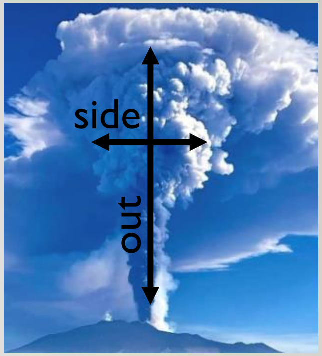
TWO-PARTICLE FEMTOSCOPIC CORRELATION MEASUREMENTS



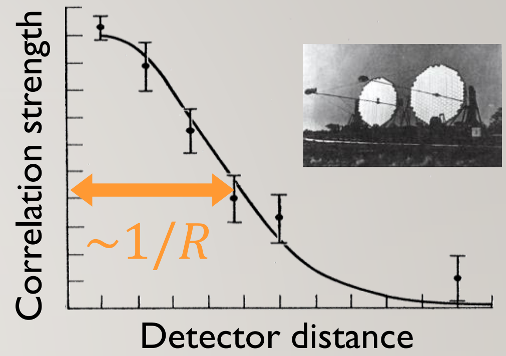
HIN-21-011, ARXIV:2306.11574, SUBMITTED TO PRC

MÁTÉ CSANÁD (EÖTVÖS U) FOR THE CMS COLLABORATION

WPCF 2023

FEMTOSCOPY IN HIGH ENERGY PHYSICS

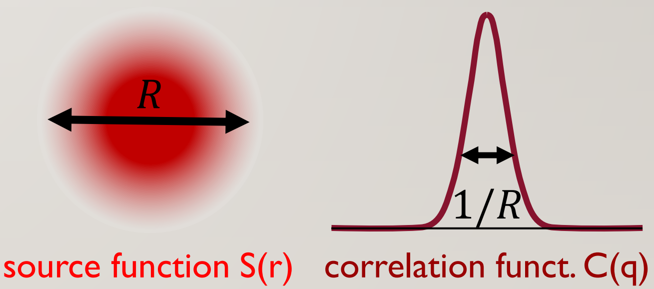
- R. Hanbury Brown, R. Q. Twiss - observing Sirius with radio telescopes
  - Intensity correlations vs detector distance ⇒ source size
  - Measure the sizes of apparently point-like sources!
- Goldhaber et al: applicable in high energy physics
- Understanding: Glauber, Fano, Baym, …
  Phys. Rev. Lett. 10, 84; Rev. Mod. Phys. 78 1267, …



  - Momentum correlation $C(q)$ related to particle emitting source $S(r)$

    $C(q) \cong 1 + \left|\int S(r) e^{iqr} dr\right|^2$ (under some assumptions)
  - With distance distribution $D(r)$:

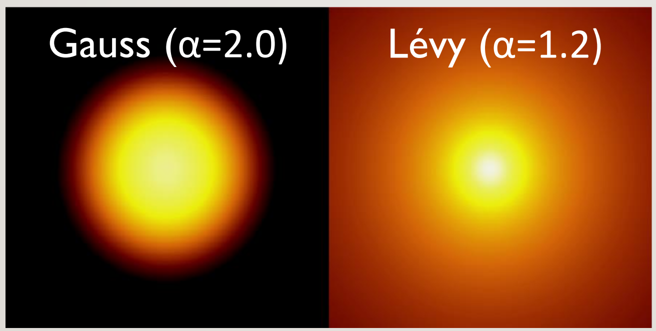
    $C(q) \cong 1 + \int D(r) e^{iqr} dr$
  - Neglected: pair reconstruction,
    final state interactions,
    N-particle correlations, coherence, …

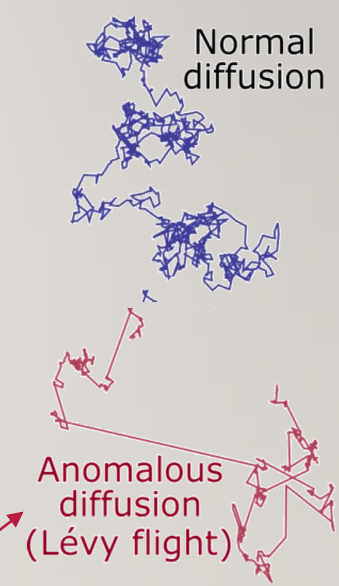


- Only way to map out source space-time geometry on femtometer scale!

SOURCE SHAPE AND CORRELATIONS

- Central limit theorem (diffusion) and thermodynamics lead to Gaussians
- Measurements suggest phenomena beyond Gaussian distribution
- Lévy-stable distribution: $\mathcal{L}(\alpha, R; r) = (2\pi)^{-3} \int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$
  - From generalized central limit theorem, power-law tail $\sim r^{-1-\alpha}$
  - Special cases: α = 2 Gaussian, α = 1 Cauchy

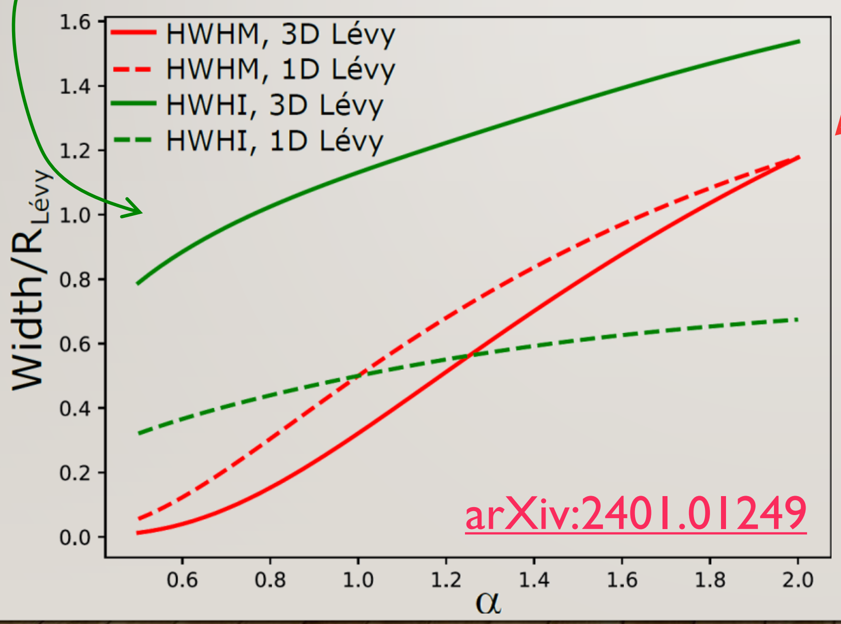


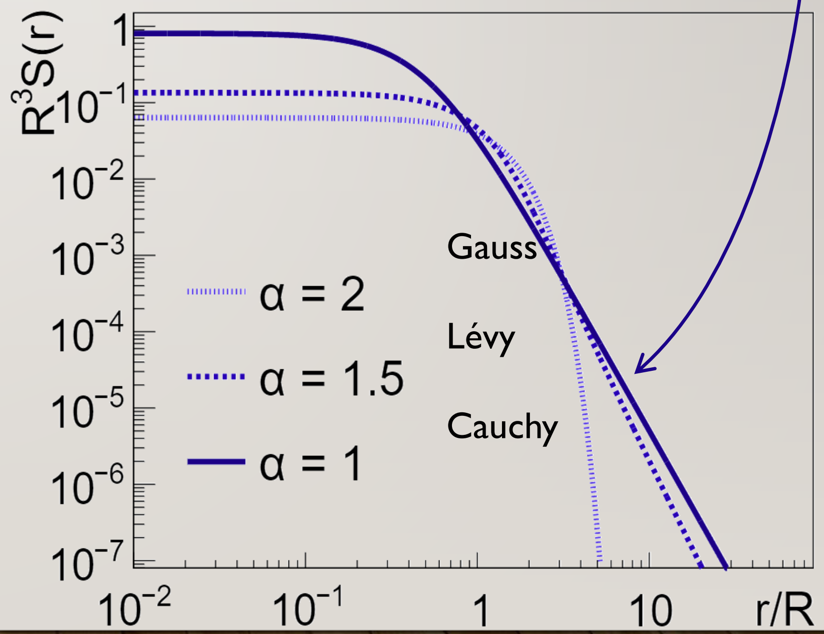


- Shape of the correlation functions with Lévy source:
  - $C_2(q) = 1 + \lambda \cdot e^{-|qR|^\alpha}$; $\alpha = 2$: Gaussian; $\alpha = 1$: exponential
    Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67-78
- A possible reason for Levy source: anomalous diffusion, jet fragmentation, critical phenomena, decays, averaging (see backup slide for details)

MEANING OF HBT SCALE R

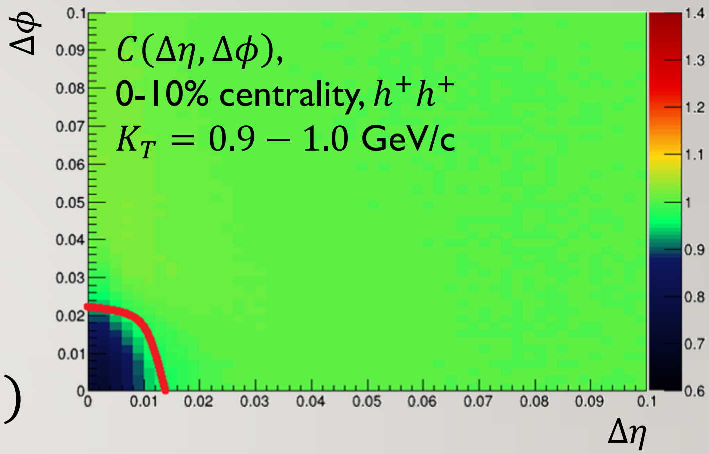
- No tail if $\alpha = 2$, power law if $\alpha < 2$; tail depends on α ($r^{-1-\alpha}$)
- In principle, RMS $= \infty$ if $\alpha < 2$, in practice finite but depends on cutoff
- Wrong assumption → α and $R_{\text{Lévy}}$ entangle in observed source size
  - See backup slide for details
- Alternative measures:
  - Width at half integral (HWHI) or width at half maximum (HWHM)
  - Nontrivially connected to α and R

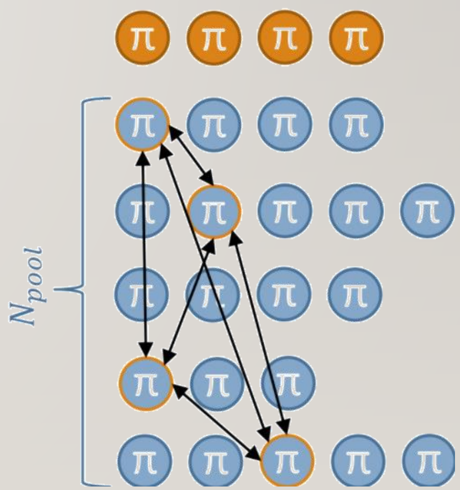




MEASURING CORRELATION FUNCTIONS

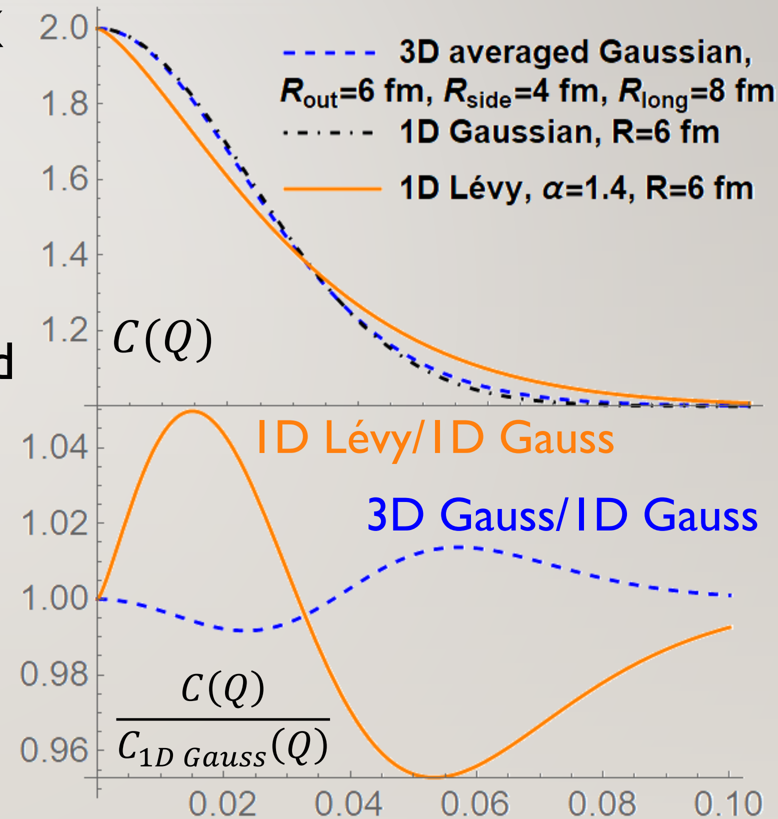
- $\sqrt{s_{NN}} = 5.02$ TeV PbPb, 3B MinBias events
  - vtx cut, centrality classes, std single-track cuts
- Pair cuts needed in Δη, Δϕ to reduce splitting and merging
- Measuring correlation functions via mixed event background: $C(q) = A(q)/B(q)$
- $C(q)$ for large q may contain remaining effects
  - Energy and momentum conservation, resonances, minijets…
- $BG(q)$ long-range background fit to $C(q)$
- Double ratio calculated: $DR(q) = \frac{C(q)}{BG(q)}$
- Very small remaining linear background handled in fit
  - … with a $(1 + \epsilon \cdot q)$ factor





ROLE OF 1D ANALYSIS IN SHAPE

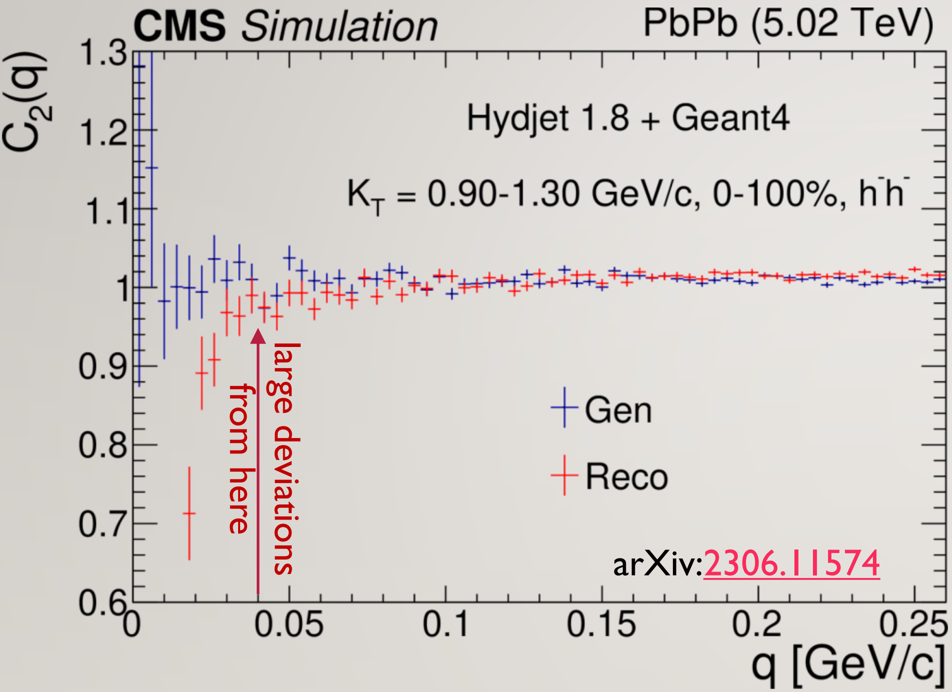
- Approximate spherical symmetry observed by ALICE with Gaussian radii
  - PRC 93 (2016) arXiv:1507.06842, PRL 118 (2017) arXiv:1702.01612 (similarly at RHIC)
- Preliminary 3D Lévy analysis by PHENIX showed $\alpha_{1D} \approx \alpha_{3D}$
  - APPoIB Proc. S. 12 (2019) arXiv:1809.09392
- This CMS analysis: geometry explored in $(q_0, |q|)$ and (q_L, q_T), sphericality valid
- 3D Gaussian does *not* result in 1D Lévy
  - Difference: several percent
  - Available experimental precision: much better than this difference
  - Experimental uncertainties in this analysis: few permille (‰)

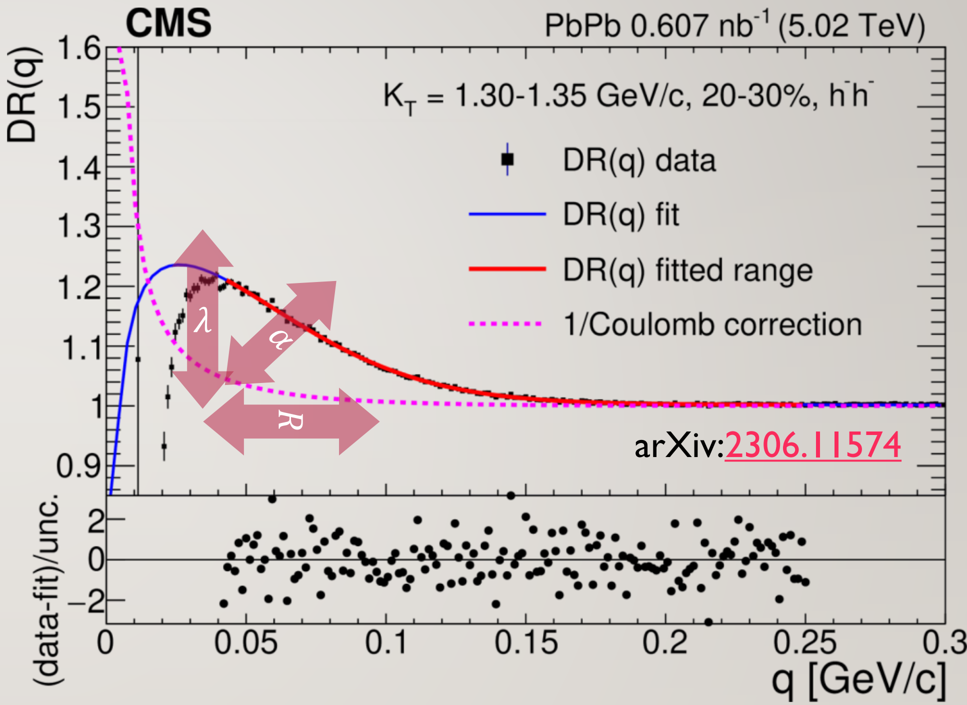


arXiv:2401.01249

FITTING CORRELATION FUNCTIONS

- Small q values: measurement not reliable





- Fit: $N(1+\varepsilon q)\left[1-\lambda+\lambda\left(1+e^{-|qR|^{\alpha}}\right)K_C(q;R,\alpha)\right]$
  - K_C: Coulomb corr., Phys. Part. Nucl. 51, 238 (2020) [See talk by M. Nagy on this subject]
- R,α,λ: physical parameters of Lévy source, N: normalization; ε: background
  - 6 centrality (0-60%) & 24 K_T (0.5-1.9 GeV/c) bins

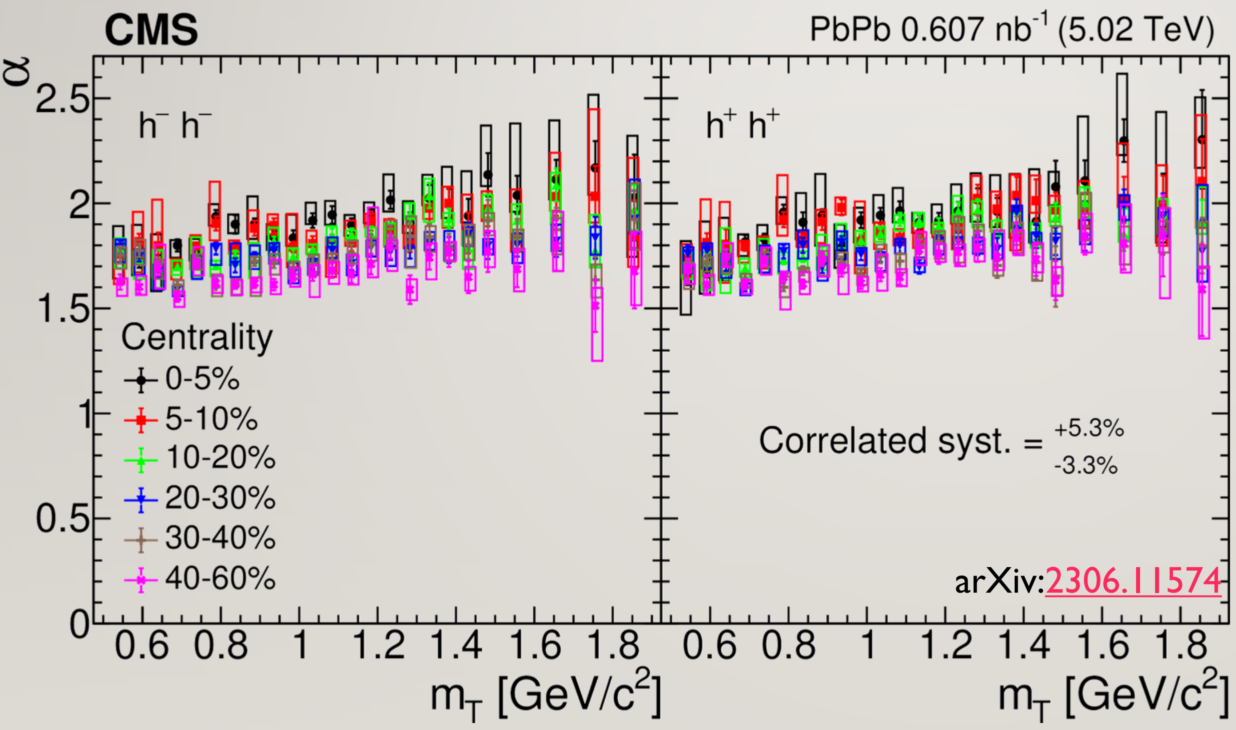
SYSTEMATIC UNCERTAINTY SOURCES

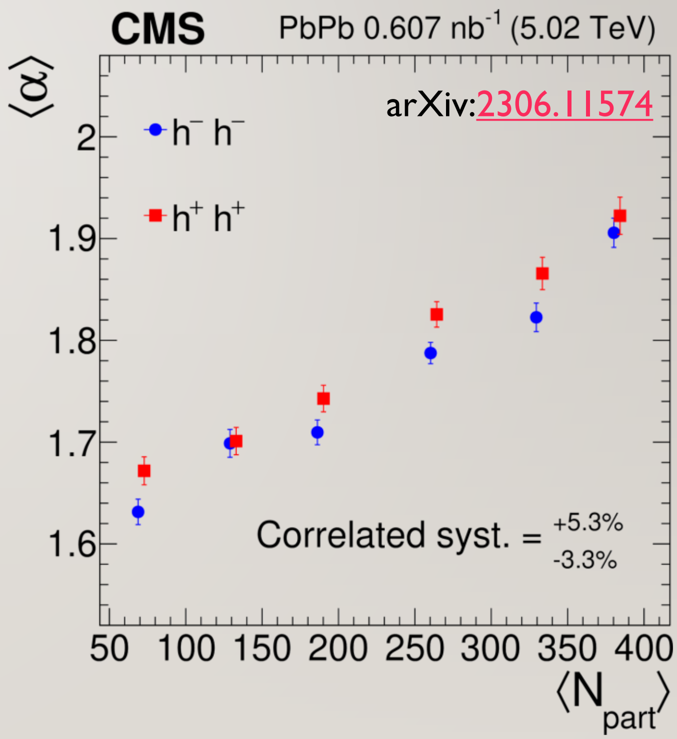
Systematic source	Default	Low	High
vertex z selection	<15 cm	<12 cm	<18 cm
p_T selection	>0.5 GeV/c	>0.55 GeV/c	>0.5 GeV/c
δp_T selection	<10%	<5%	<15%
$\lvert\eta\rvert$ selection	<0.95	<0.9	<1
$N_{\text{pixel-hit}}$ selection	>1	>2	>0
$\chi^2/N_{\text{dof}}/N_{\text{layer}}$ selection	<0.18	<0.15	<0.18
$\lvert d_{xy}/\sigma(d_{xy})\rvert$ selection	<3	<2	<5
$\lvert d_z/\sigma(d_z)\rvert$ selection	<3	<2	<5
$(\Delta\eta, \Delta\phi)$ pair selection	$\Delta\eta_{\min} = 0.014$ $\Delta\phi_{\min} = 0.022$	$\Delta\eta_{\min} = 0.017$ $\Delta\phi_{\min} = 0.028$	$\Delta\eta_{\min} = 0.011$ $\Delta\phi_{\min} = 0.016$
$q_{\min}$ lower fit limit	$q^0_{\min}(K_T, \text{cent})$	$q^0_{\min} - 0.004$	$q^0_{\min} + 0.004$
$q_{\max}$ upper fit limit	$q^0_{\max}(K_T, \text{cent})$	$0.85 q^0_{\max}$	$1.15 q^0_{\max}$
centrality edges	Default values	Lower values	Higher values

- Event and track cuts: 2-4%, pair cuts: 4-6%, fit range: 2-9% → largest effect
- Largest uncertainties for central collisions and for λ parameter
- Separation of point-to-point (fluctuating) and constant part (overall factor)

LÉVY STABILITY INDEX α

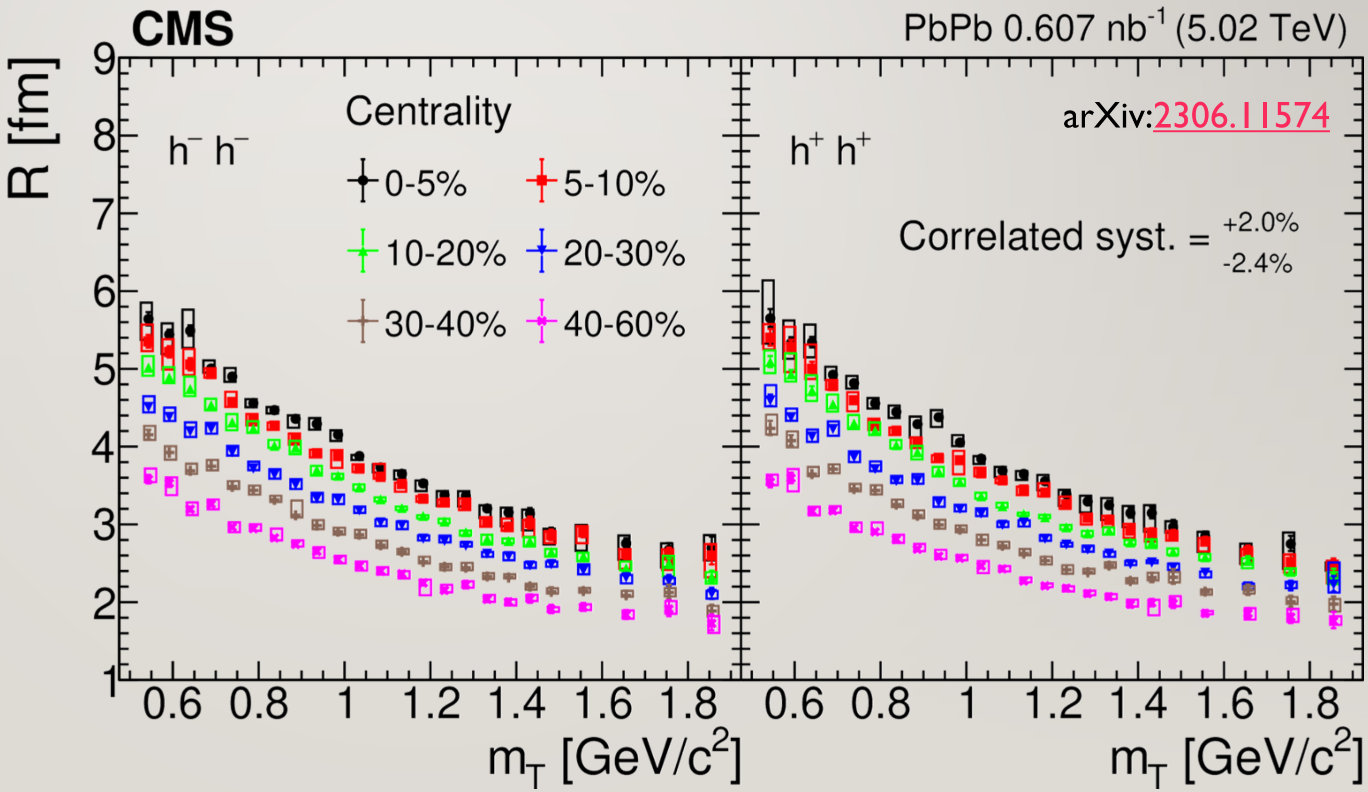
- Source shape not Gaussian ($\alpha \neq 2$)
- Close to constant in each centrality class, average value: 1.6-2.0
- Lévy α larger in central collisions (unlike at RHIC, see talk by D. Kincses)





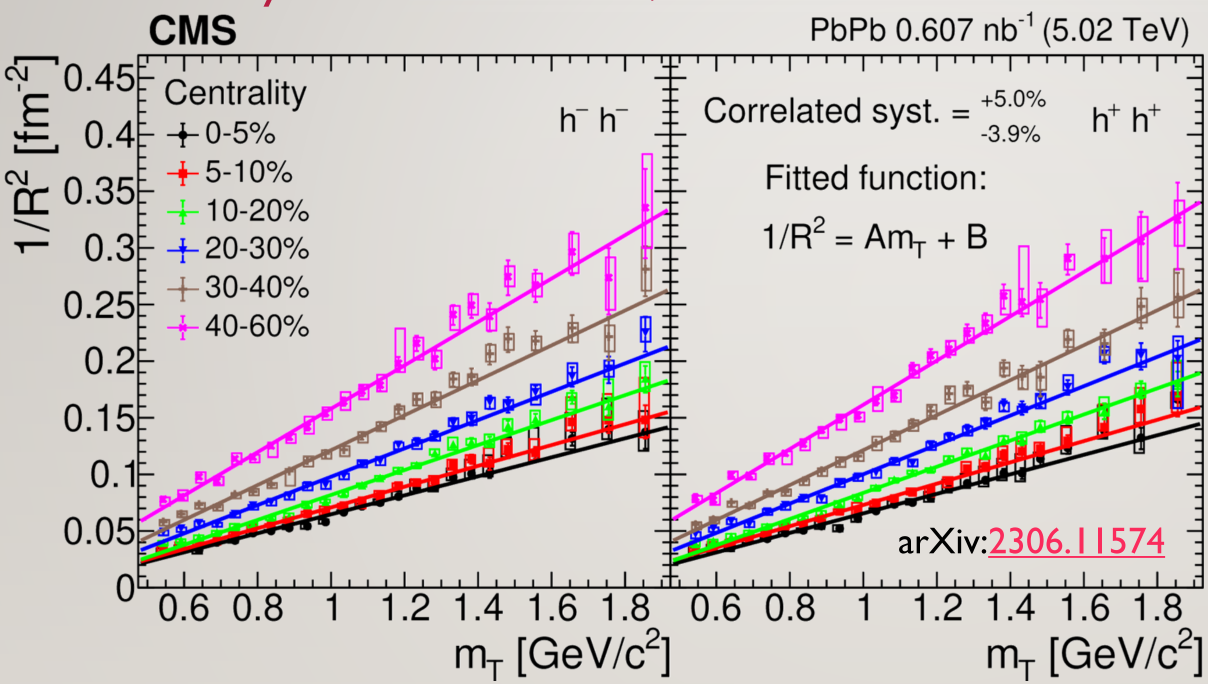
THE LÉVY SCALE PARAMETER: R VS m_T

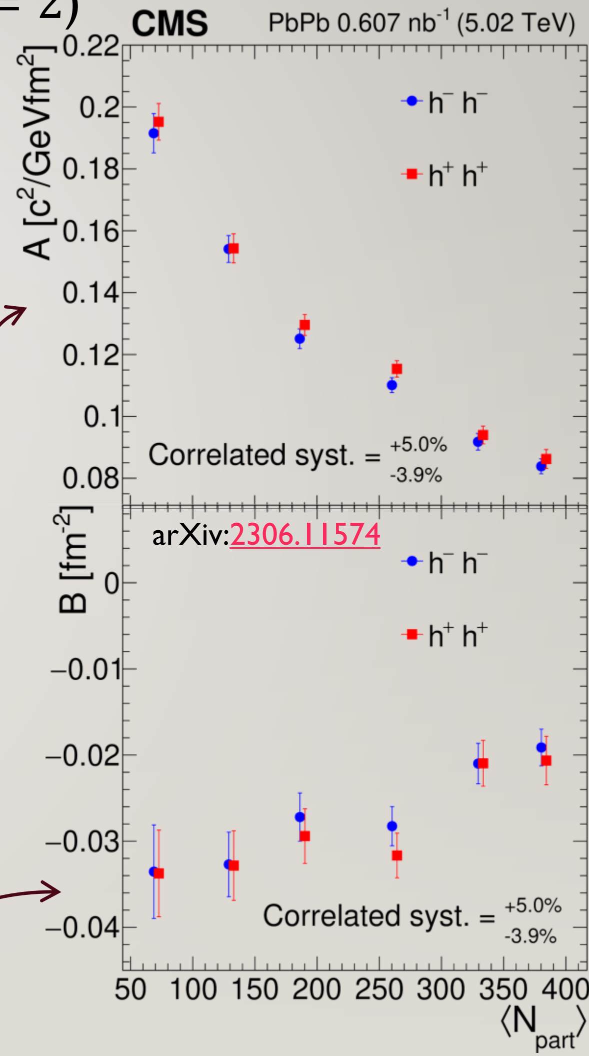
- Pair transverse mass: $m_T = \sqrt{m^2 + (K_T/c)^2}$
- Source homogeneity length R: smooth m_T dependence
  - Usual decrease with m_T, as predicted by hydro for transverse flow
- Centrality dependence:
  - Decrease for peripheral collisions
- Compatible with hydro?



HYDRODYNAMICAL SCALING OF LÉVY R?

- Hydro model prediction: $R^{-2} \approx A \cdot m_T + B$ (for $\alpha = 2$)
  - Slope $A = H^2/T_f$: flow; Intercept $B = R_f^{-2}$: freeze-out size?
- Hydro fits work well, but source not Gaussian?!

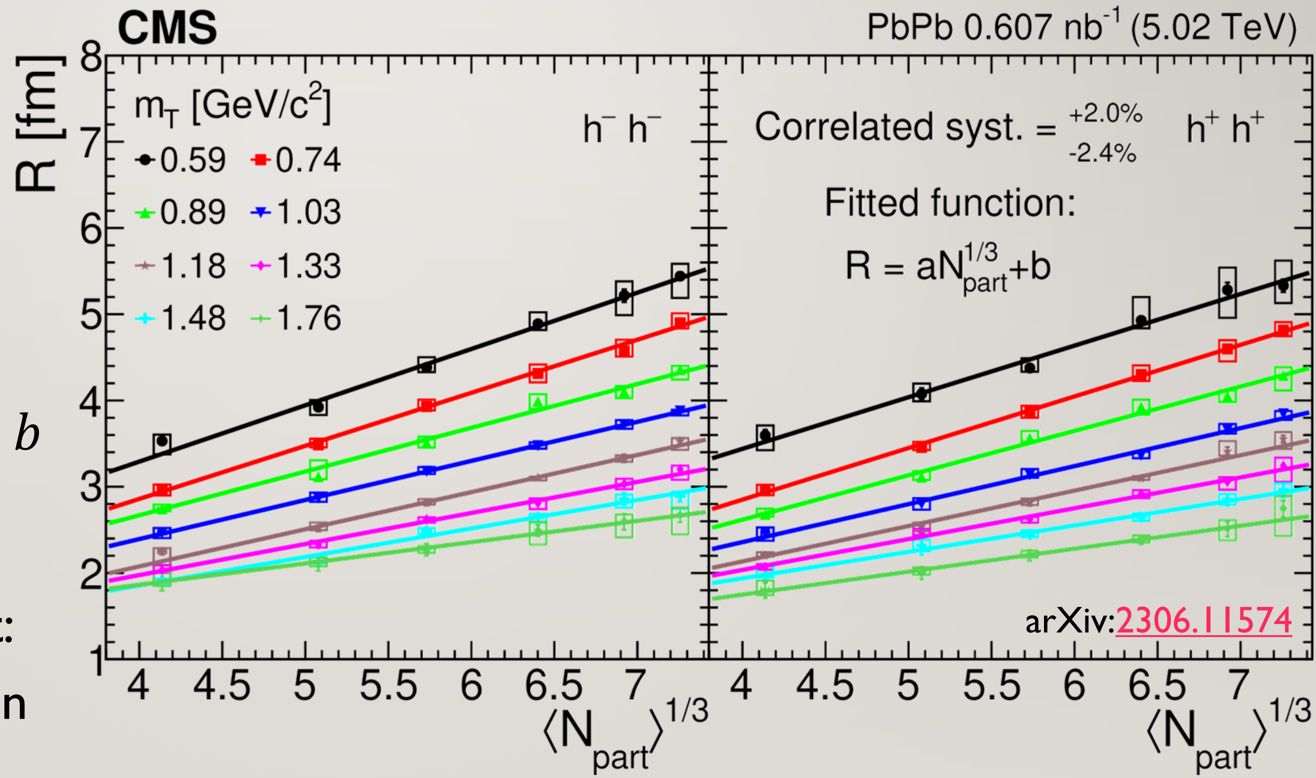




- Hubble constant: $0.10 - 0.17\ \mathrm{fm}^{-1}$
  - Centrality dependence of radial flow
- Negative intercept!

GEOMETRICAL SCALING: R VS N_{part}

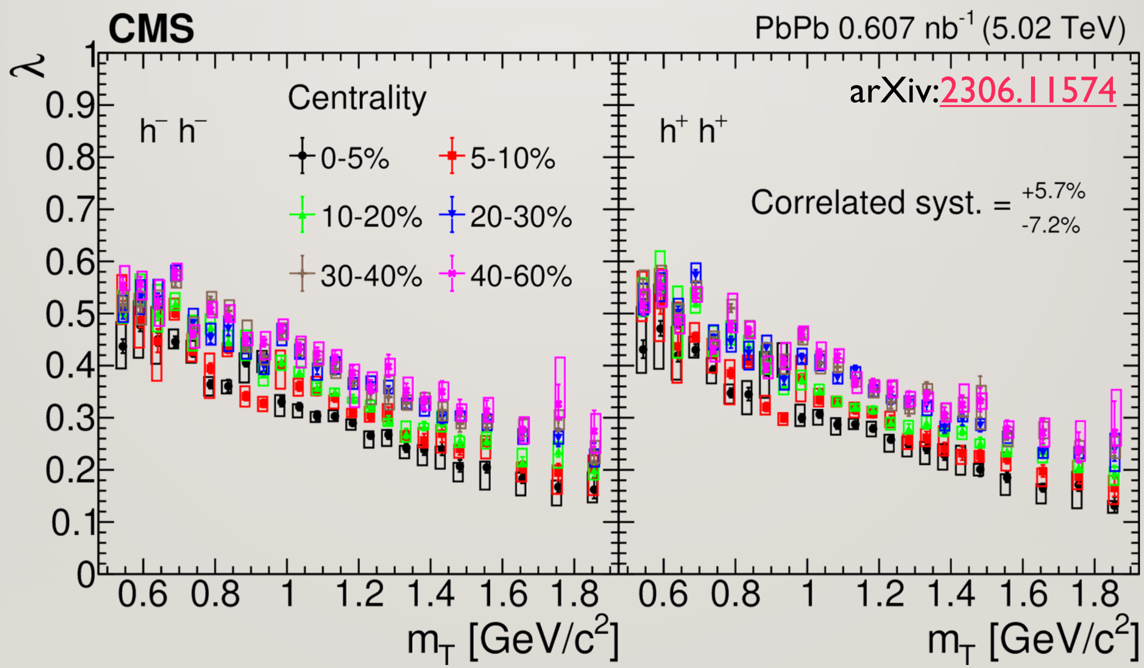
- $\langle N_{\text{part}} \rangle$: average number of participating nucleons in the collision
- $\langle N_{\text{part}} \rangle^{1/3} \sim$ initial one-dimensional size
- If $R \sim \langle N_{\text{part}} \rangle^{1/3}$: R connected to initial geometry
- Linear scaling $R = a \cdot \langle N_{\text{part}} \rangle^{\frac{1}{3}} + b$ verified
- Slope and intercept: related to expansion



arXiv:2306.11574

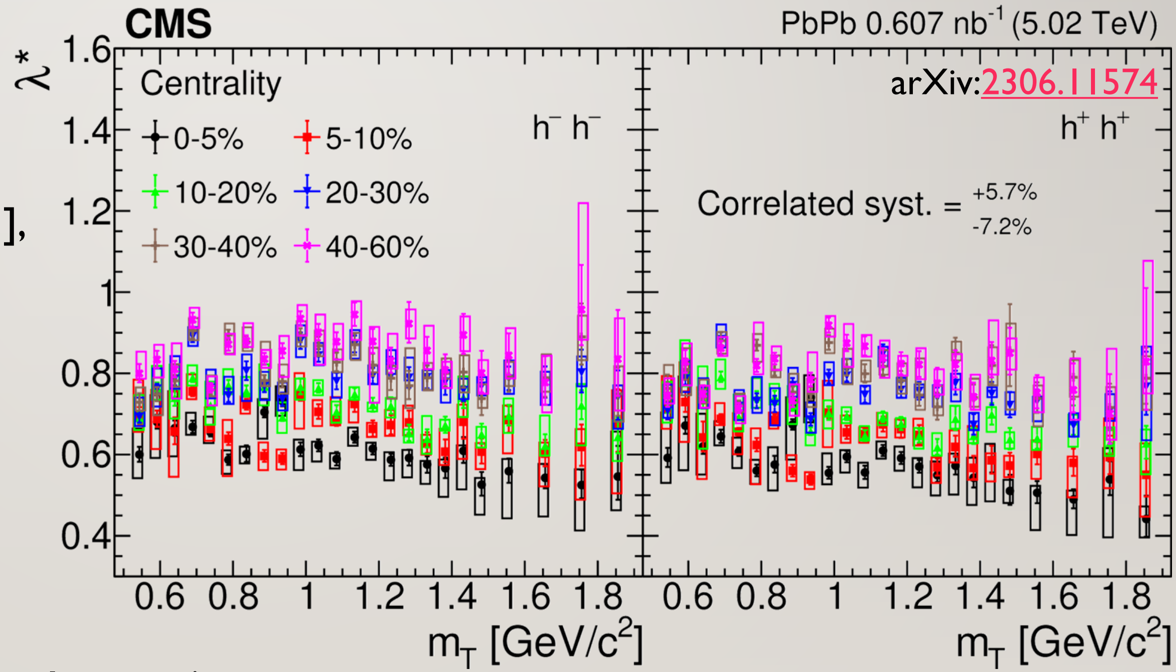
CORRELATION STRENGTH λ

- λ may be influenced (at least) by:
  - Core fraction (f_c) and partial coherence (p_c): increase with f_c, decrease with p_c
    $\lambda = f_c^2[(1-p_c)^2 + 2p_c(1-p_c)]$ (see e.g., Csörgő, hep-ph/0001233)
  - Lack of particle identification: $\lambda \leq (N_\pi/N_{\text{hadron}})^2$
- Strongly decreasing trend with m_T: caused by lack of PID?



RESCALED CORRELATION STRENGTH: λ^*

- Proton and kaon to pion ratio increases with m_T
  - See for example ALICE result Phys.Rev.C 101 (2020) 4, 044907
  - Can rescale with it: $\lambda^* = \lambda \cdot (N_{\text{hadron}}/N_\pi)^2$
- Close to constant trend vs m_T
  - RHIC observes $U_A(1)$ restoration at $m_T \lesssim 300$ MeV/c² [PRC 97 (2018) 064911], not resolvable here
- Centrality dependence: more coherence in central collisions?
- Test with 3-particle correlations!

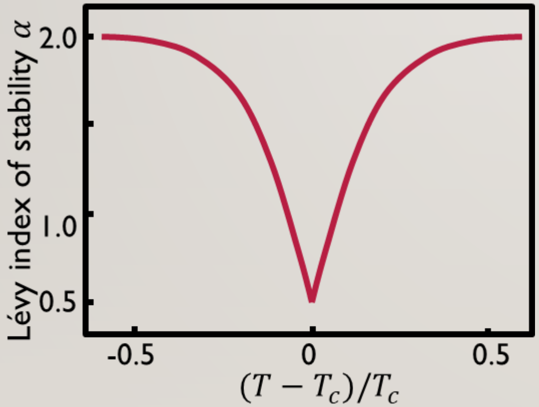


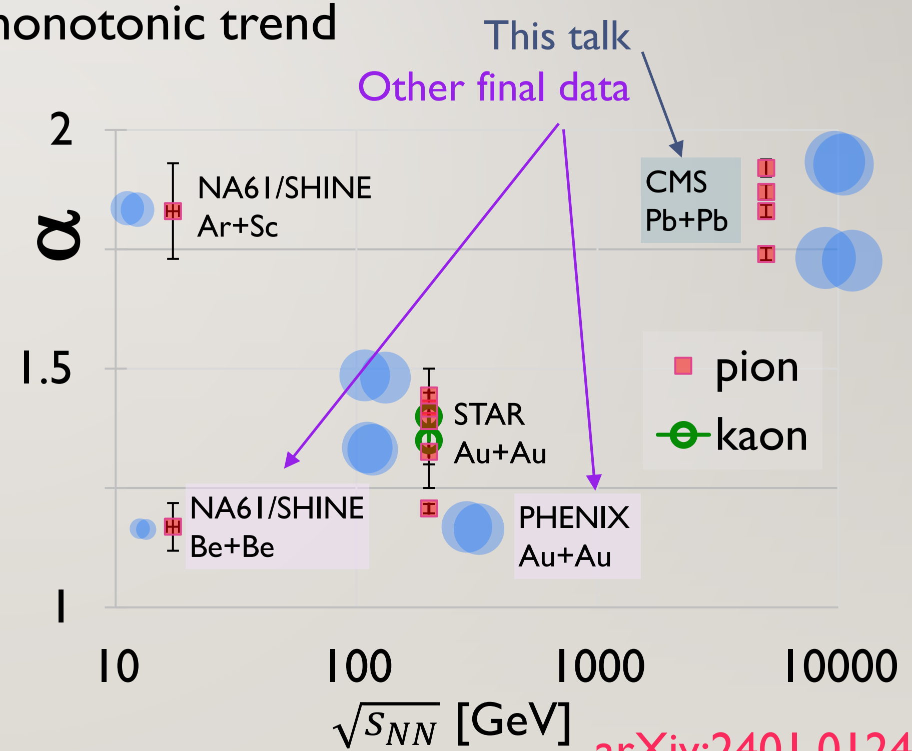
STABILITY PARAMETER α FROM SPS TO LHC

- Decrease from LHC to RHIC, again increase towards SPS (Ar+Sc)
- Different values for small (Be+Be) & medium (Ar+Sc) systems at SPS
  - Also true for Pb+Pb and p+p at LHC? ($\alpha = 1$ assumed so far in p+p at LHC)
- Medium and large systems: non-monotonic trend
- Compare to expectation cartoon

  Csörgő, Hegyi, Zajc,

  Eur.Phys.J. C36 (2004) 67





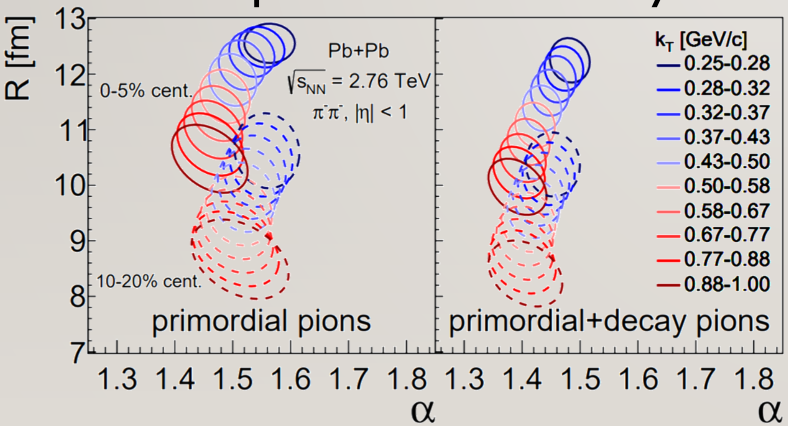
arXiv:2401.01249

COMPARING TO MODEL RESULTS

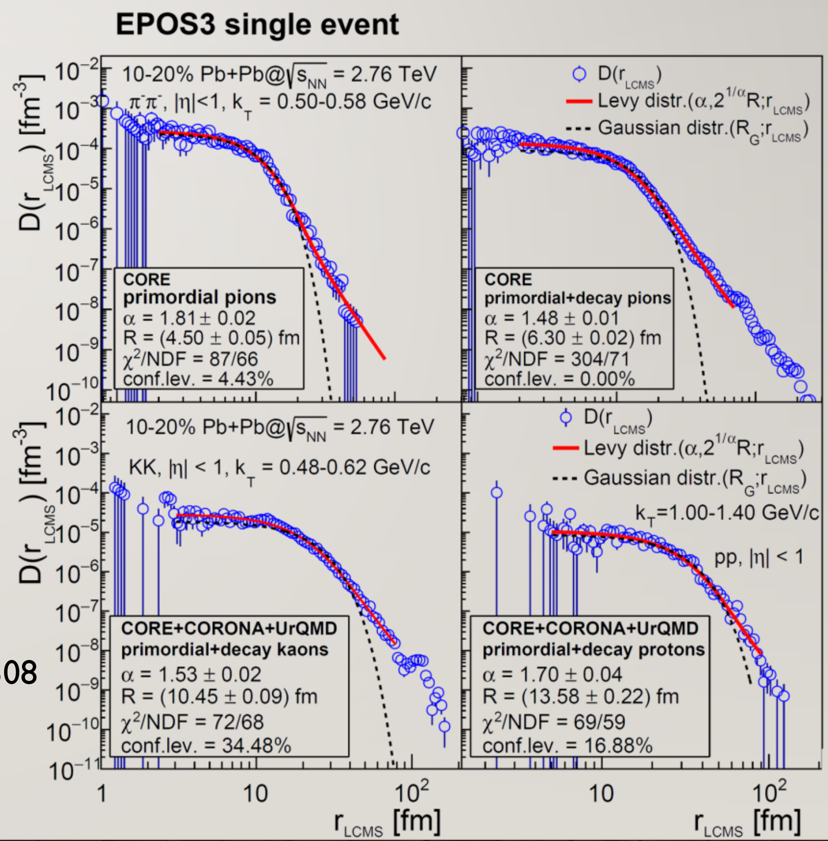
- Pion and kaon pair distributions calculated in individual EPOS events

$$D(r_{LCMS}) = \int d\Omega dt D(t, r_x, r_y, r_z)$$

- Lévy source parameters determined for each event separately
  - Fit limits: from 2-5 fm to 70-100 fm
  - Criterion: confidence level > 0.1%
  - Strongly non-Gaussian shapes observed
- In various centrality and k_T classes, primordial or decays



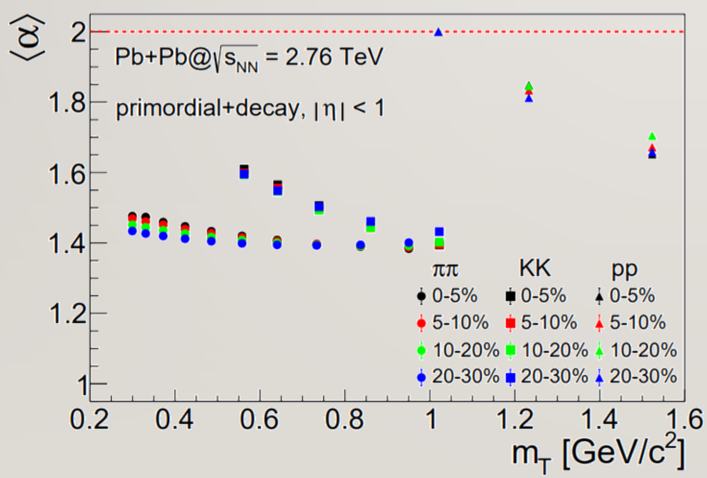
Kincses, Kórodi, Stefaniak, Csanád
Entropy 24 (2022) 308
arXiv:2201.07962
Phys. Lett. B (2023)
arXiv:2212.02980

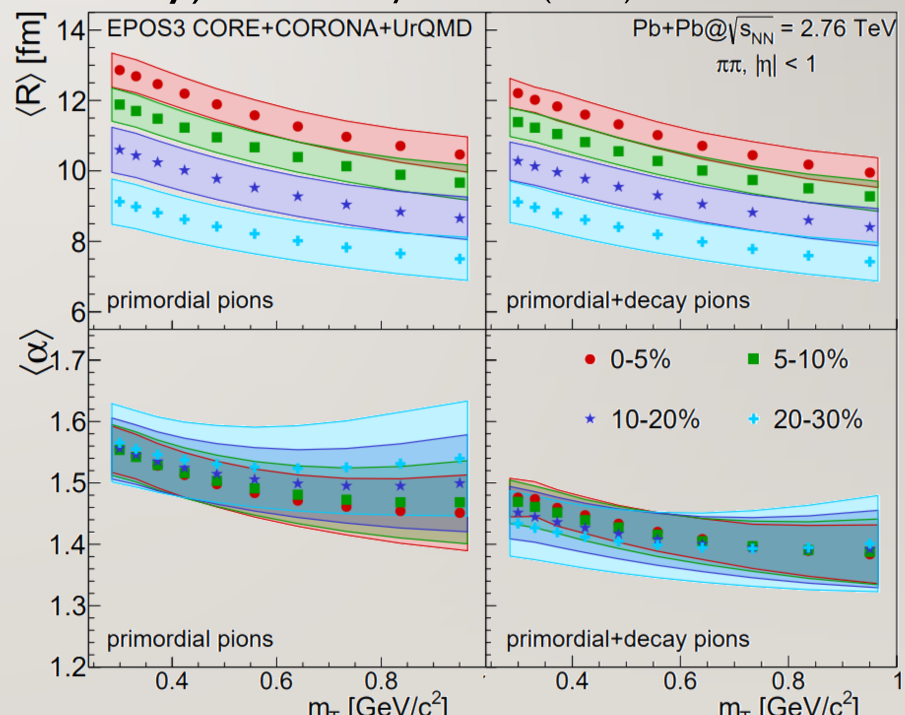


LÉVY SOURCE PARAMETERS IN EPOS

- Lévy scale parameter (R):
  - Behavior similar as in data (m_T and centrality dependence); but larger!
- Lévy stability index (α):
  - Behavior different than in data (no centrality dependence here); but smaller!
- Bands: variance of R, α in fits ($\neq$ uncertainty)
- Particle type dependence:
  - Anomalous diffusion: $\alpha_K < \alpha_\pi < \alpha_p$
  - Not exactly valid in EPOS; decays?

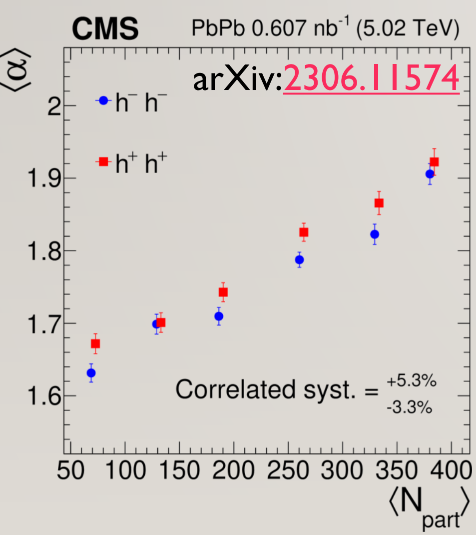
Phys. Lett. B (2023), arXiv:2212.02980

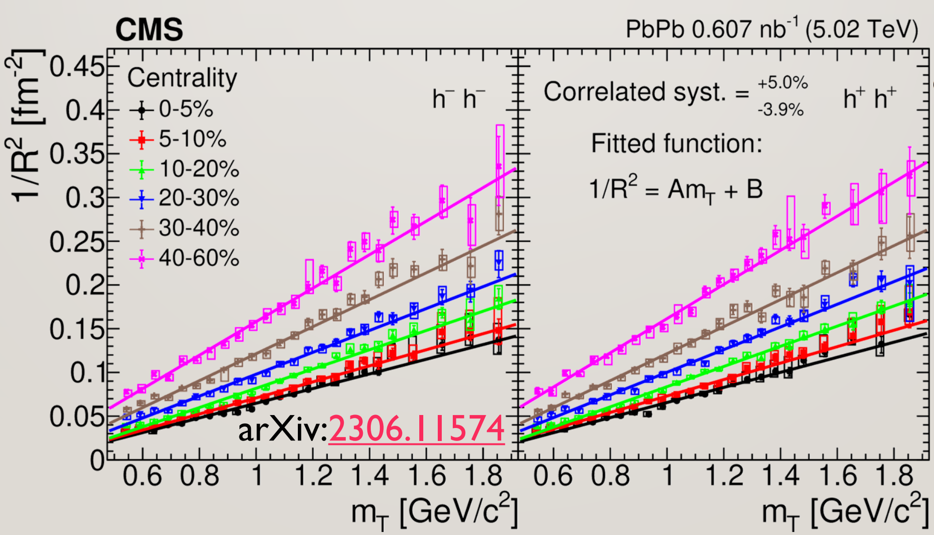


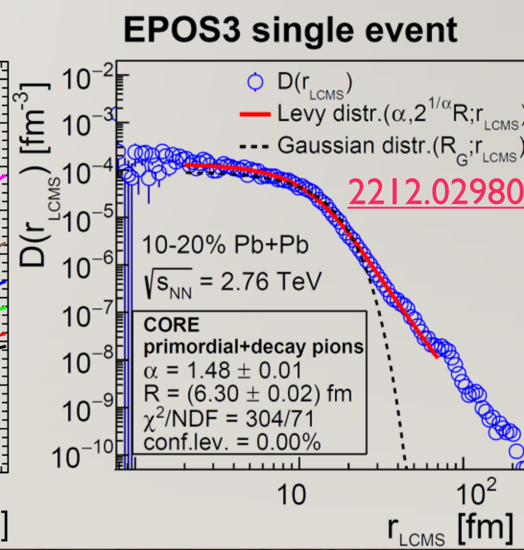


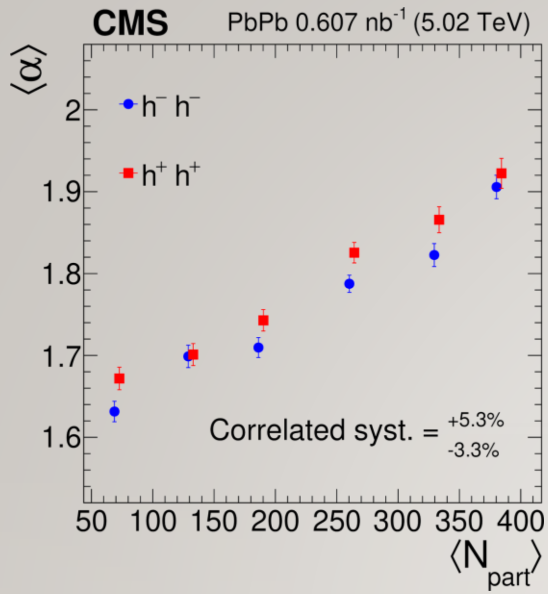
CONCLUSIONS

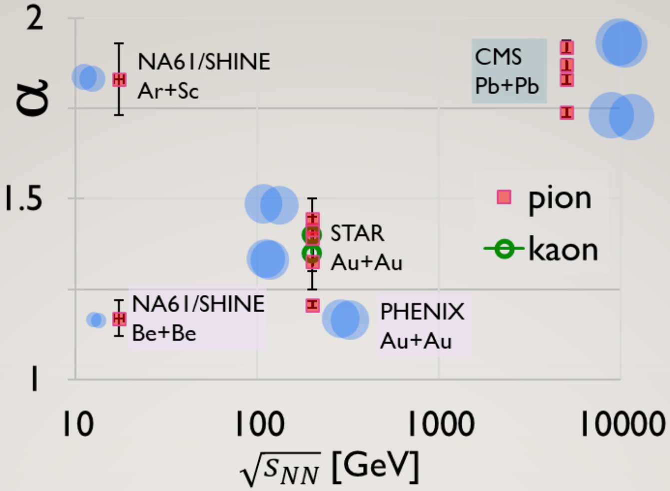
- Lévy sources appear in $\sqrt{s_{NN}} = 5.02$ PbPb collisions at LHC
  - Importance: entanglement of α and R masks energy, momentum, centrality dependence
- **Lévy α**: between 1.6 and 2
  - Larger in central collisions: larger density, less anomalous diffusion?
- **Lévy R**: hydro scaling versus m_T, despite not Gaussian source
- Possible reason: Lévy flight → checked with EPOS, Lévy in single events

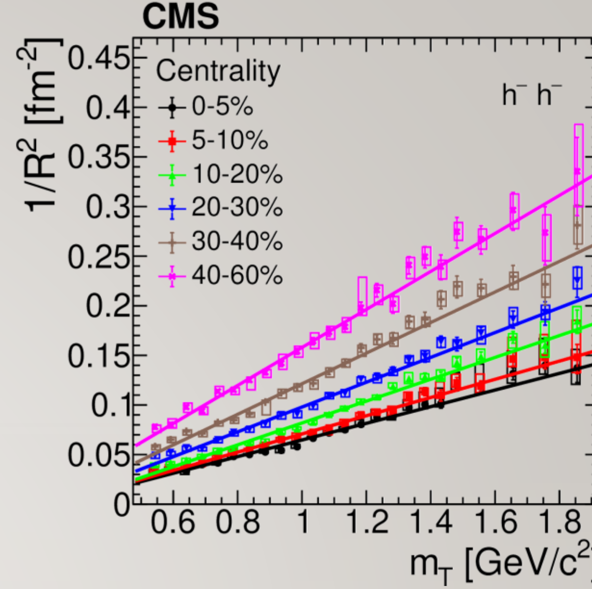












THANK YOU FOR YOUR ATTENTION

… and if you are interested in these subjects: https://zimanyischool.kfki.hu/