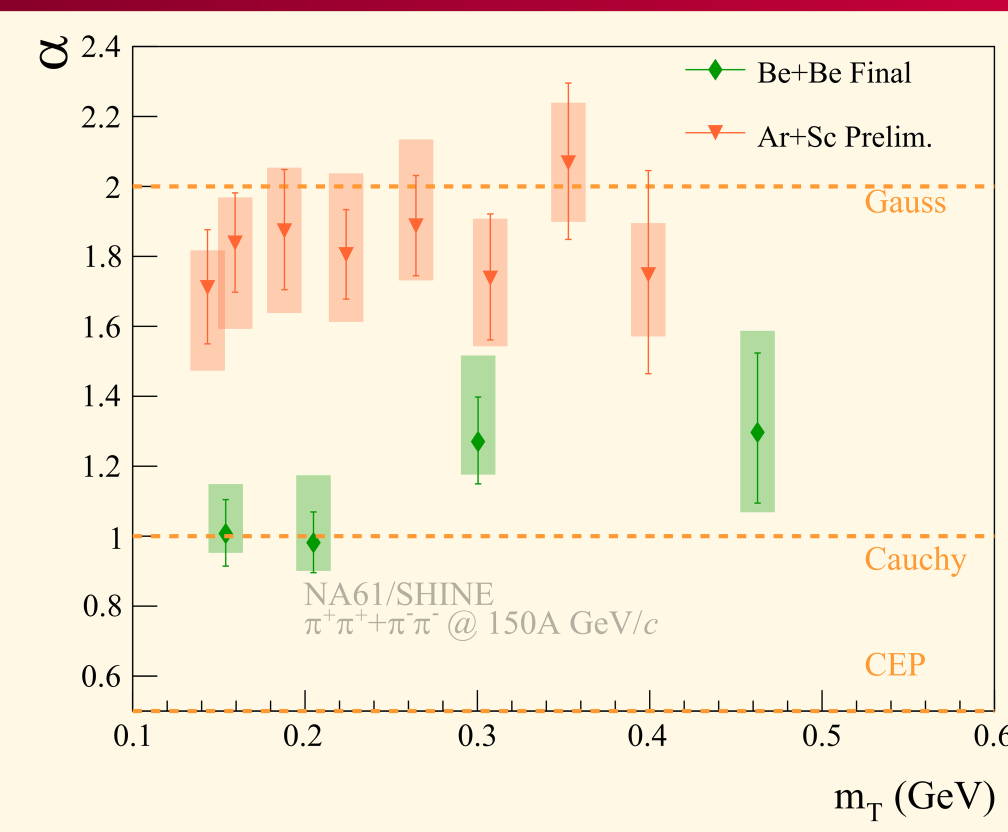
- How to quantify source size?
- Half width at half maximum (HWHM)
- Half width at half integral (HWHI)
- Their ratio to R_{Levy} depends on α!

Lévy exponent α in 5.02 TeV PbPb



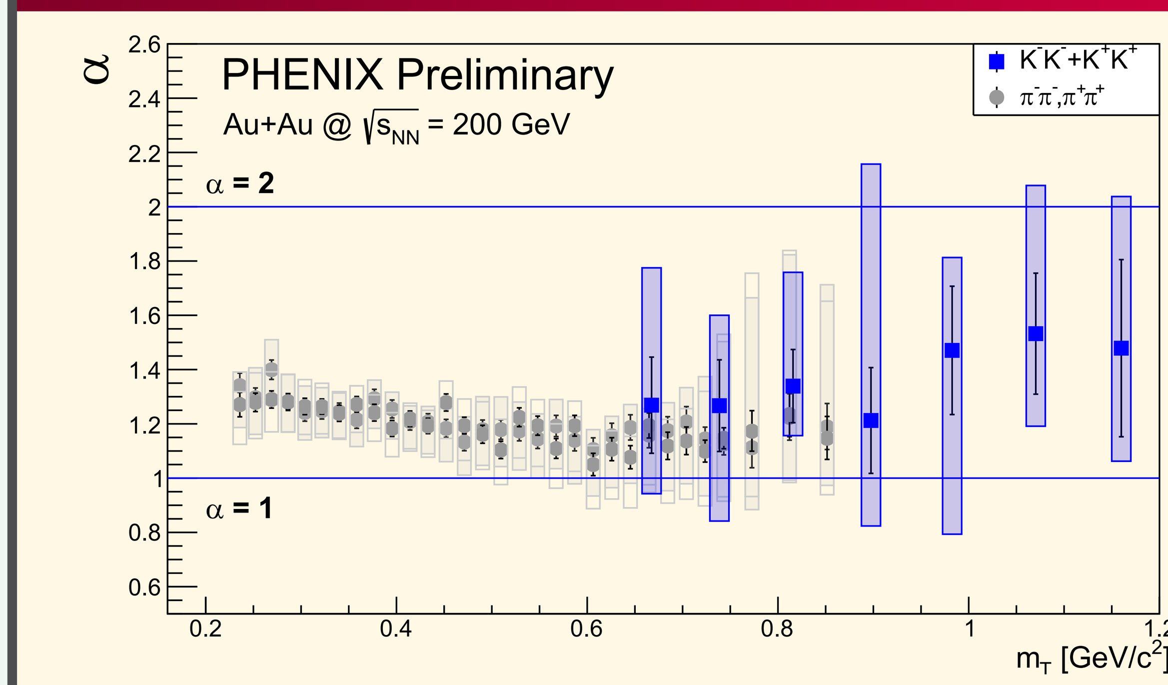
- Lévy α measured: far from 1, $\neq 2$ [4]
- Closer to Gauss ($\alpha = 2$) for central collisions
- Unlike RHIC [3], see poster by S. Lökös
- Role of particle density?

NA61/SHINE results in Ar+Sc & Be+Be



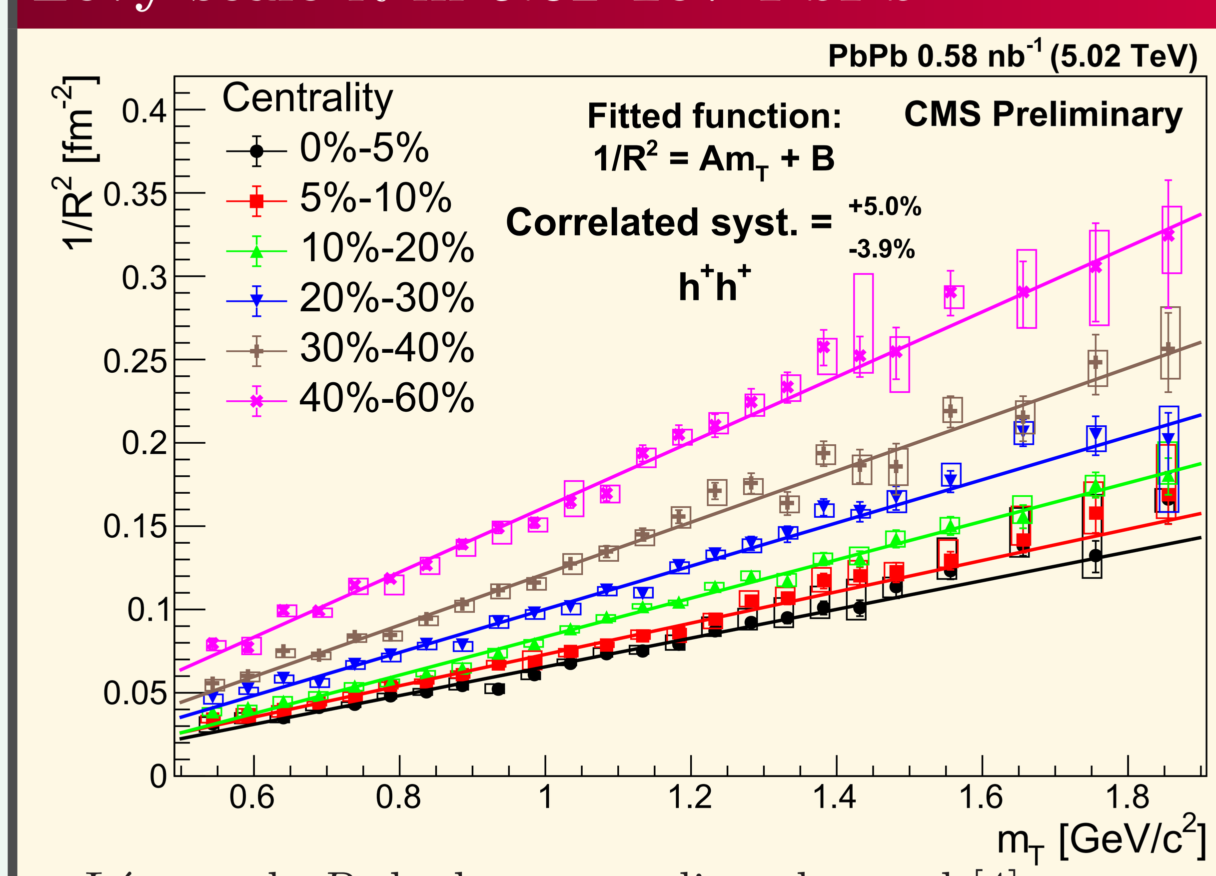
- Lévy α: difference of Be+Be [5] & Ar+Sc [6]
- Ar+Sc: close to Gauss; Be+Be: close to Cauchy
- Both far from CEP conjecture ($\alpha = 0.5$)
- Hydro inspired m_T-scaling of R [5,6]

Lévy exponent α for kaons in Au+Au



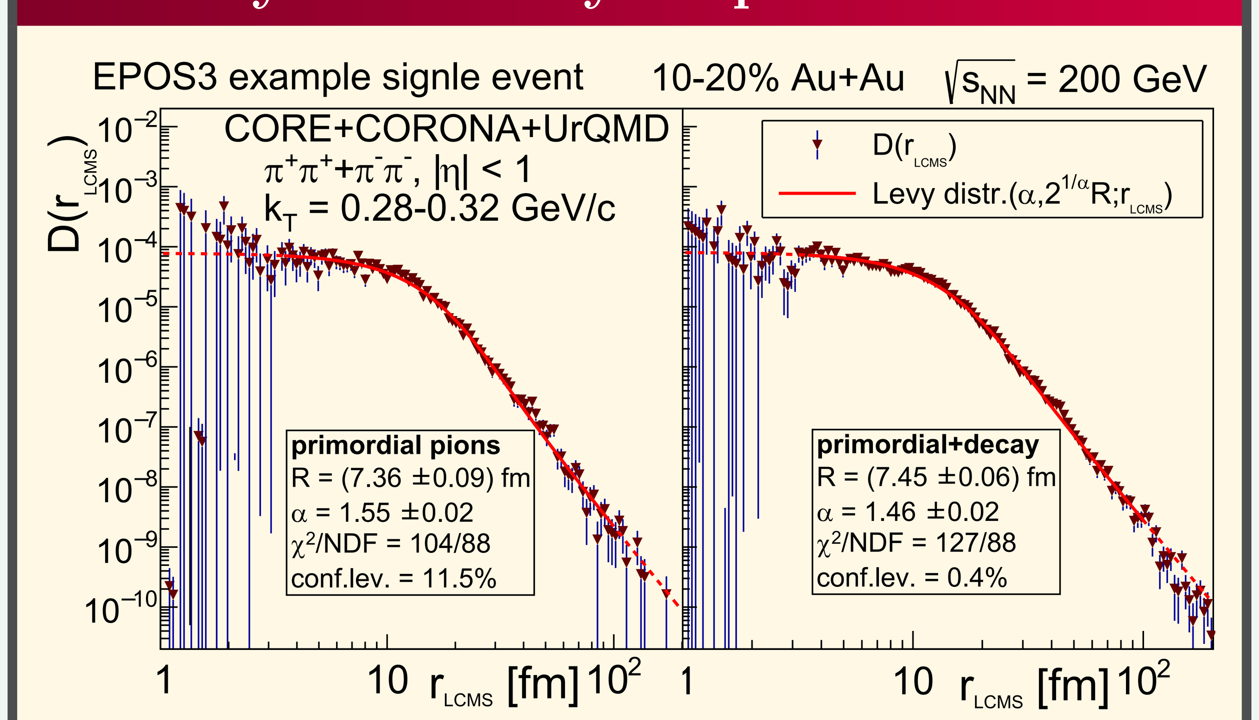
- Kaon mean free path larger: $\alpha_K < \alpha_\pi$ predicted [17]
- PHENIX & STAR preliminary data: $\alpha_K \approx \alpha_\pi$ [7,8]
- Reason for appearance of Lévy sources?

Lévy scale R in 5.02 TeV PbPb



- Lévy scale R: hydro m_T-scaling observed [4]
- Despite non-Gaussianity! Reason for scaling?
- Hubble coefficient: 0.11-0.18 c/fm; RHIC: 0.07 c/fm [1]

Event-by-event Lévy shapes in EPOS



- Event shape $D(r_{\text{LCMS}})$ calculated in EPOS [16]
- After rescattering: Lévy shape describes events
- Fluctuating α and R evt-by-evt, details in [16]
- Mean and variance extracted; with & w/o decays
- $\langle\alpha\rangle$ differs from experimental results [1,4]

References

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