



Femtoscopy with Lévy sources

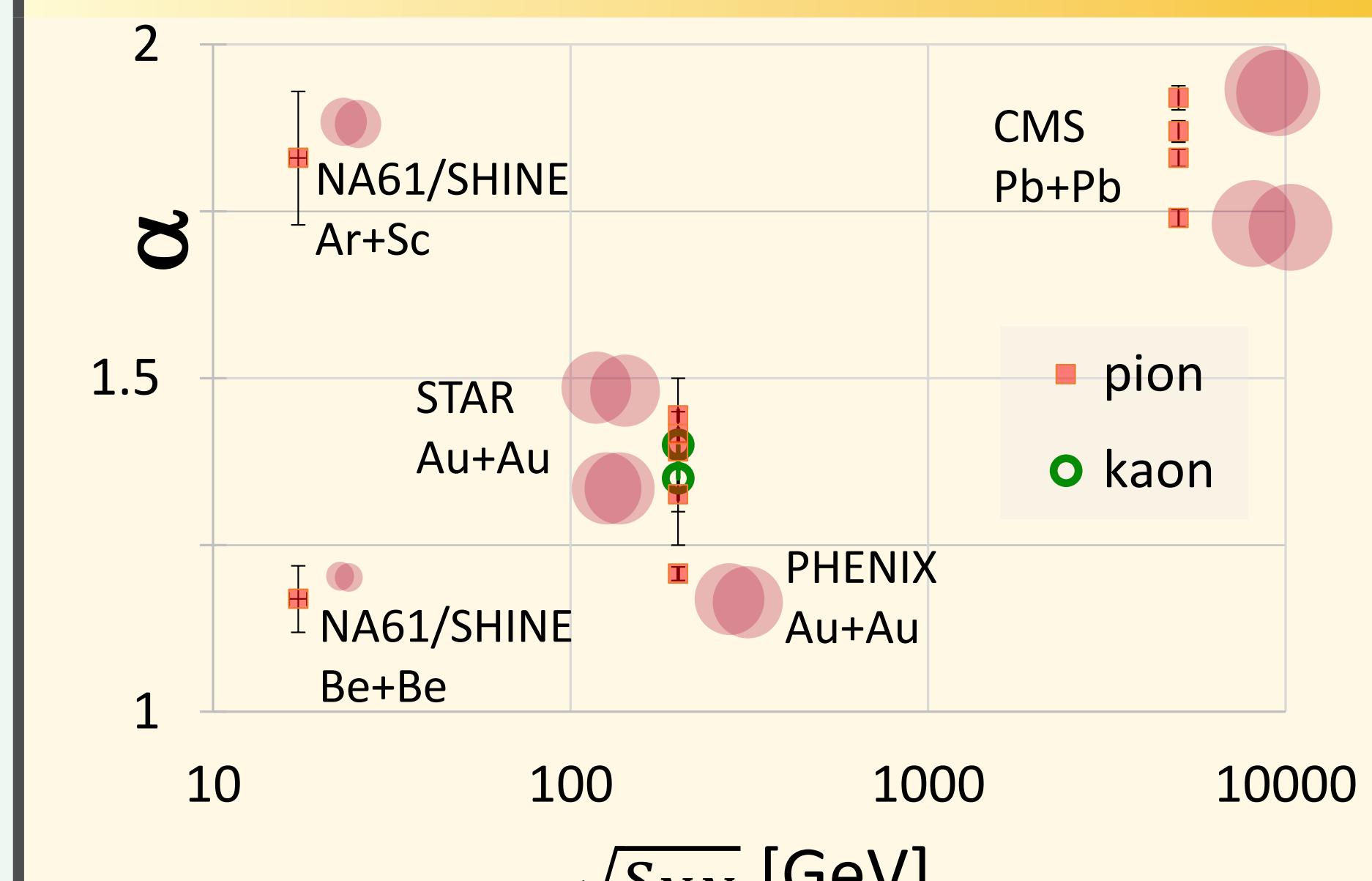
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Executive summary



- Measurements at $\sqrt{s_{NN}} = 17 - 5020$ GeV [1–9]
 - 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 [18]
 - Event average and fluctuation estimated
- Source size measures investigated: HWI, HWHM

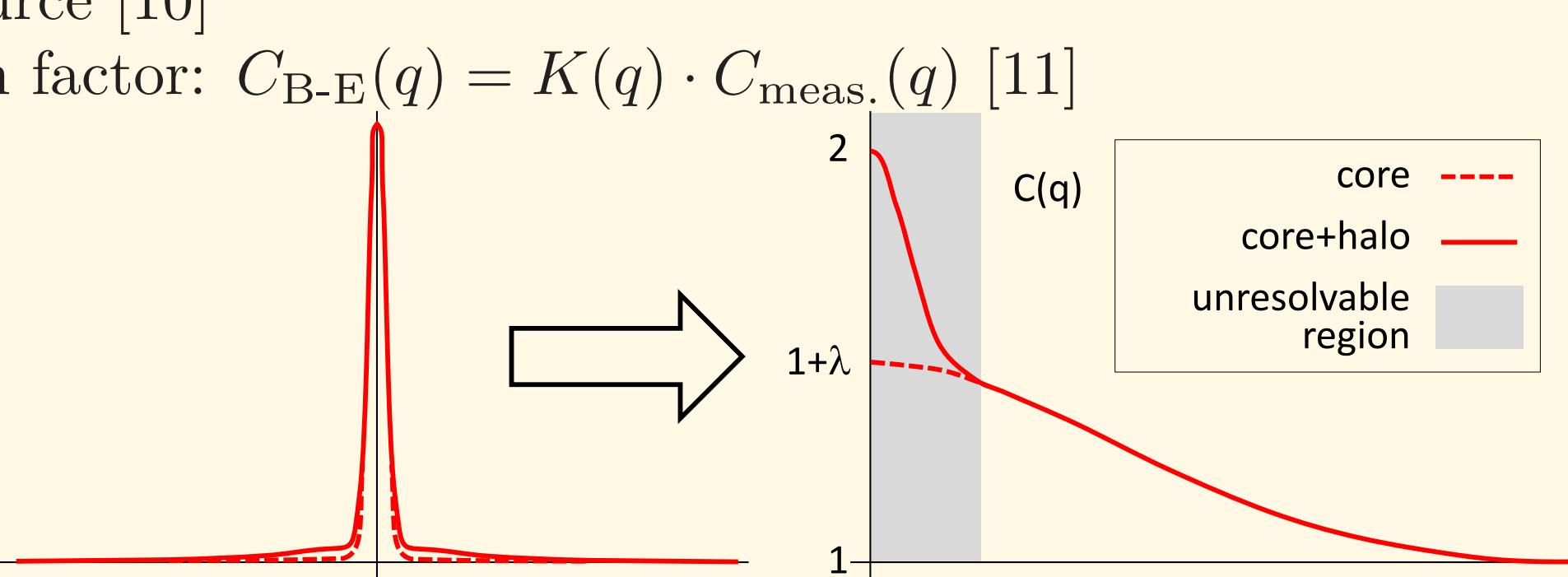
Bose-Einstein correlations map out the femtometer source

- $N_1(p), N_2(p_1, p_2)$ - invariant momentum distributions, the definition of the correlation function:
$$C_2(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)}, \text{ where } N_2(p_1, p_2) = \int S(x_1, p_1)S(x_2, p_2)|\Psi_{p_1, p_2}^{\text{symm}}(x_1, x_2)|^2 d^4x_1 d^4x_2$$
- $S(x, p)$ source function (usually assumed to be Gaussian – Lévy if more general, c.f. anomalous diffusion)
- $\Psi_{p_1, p_2}^{\text{symm}}$ two-particle symmetrized wave function – interaction free case: $|\Psi_{q=p_1-p_2}^{\text{symm}}(x=x_1-x_2)|^2 = 1 + \cos(qx)$
- Coulomb final state effect: integral doable via Lebesgue's and Fubini's theorems [12]
- In absence of final state interactions, leads to \tilde{S} , the Fourier-transformed of S ; if S normalized:

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

Final state interactions, resonances to take into account

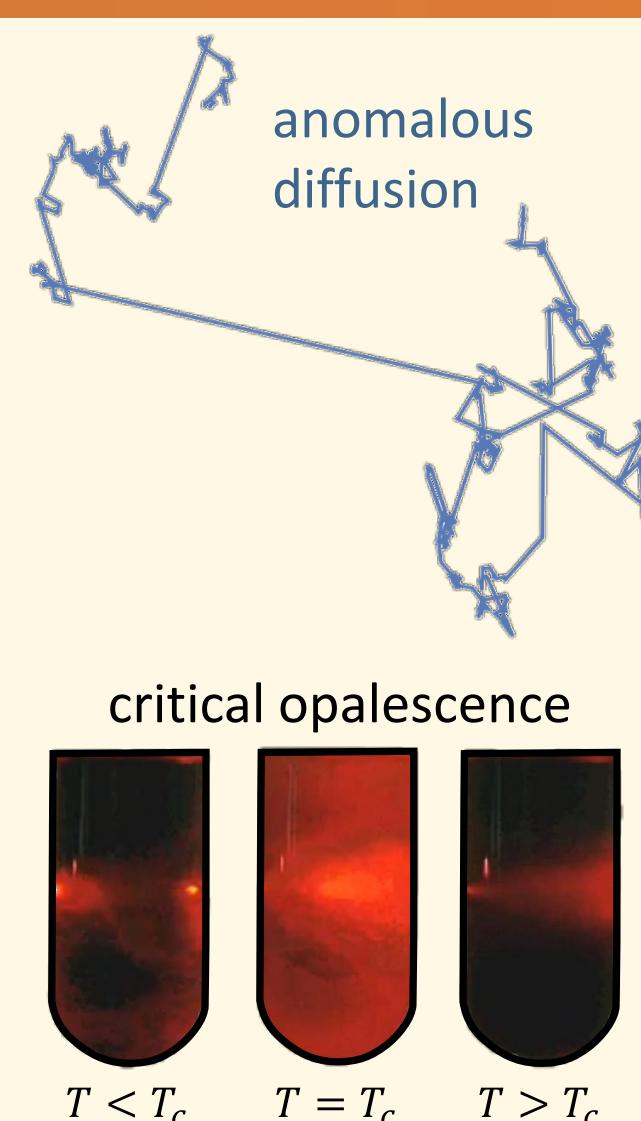
- Identical charged pions: final state interaction distort the simple picture
- Small role of strong interaction for pions with Lévy source [10]
- Different methods of handling, e.g. Coulomb-correction factor: $C_{B-E}(q) = K(q) \cdot C_{\text{meas.}}(q)$ [11]
- Two-component pion source: $S = S_{\text{core}} + S_{\text{halo}}$
 - Primordial pions: core $\lesssim 10$ fm
 - Resonance pions - from very far regions: halo
 - Observed $C_2(q \rightarrow 0) = 1 + \lambda \neq 2$
 - Measure: $\sqrt{\lambda} = f_c = \text{core}/(\text{core+halo})$
 - Resonances reduce correlation function [13]



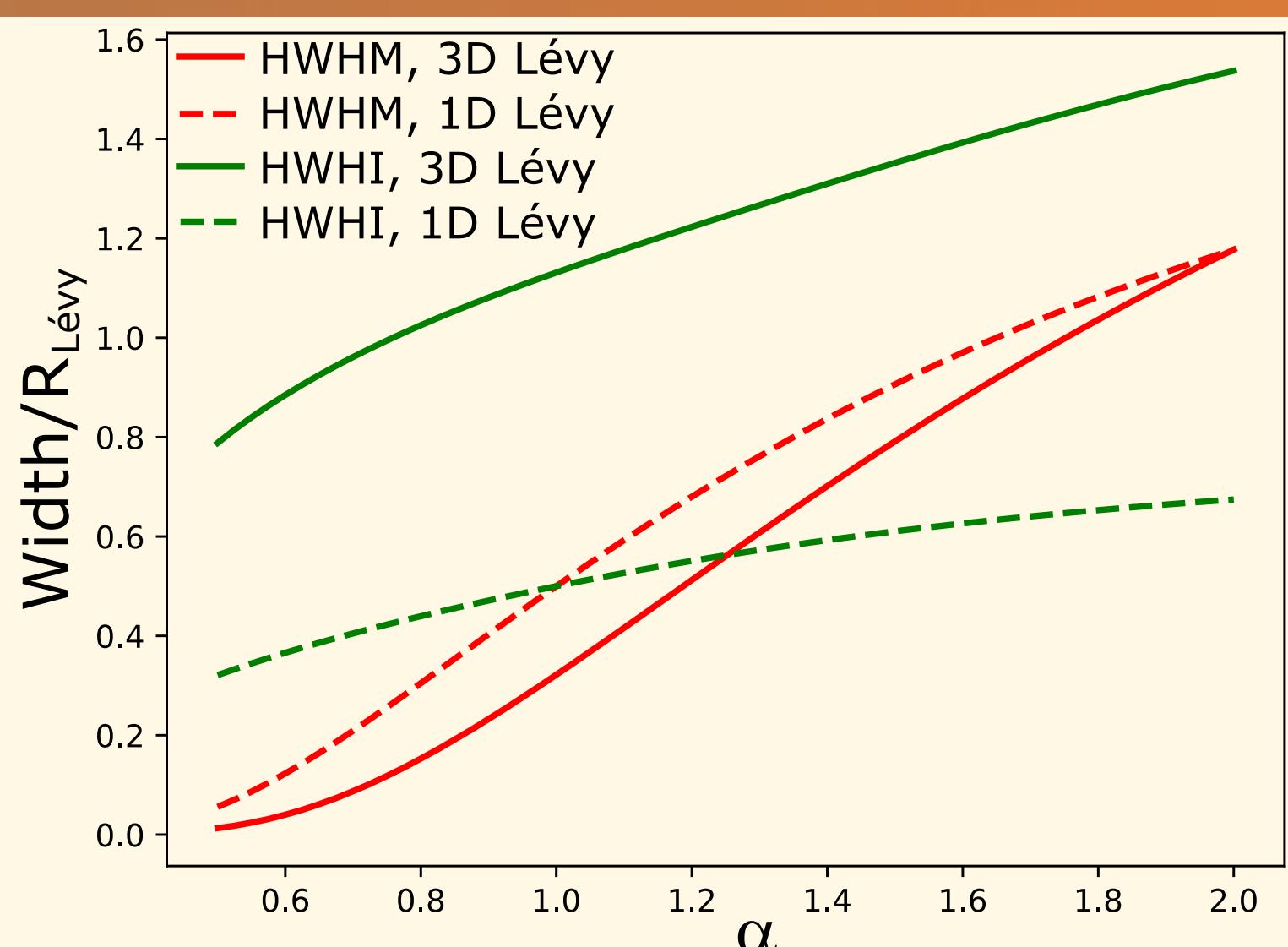
Appearance of Lévy-distributed sources in heavy-ion collisions

- Generalized central limit theorem \rightarrow Lévy-distribution

$$\mathcal{L}(\alpha, R, r) = (2\pi)^{-3} \int d^3qe^{iqr}e^{-\frac{1}{2}|qR|^\alpha}, \quad \alpha = 1 : \text{Cauchy}, \quad \alpha = 2 : \text{Gauss}$$
- Shape of the correlation function [14]: $C_2(|q|) = 1 + \lambda \cdot e^{-(R|q|)^\alpha}$
- Note: 1D & 3D α results compatible [1, 2], validates 1D approach
- One possible reason: anomalous diffusion**
 - Expanding medium, increasing mean free path \rightarrow anomalous diffusion, Lévy-flight
- Another possible reason: critical behavior**
 - Spatial correlations at CEP $\propto r^{-(d-2+\eta)}$ \rightarrow defines critical exponent $\eta \quad \left. \alpha \equiv \eta \right\}$
 - Symmetric Lévy-stable distributions lead to source $\propto r^{-1-\alpha}$
 - QCD universality class: 3D Ising [15] $\left. \begin{cases} \eta(\text{CEP}) = 0.03631(3) \text{ (3D Ising)} [16] \\ \eta(\text{CEP}) = 0.5 \pm 0.05 \text{ (rand. field 3D Ising)} [17] \end{cases} \right\}$

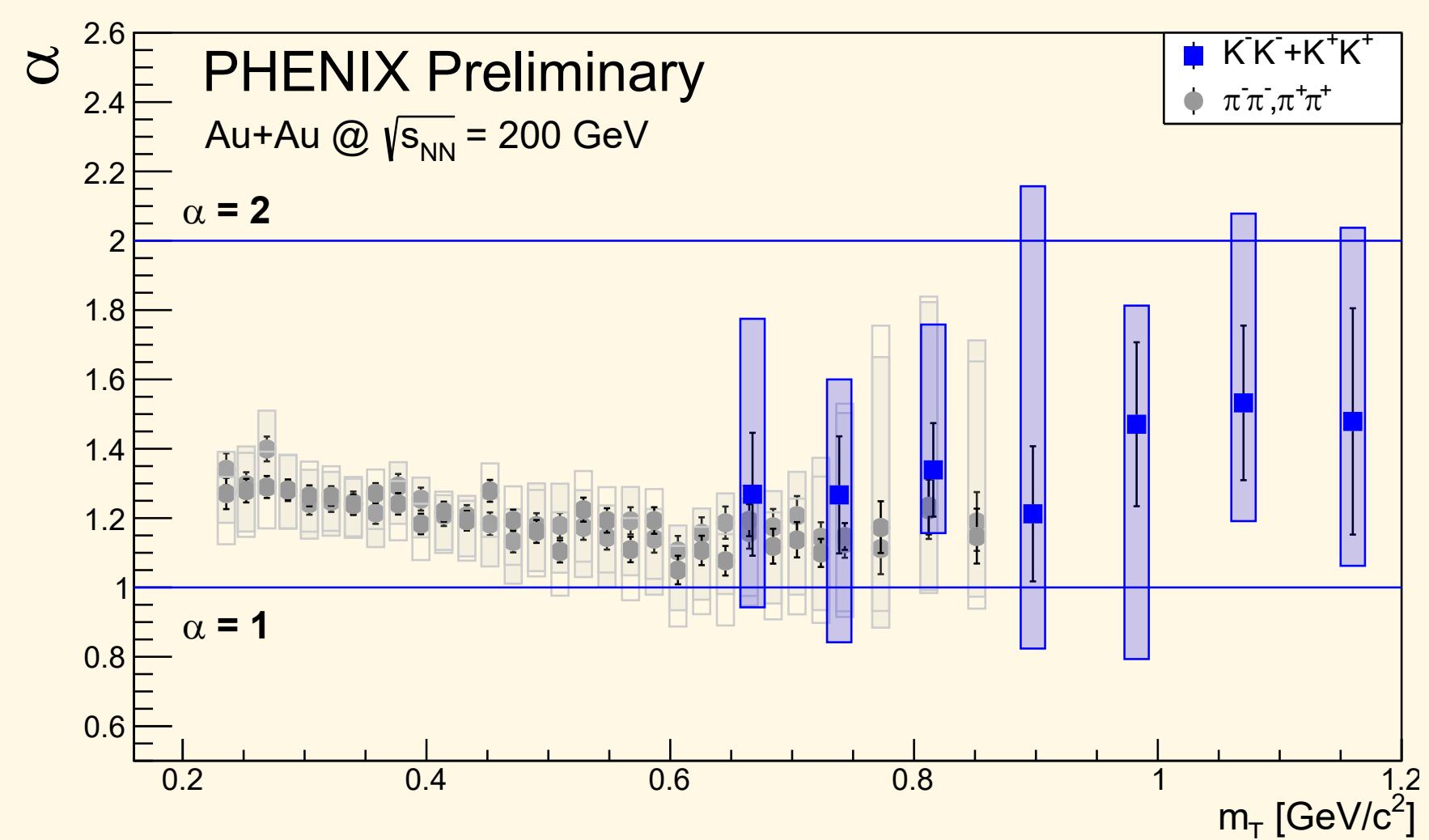


What is the true source size?



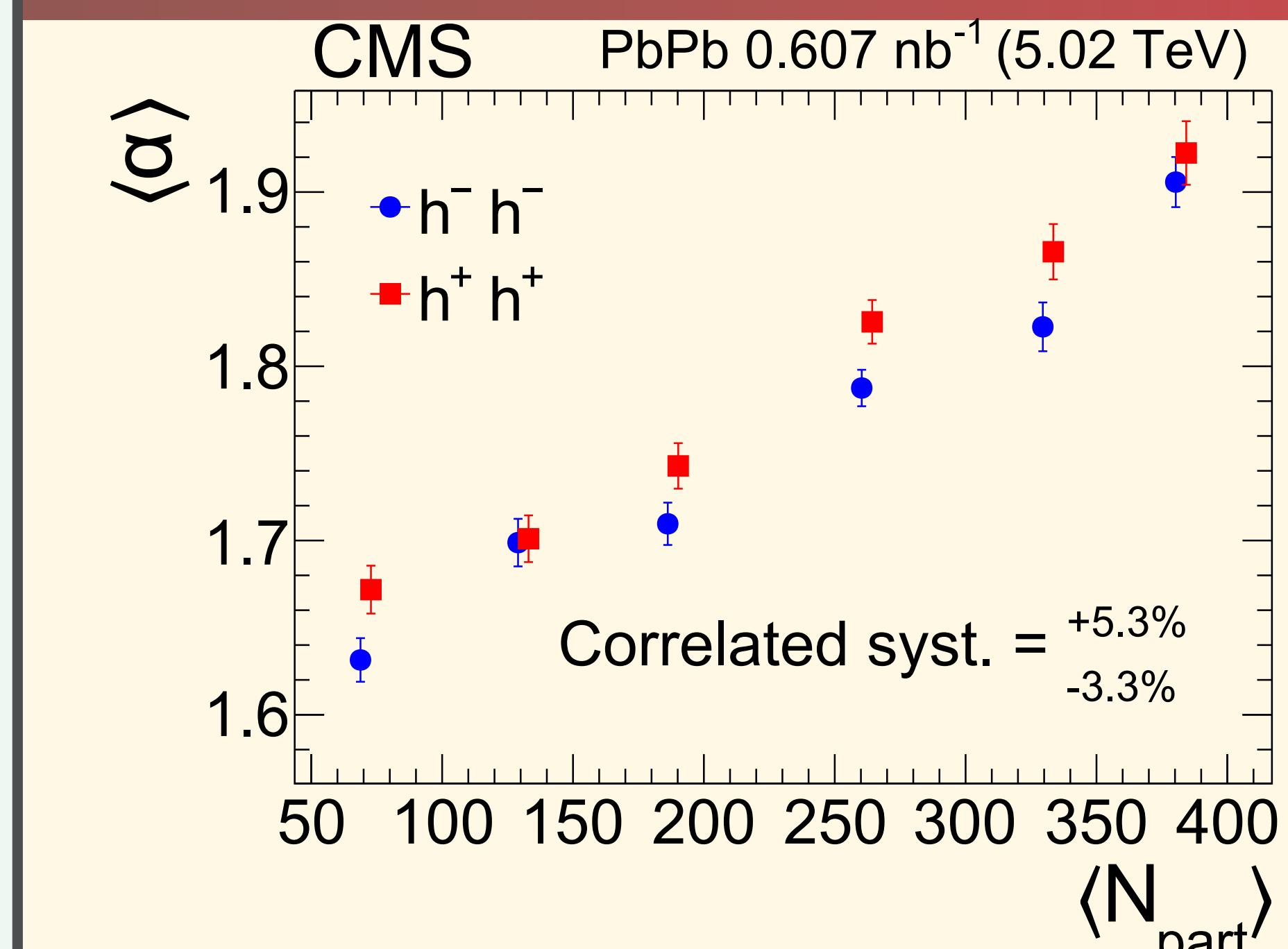
- How to quantify source size?
- Half width at half maximum (HWHM)
- Half width at half integral (HWI)
- Their ratio to R_{Levy} depends on α !

Lévy exponent alpha for kaons in Au+Au



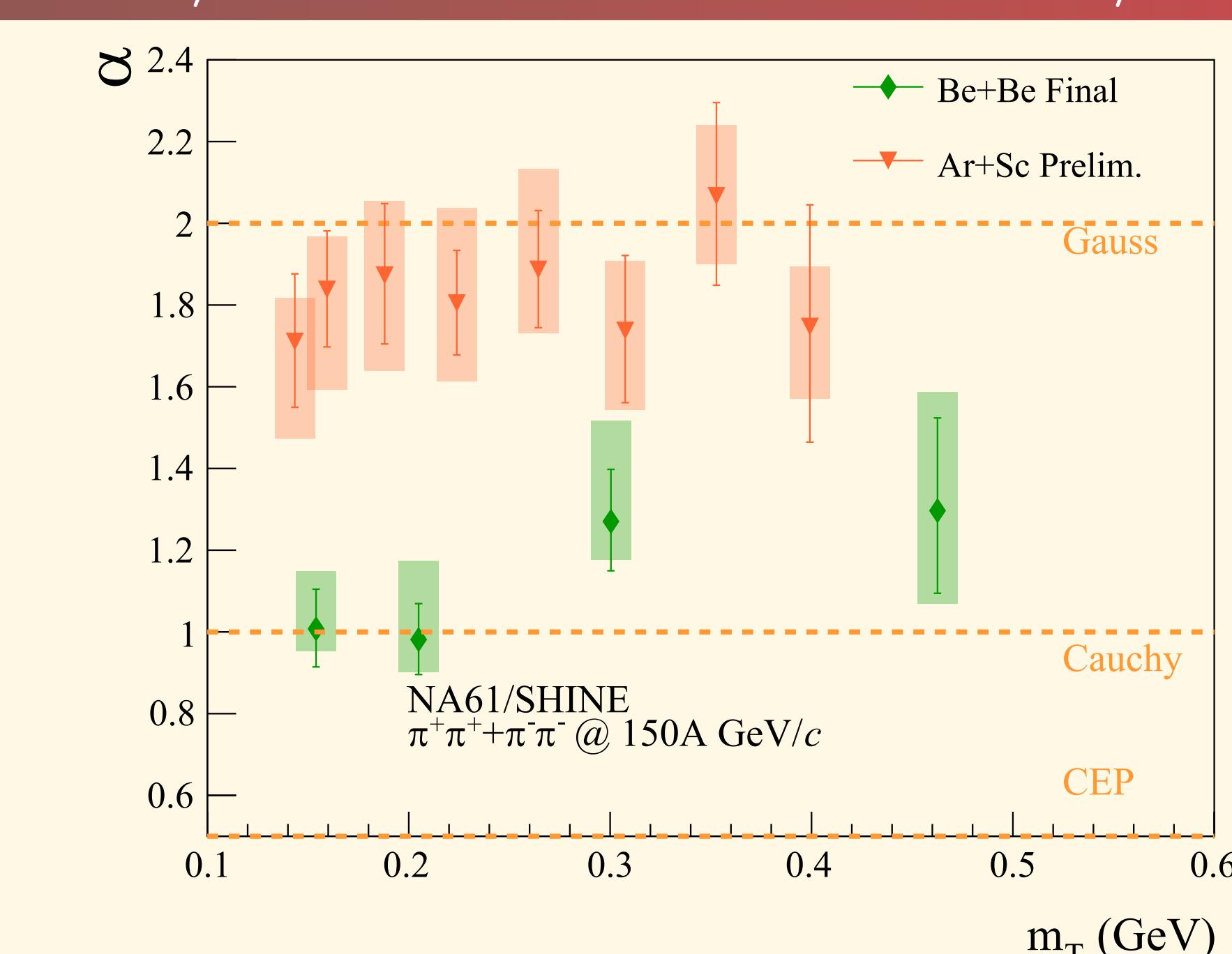
- Kaon mean free path larger: $\alpha_K < \alpha_\pi$ predicted [20]
- PHENIX & STAR preliminary data: $\alpha_K \approx \alpha_\pi$ [7, 8]
- Reason for appearance of Lévy sources?

CMS results in 5.02 TeV PbPb



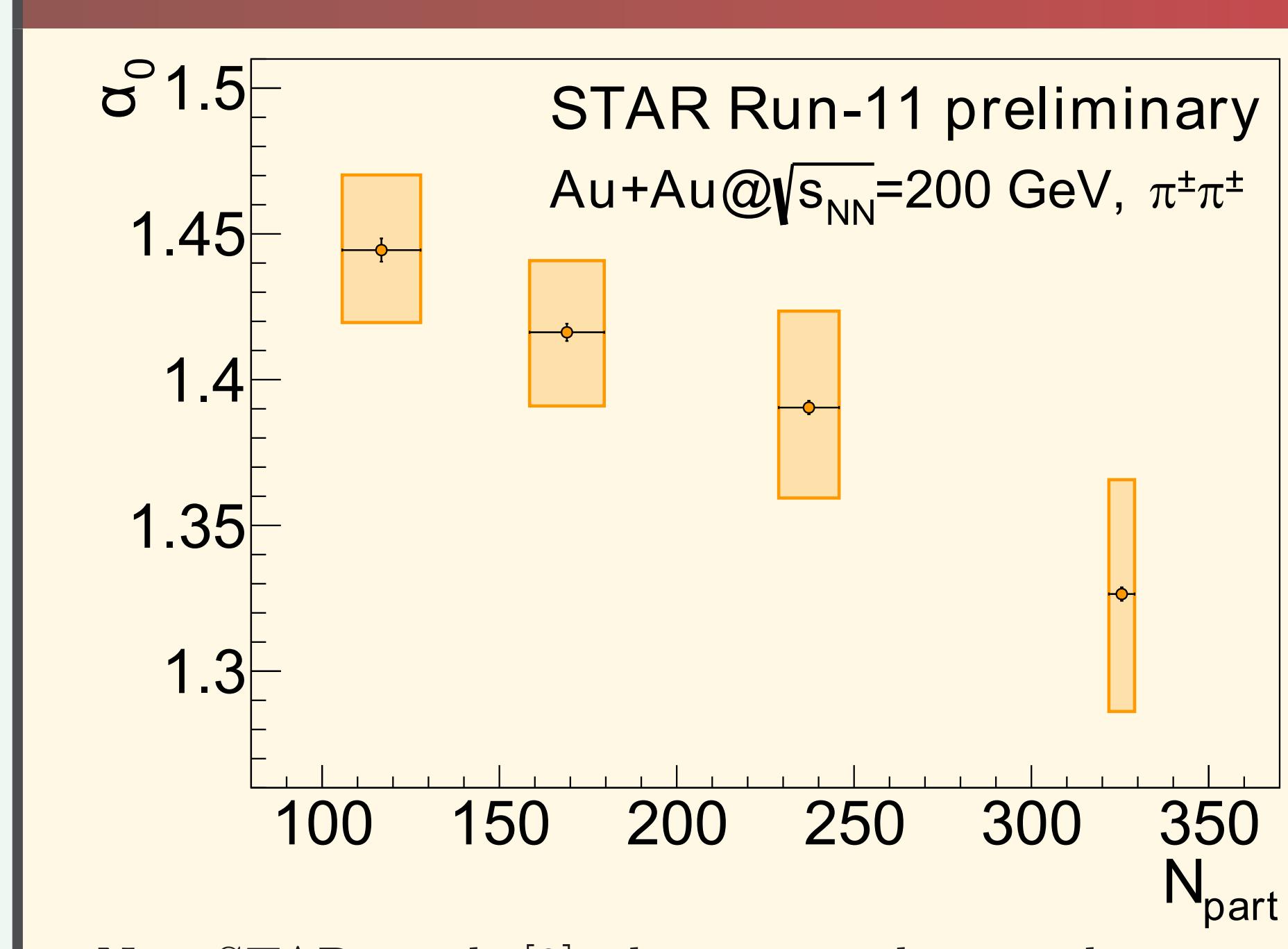
- Lévy α measured: far from 1, also not Gauss [4]
- Closer to Gauss ($\alpha = 2$) for central collisions
- Unlike RHIC [3], see also new STAR result below
- Role of particle density or mean free path?

NA61/SHINE results at 150A GeV/c



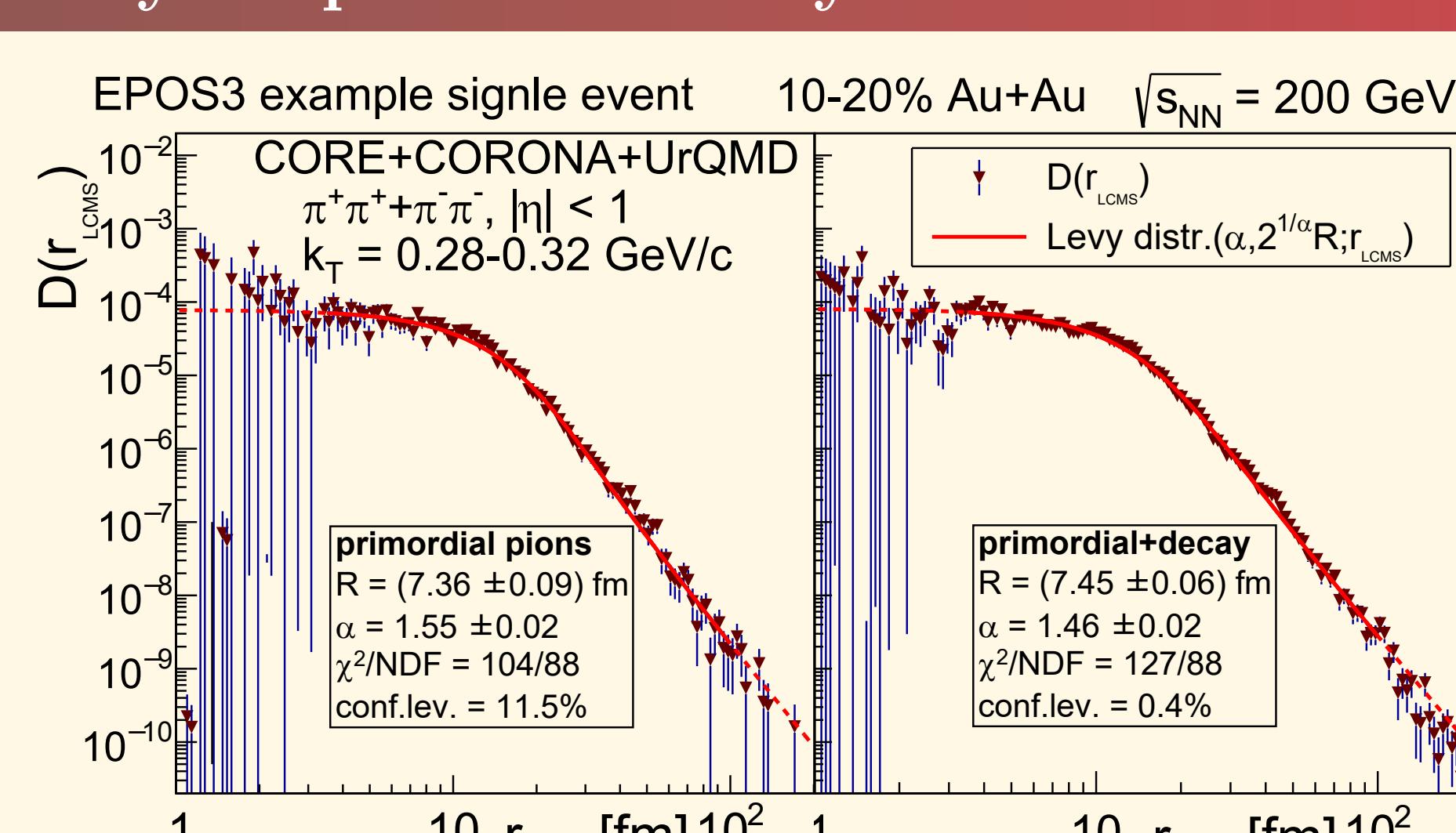
- Lévy α : difference of Be+Be [5] & Ar+Sc [6]
- Ar+Sc: close to Gauss; Be+Be: close to Cauchy
- Both far from CEP conjecture ($\alpha = 0.5$)
- Hydro inspired m_T -scaling of R [5, 6]

STAR results in 200 GeV AuAu



- New STAR result [9]: decrease with centrality
- Similarly to PHENIX [3]
- In contrast to CMS results at 5.02 TeV [4]

Lévy shapes in event-by-event EPOS



- Event shape $D(r_{\text{LCMS}})$ calculated in EPOS [18, 19]
- After rescattering: Lévy shape describes events
- Fluctuating α and R evt-by-evt, details in Refs. [18, 19]
- Mean and variance extracted; with & w/o decays
- $\langle \alpha \rangle$ differs from experimental results [1, 4]

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