



Centrality Dependent Lévy Analysis of two-pion BEC Functions at PHENIX

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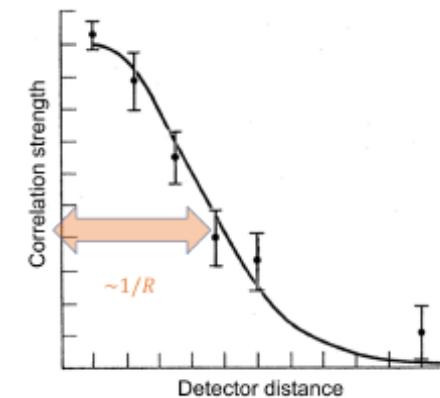
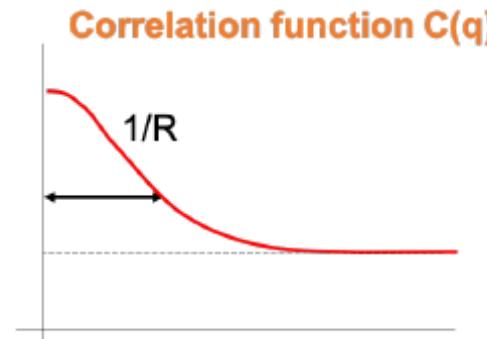
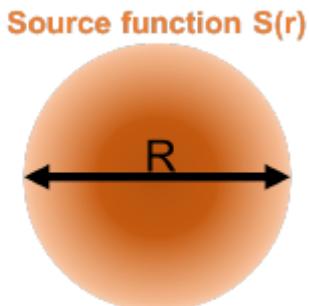
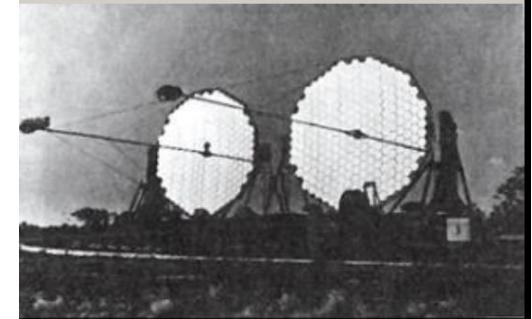


24–28 Oct 2022
University of Santiago de Compostela



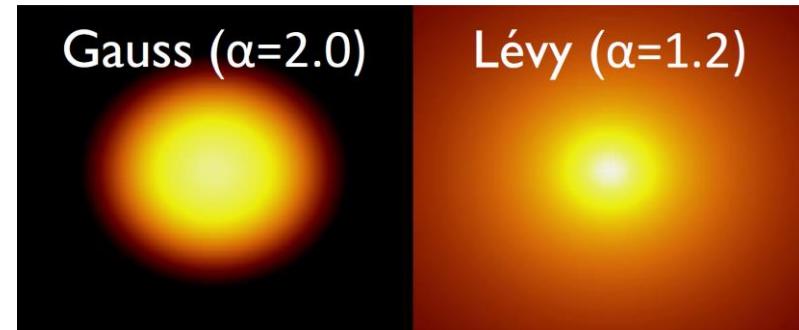
The HBT-effect in Femtoscopy

- R. Hanbury Brown, R.Q.Twiss observed Sirius with radio telescopes
- R. Hanbury Brown and R. Q. Twiss 1956 Nature 178
 - Intensity correlations as a function of detector distance
 - Measuring size of point-like sources
- Goldhaber et al: applicable in high energy physics: (for identical pions)
- G. Goldhaber et al 1959 Phys.Rev.Lett. 3 181
 - Momentum correlation $C(q)$ is related to the source $S(x)$:
$$C(q) \cong 1 + |\tilde{S}(q)|^2$$
, where $\tilde{S}(q)$ is Fourier transform of $S(q)$.



Lévy Distributions in Heavy Ion Physics

- Usual assumption that $S(r)$ is Gaussian \rightarrow Gaussian $C(q)$
- Measurements suggest phenomena beyond Gaussian distribution
- Lévy stable distribution: $\mathcal{L}(\alpha, R; r) = (2\pi)^{-3} \int d^3 q e^{iqr} e^{-1/2|qR|^\alpha}$
 - From generalized central limit theorem, power law tail $\sim r^{-(1+\alpha)}$
 - Special cases: $\alpha = 2$ Gaussian, $\alpha = 1$ 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: criticality, anomalous diffusion, many others

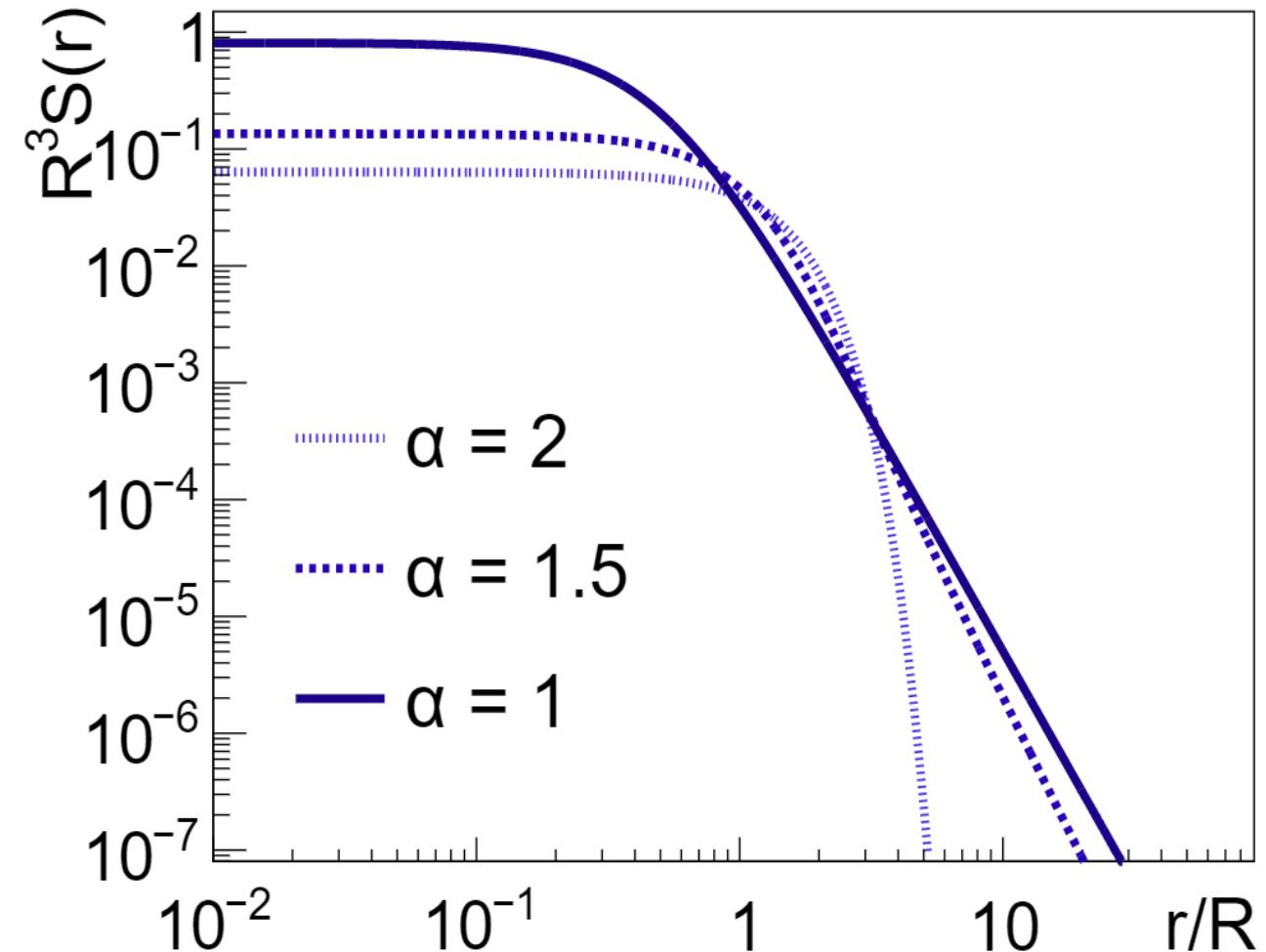
Lévy vs. Gaussian vs. Exponential

- No tail if $\alpha=2$, power law if $\alpha<2$; tail strength depends on α
- If $S(r)$ Lévy, the distance distribution $D(r)$ also Lévy with same α and $R \rightarrow 2^{1/\alpha} R$
- Critical spatial correlation:
 $\sim r^{-(d-2+\eta)}$

Lévy source: $\sim r^{-(1+\alpha)}$; $\alpha \Leftrightarrow \eta$?

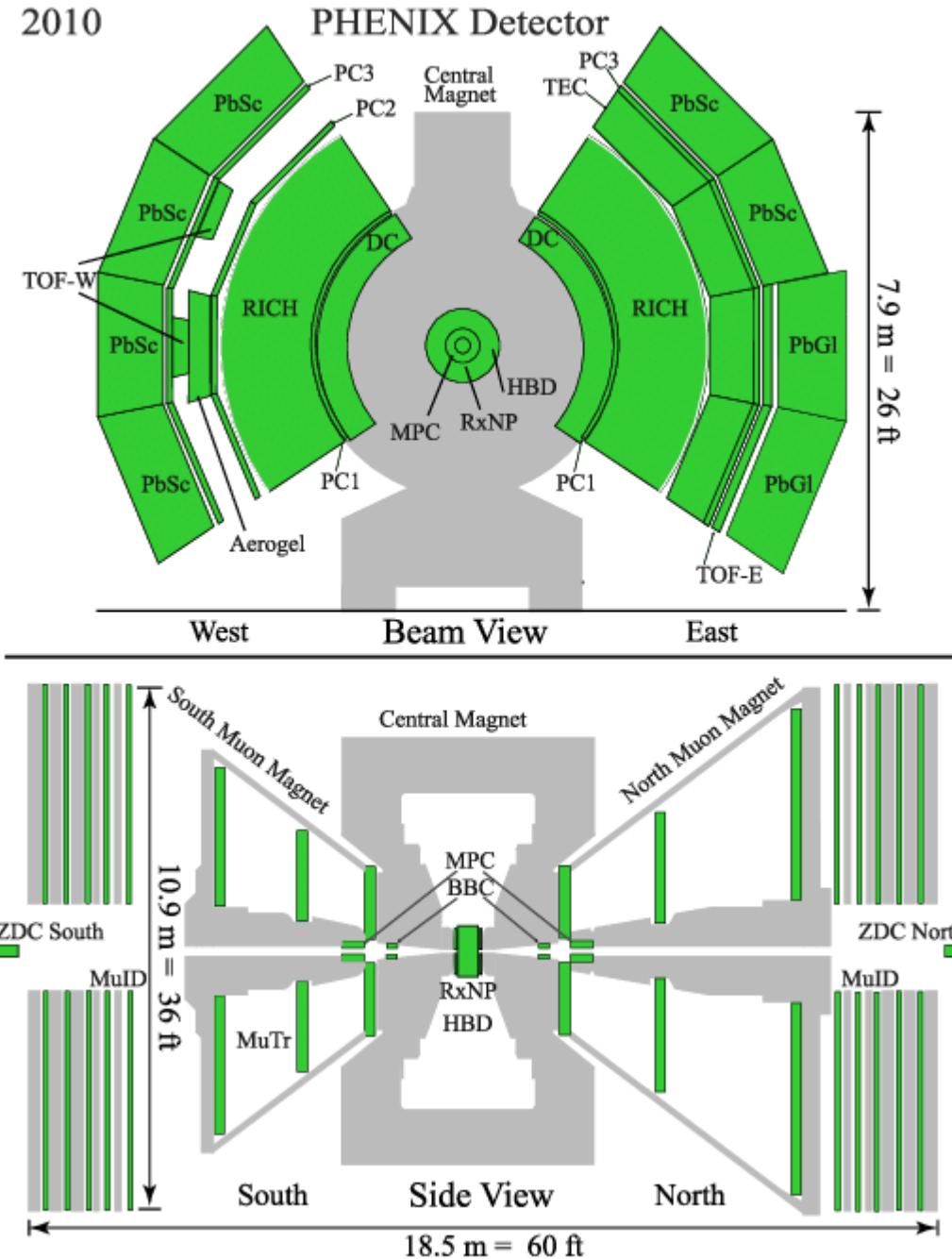
Csörgő, Hegyi , Zajc , Eur.Phys.J . C36 (2004)

Motivation for precise Lévy HBT!



The PHENIX Experiment

- Experiments of RHIC (Brookhaven):
 - PHENIX, STAR, BRAHMS, PHOBOS
- Tracking system:
 - Drift Chamber (trajectories of charged particles)
 - Pad Chamber (track coordinates)
 - Time of Flight detector
- Observing collision of p+p, p+Al, p+Au, d+Au, Au+Au, U+U
- Charged pion ID from ~ 0.2 to 2 GeV
- Typical Au+Au: $\sqrt{s_{NN}} = 130 \text{ GeV}$, 200 GeV

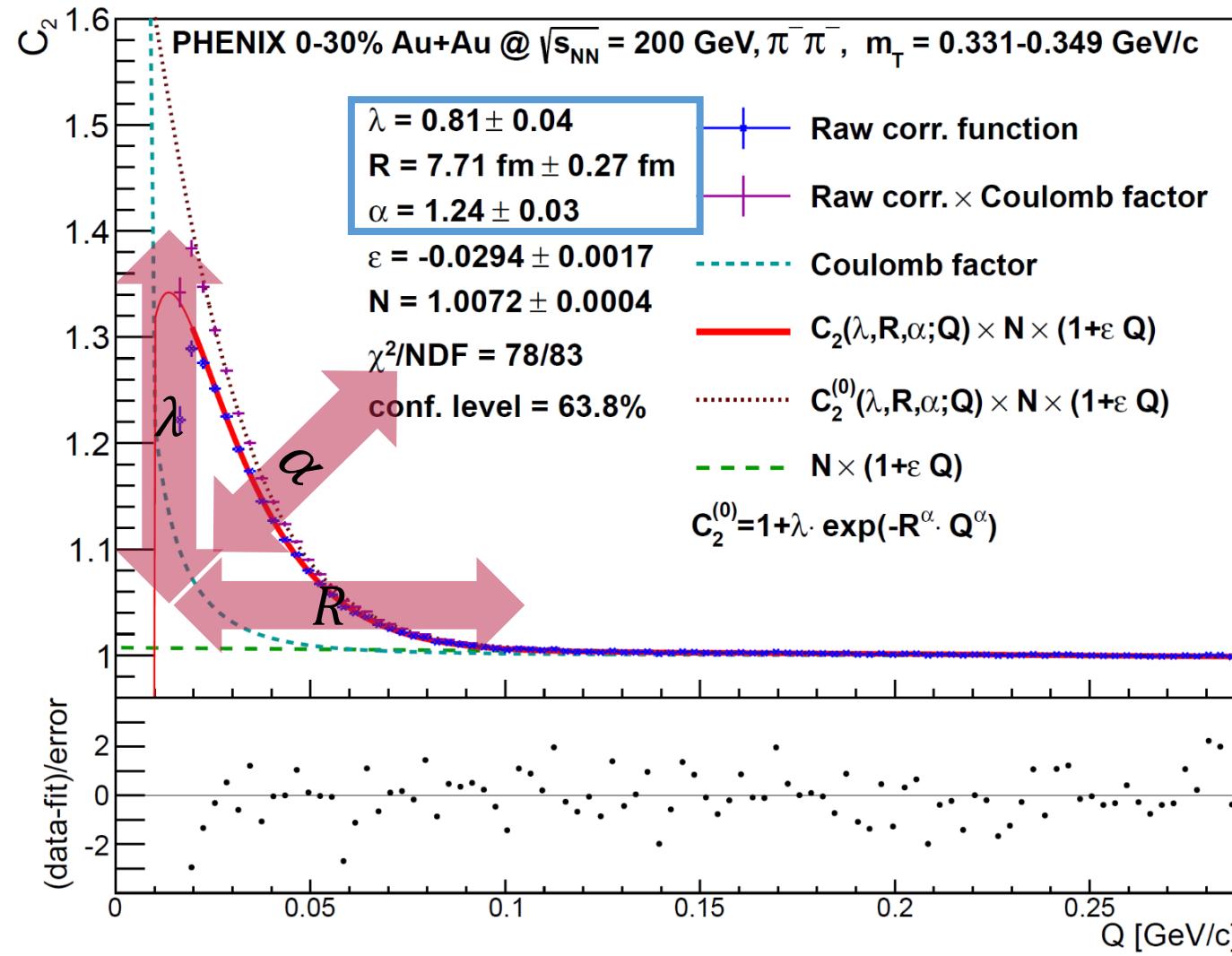


PHENIX Lévy-HBT Analysis Overview

- Data set: $\sqrt{s}_{NN} = 200, 62, 39 \text{ GeV Au+Au}$, identified pions
- Some details of the analysis:
 - 1D $\pi^\pm\pi^\pm$ corr. func . as a function of m_T and centrality
 - Investigation of systematic uncertainties:
 - One and two particle criteria (PID, matching, paircuts)
 - Other sources of syst. Uncertainties (e. g. fit stability , Coulomb effect)
 - Fitting the measured correlation function with Lévy shape
 - Investigation of the source parameters (λ, R, α)

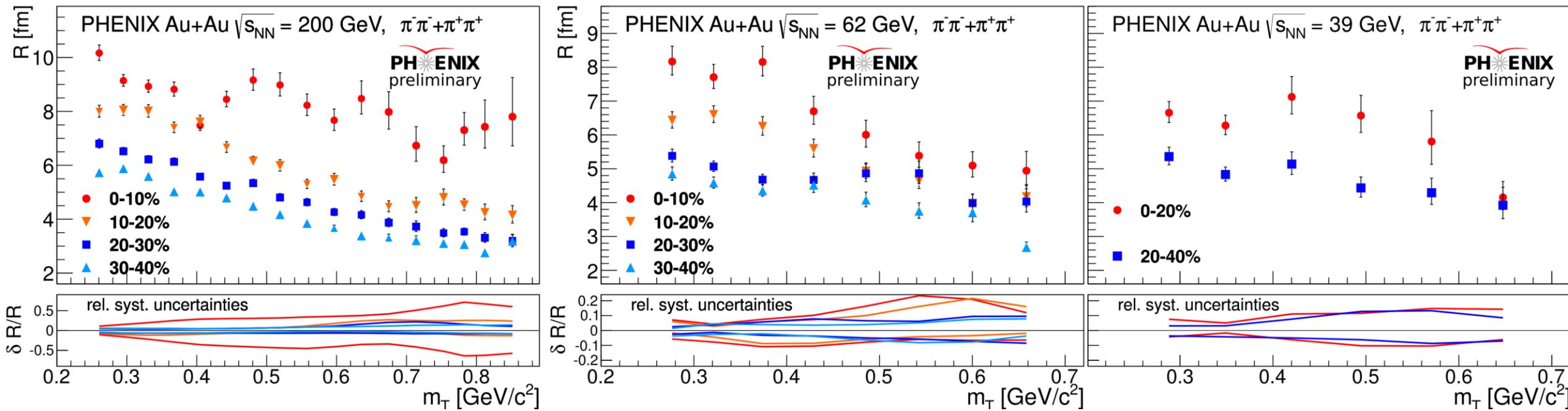
Example Correlation Function

- Fit with calculation based on Lévy distribution
 - Physical parameters: R , α , λ measured versus pair m_T
 - R : homogeneity length, dynamics, sizes
 - α : shape, criticality, anomalous diffusion
 - λ : particle creation mechanisms, in-medium mass modification
- Lévy works well



R – Centrality and m_T dependence

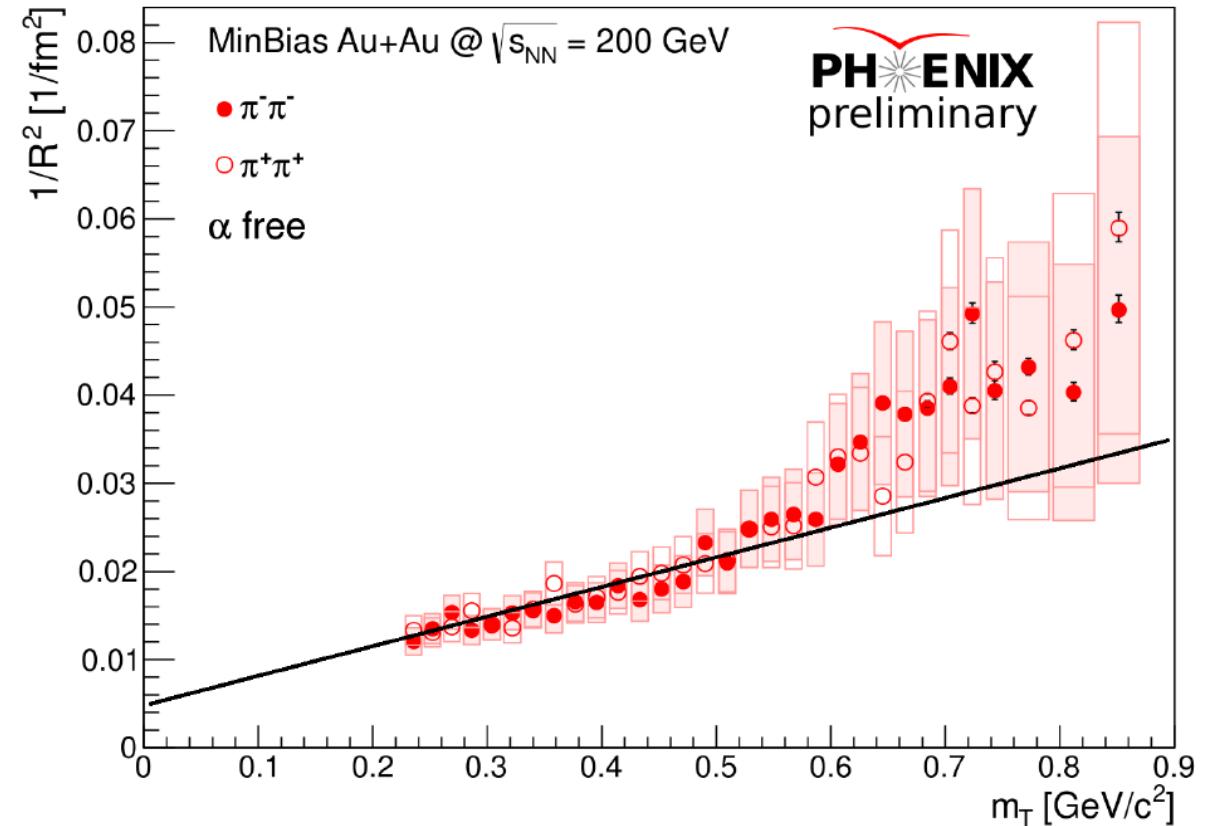
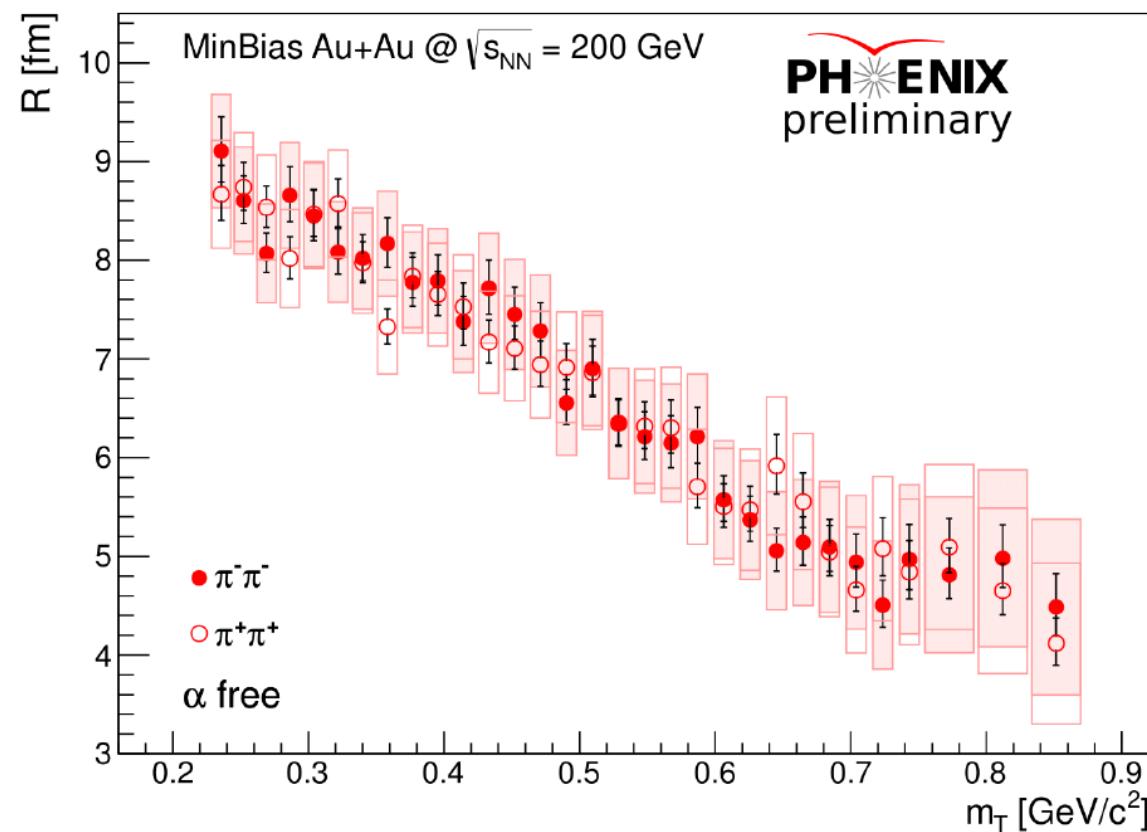
D. Kincses, Universe 4 (2018) 11



- Geometrical centrality dependence
- Usual decrease with m_T is present

Lévy scale parameter - R

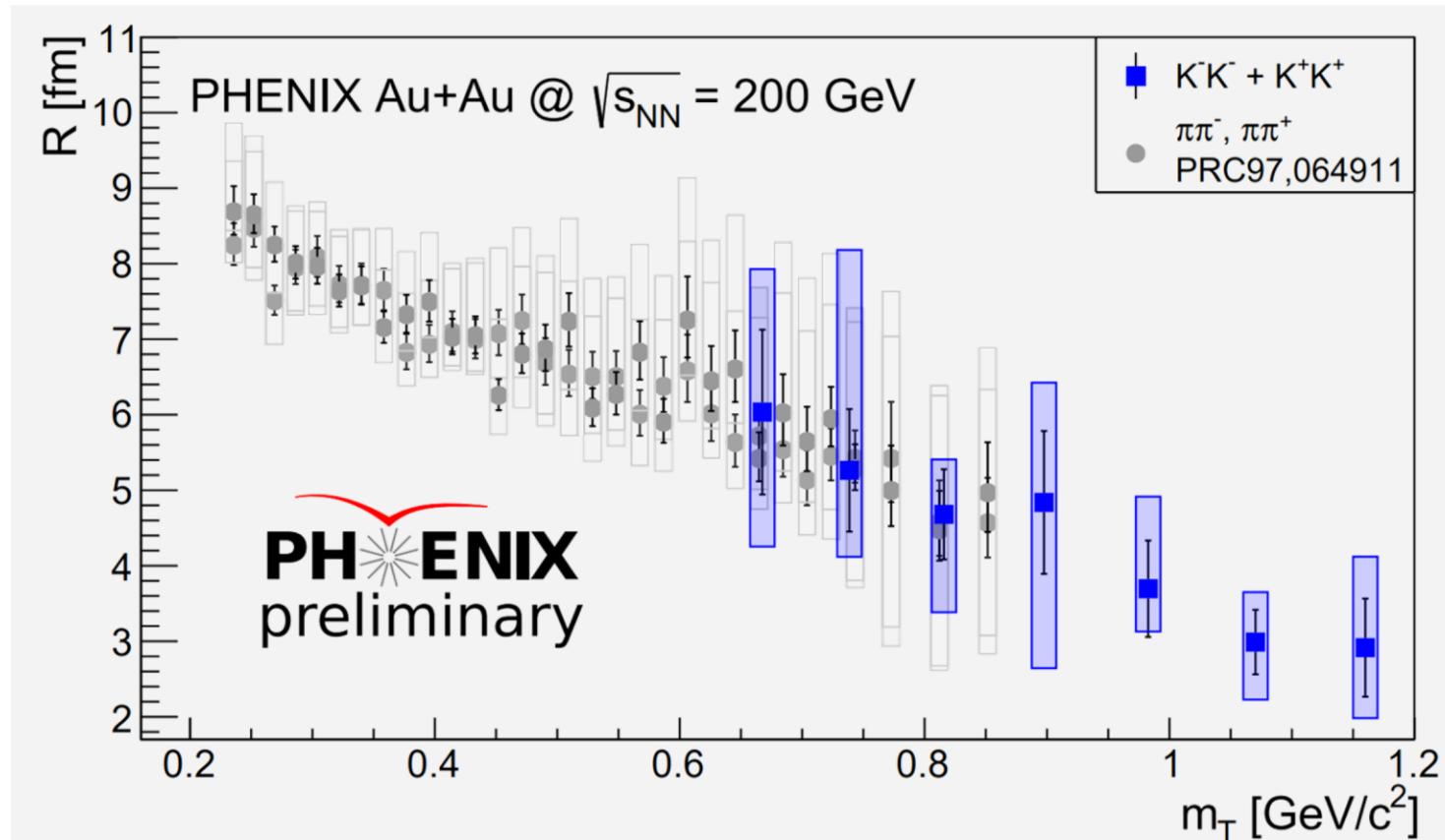
Phys. Rev. C 97, 064911



- Hydro calculations for Gaussian radii $\rightarrow 1/R^2 \sim m_T$
- In case of low m_T , the linear scaling of $1/R^2$ holds

Kaon Lévy Scale - R

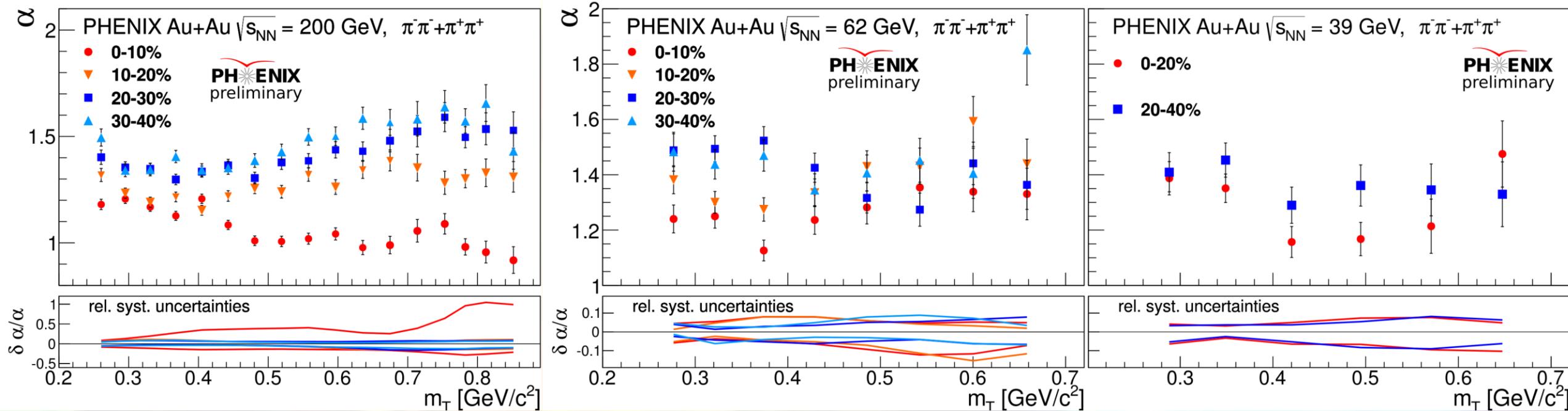
Talk of L. Kovács, WPCF 2022



- R of kaons consistent with R of pions
- Decreasing trend with m_T

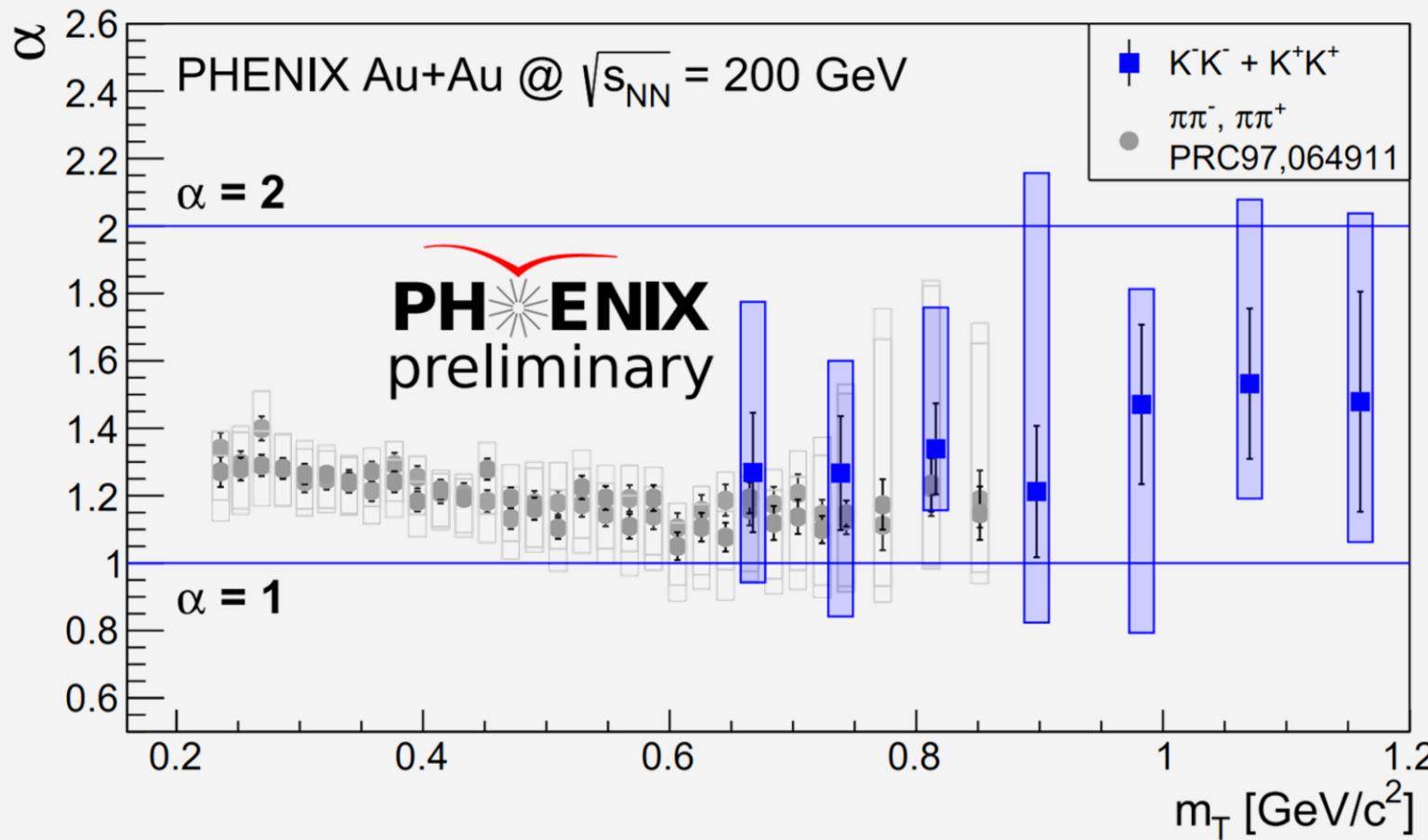
α – Centrality and m_T dependence

D. Kincses, Universe 4 (2018) 11



- Measured value far from Gaussian ($\alpha = 2$), inconsistent with expo. ($\alpha = 1$)
- Far from random field 3D Ising value at CEP ($\alpha = 0.5$)
- Approximately constant (at least within systematic uncertainties)

Kaon Lévy shape - α



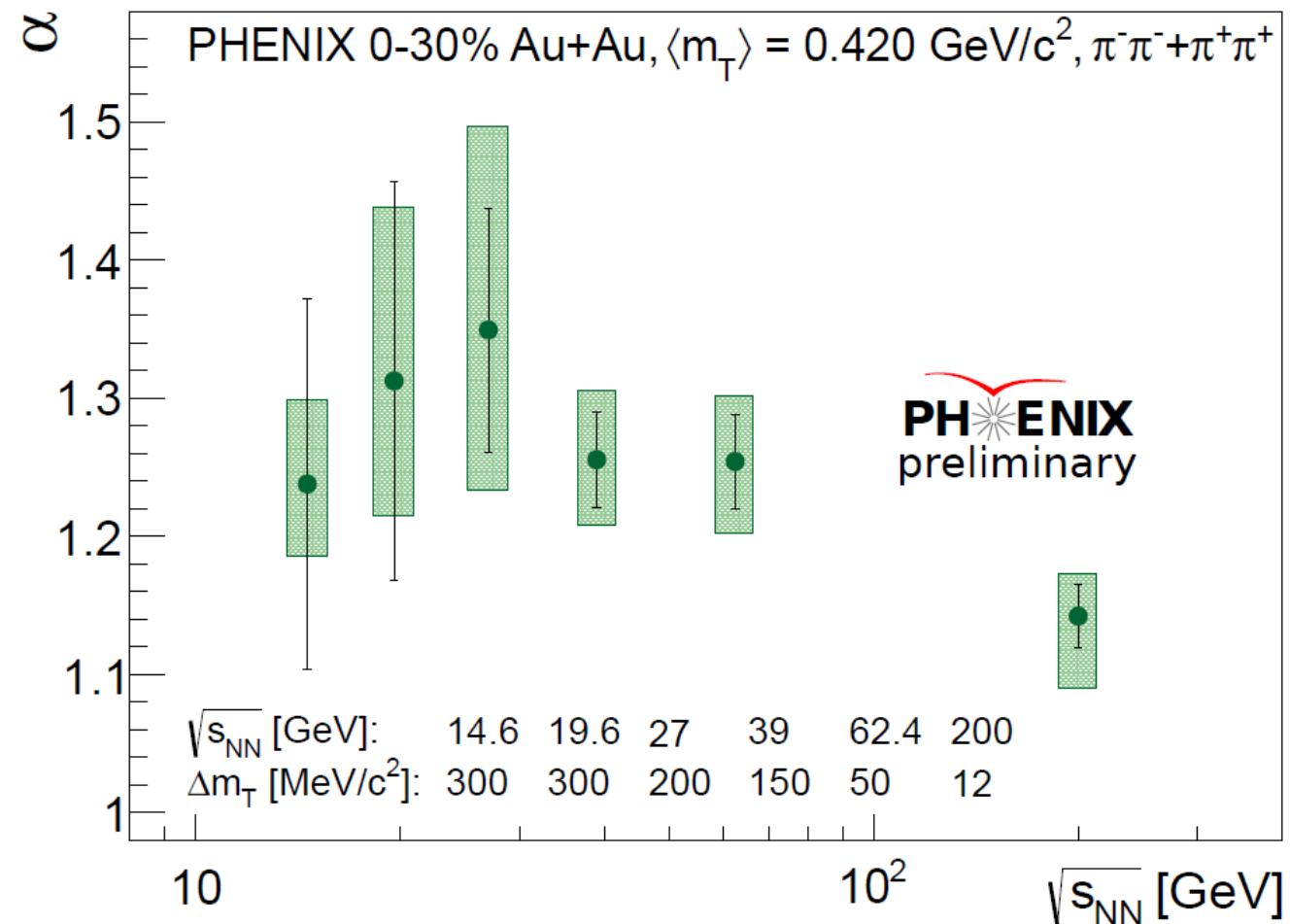
- Does not exhibit strong dependence on transverse mass
- Kaon α consistent with pions, weak $\alpha(K) \geq \alpha(\pi)$ indication
- Anomalous diffusion suggests $\alpha(K) < \alpha(\pi)$

[M. Csanad, T. Csorgo, M. Nagy, Braz.J.Phys. 37 (2007) 1002]

Collision Energy Dependence

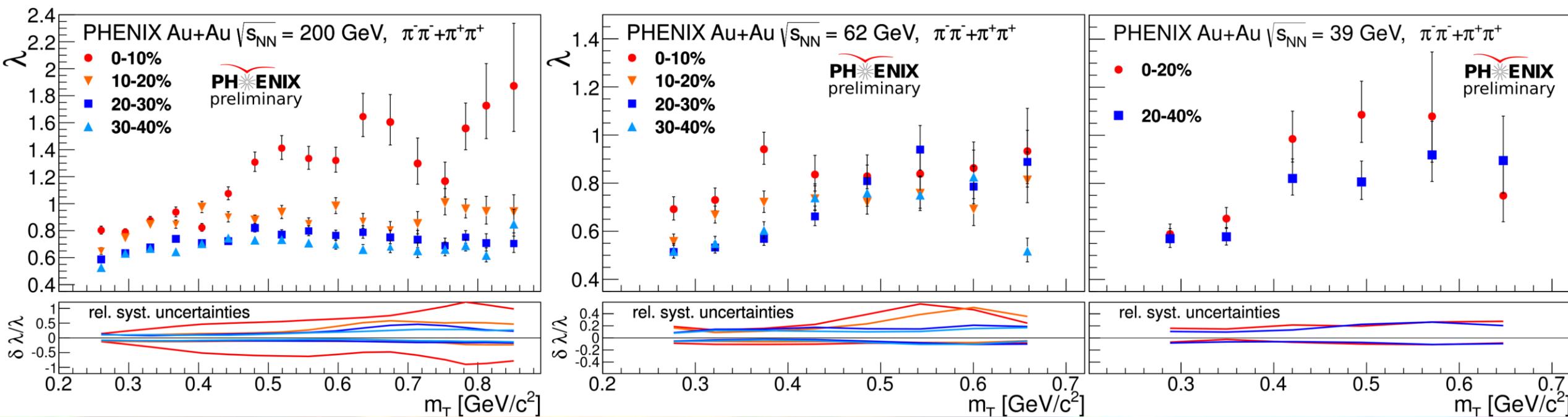
S. Lökö, Universe 4 (2018) 31

- α approximately monotonic versus $\sqrt{s_{NN}}$
 - No clear interpretation or understanding of this trend
 - Important w.r.t. shape averaging interpretation of $\alpha \neq 2$
- Lévy exponent α still far from conjectured CEP limit of 0.5



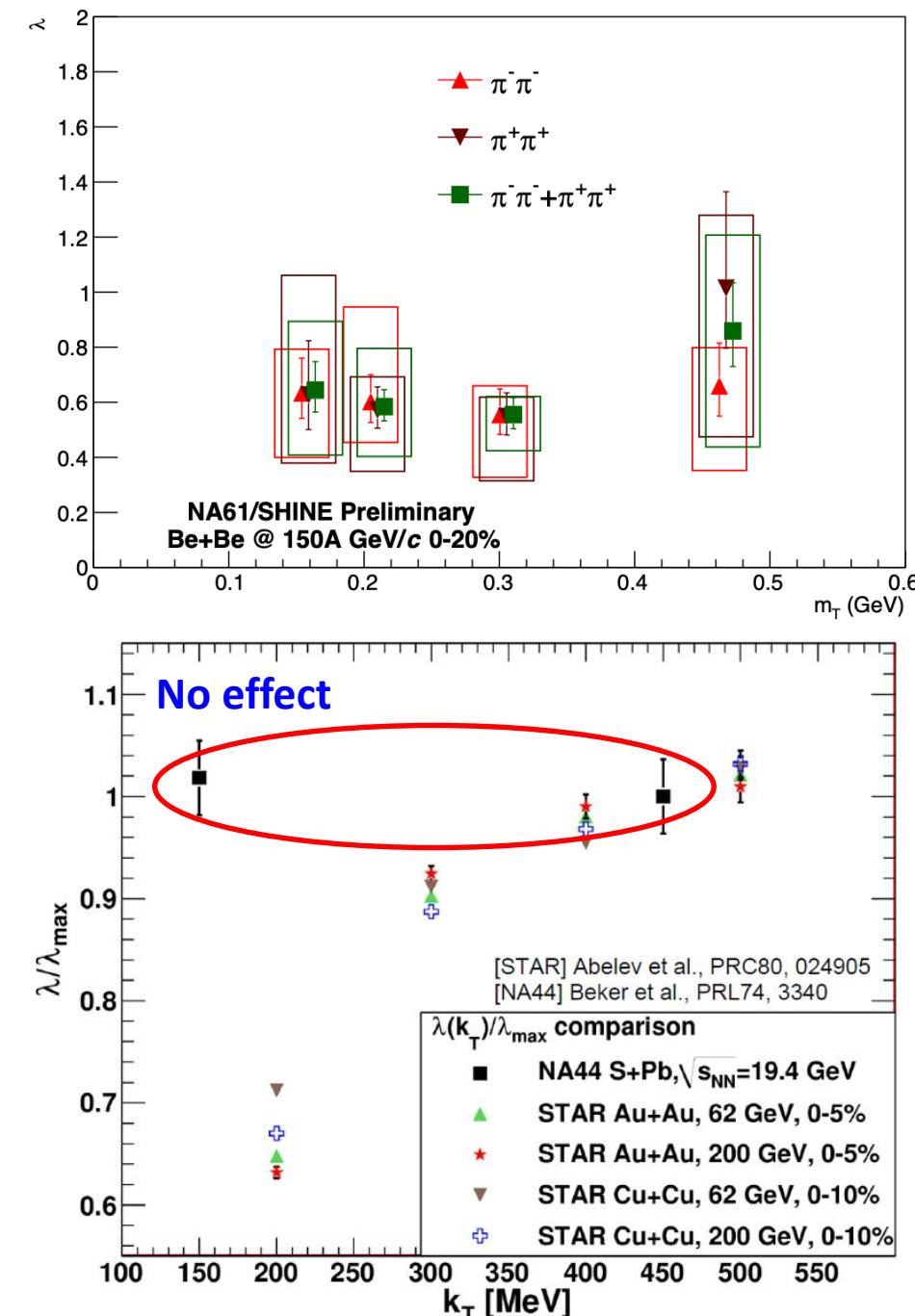
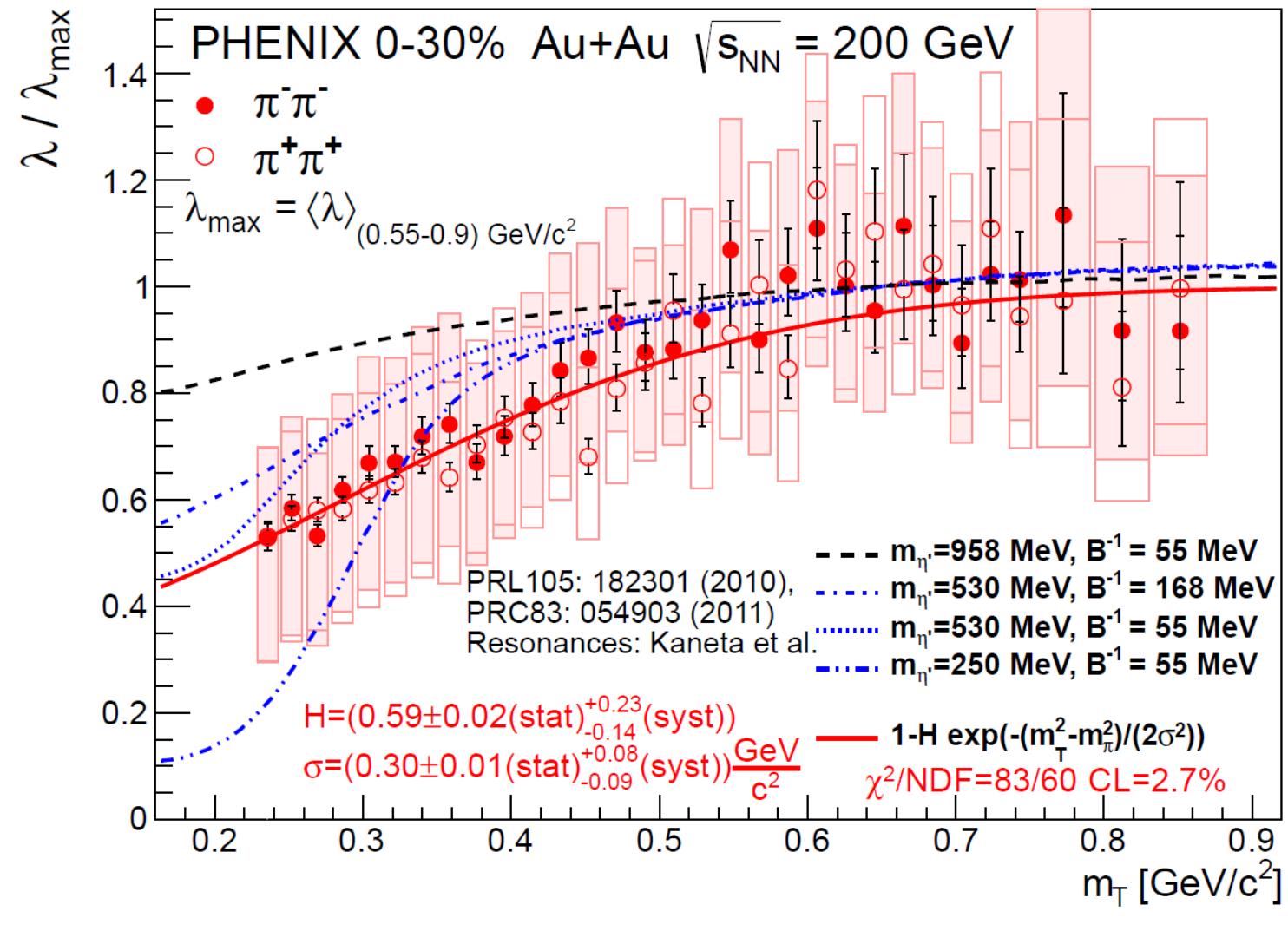
λ – Centrality and m_T dependence

S. Lökö, Universe 4 (2018) 31



- From the Core-Halo model, measure the core-halo fraction: $\lambda = \left(\frac{N_C}{N_C + N_H} \right)^2$
- Observed suppression at small m_T , increase of halo fraction

Hole in λ (m_T): λ / λ_{\max}



Summary and outlook

- HBT in Femtoscopy
- Lévy in HBT
- Centrality and m_T dependence of Lévy physical parameters: R , α , λ
- Comparison with Kaon data
- Detailed Lévy analysis at Phenix coming soon



Andrea Katalin Gulyás: Error 2

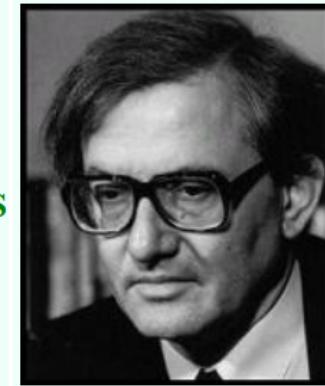
22nd ZIMÁNYI SCHOOL

WINTER WORKSHOP

ON HEAVY ION PHYSICS

December 5-9, 2022

Budapest, Hungary

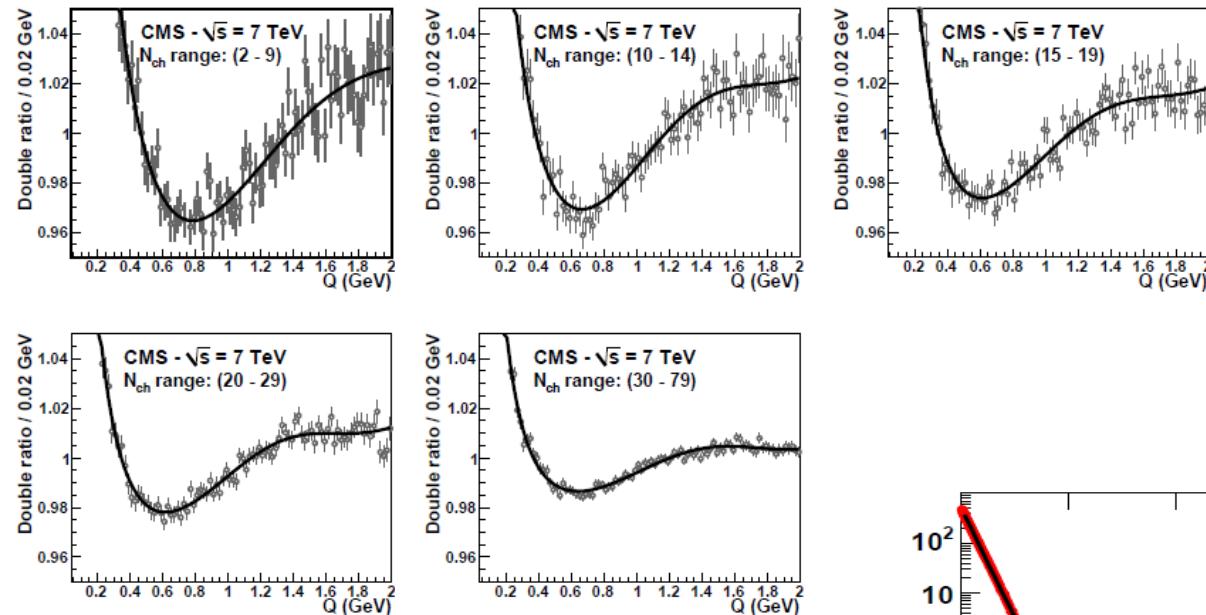
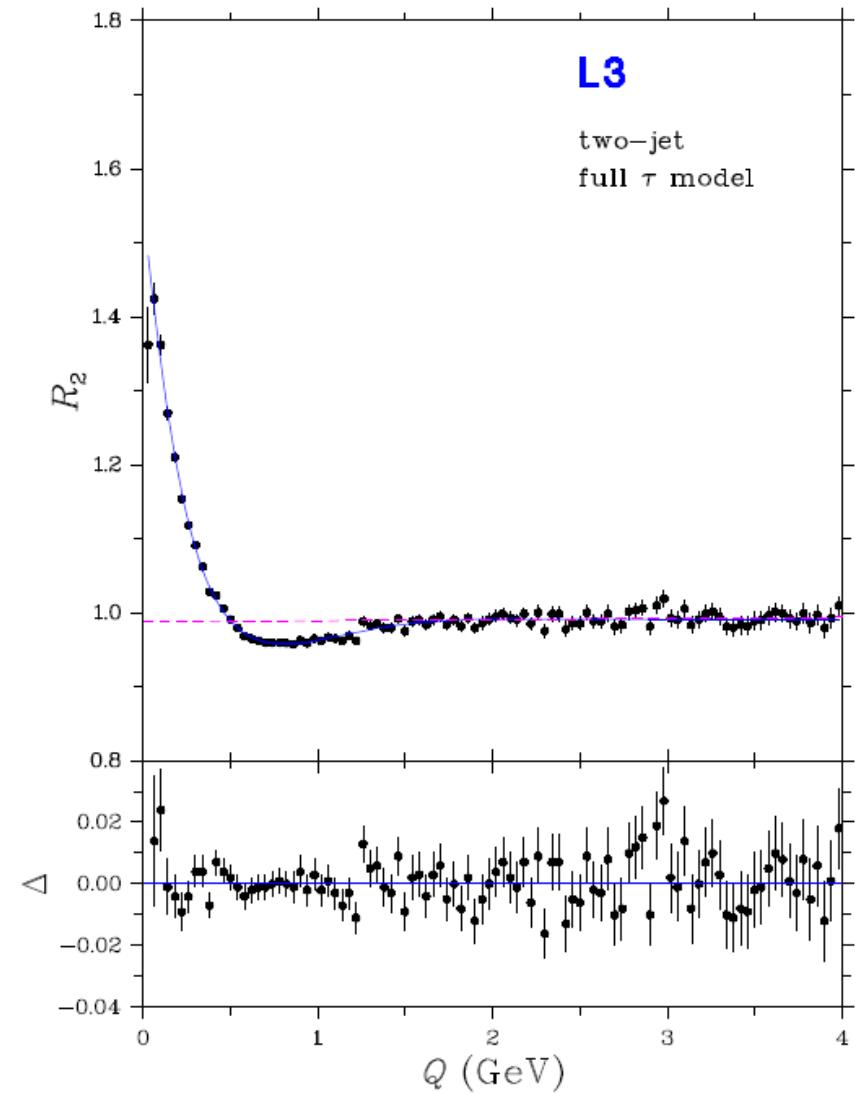


József Zimányi (1931 - 2006)

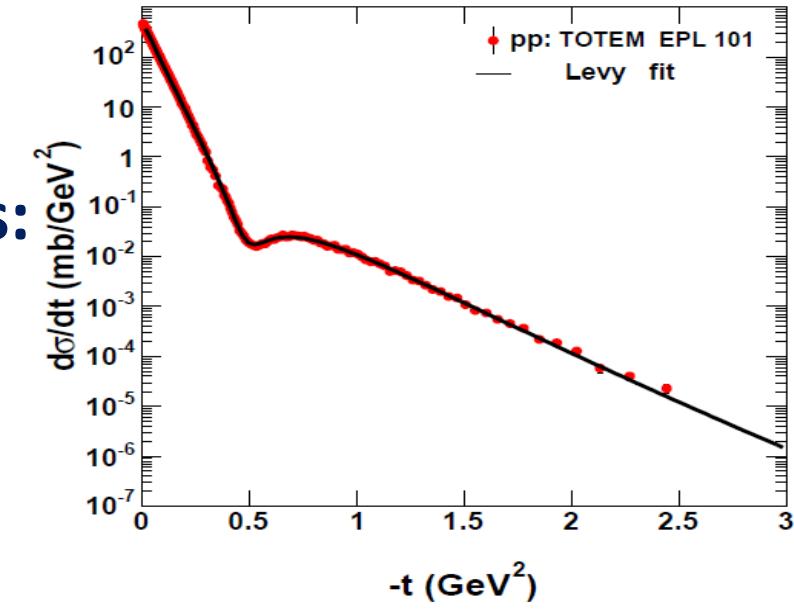
Thank you for your attention!

For more PHENIX results → see M. Csanad talk on Wednesday.

Earlier Experimental Applications of Lévy

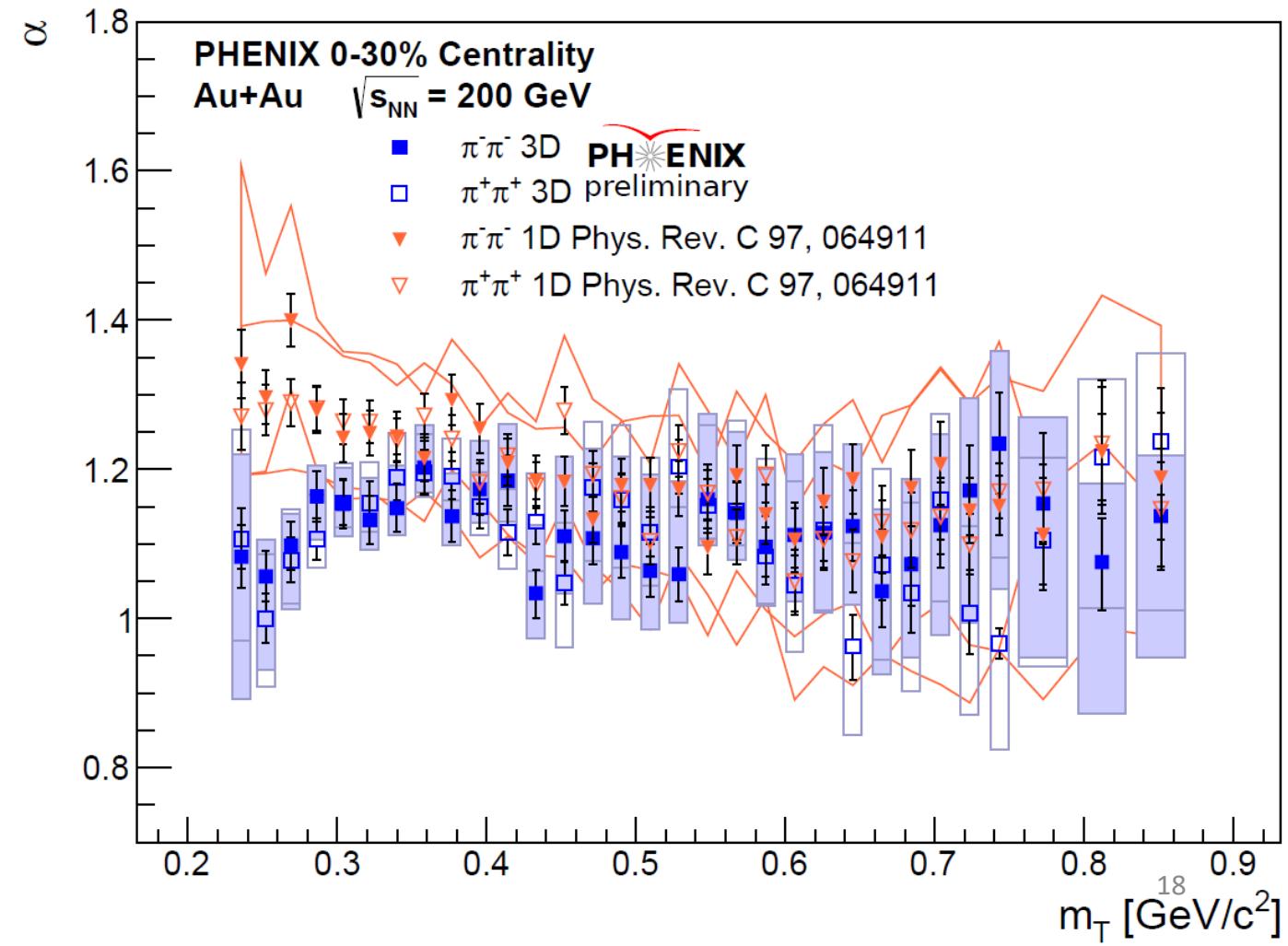


- Three experimental results:
 - L3 e+e-at LEP
 - CMS pp at LHC
 - TOTEM at LHC



Cross-check with a 3D analysis

- Lévy exponent α in 3D analysis similar to 1D result
- On average still far from 2
- Observable differences at low m_T
- Maybe due to lack of spherical symmetry?
- Coulomb effect for non-spherical sources?
 - Approximation possible
B. Kurylis, arXiv:2007.10173



Coherence with three-pion Lévy

Recall: two particle correlation strength $\lambda = f_C^2$ where $f_C = N_{\text{core}}/N_{\text{total}}$

Generalization for higher order correlations: $\lambda_2 = f_C^2, \lambda_3 = 2f_C^3 + 3f_C^2$

If there is partial coherence (p_C):

$$\begin{aligned}\lambda_2 &= f_C^2[(1 - p_C)^2 + 2p_C(1 - p_C)] \\ \lambda_3 &= 2f_C^3[(1 - p_C)^3 + 3p_C(1 - p_C)^2] + 3f_C^2[(1 - p_C)^2 + 2p_C(1 - p_C)]\end{aligned}$$

Introduce core-halo independent parameter $\kappa_3 = \frac{\lambda_3 - 3\lambda_2}{2\sqrt{\lambda_2^3}}$

does not depend on f_C

$\kappa_3 = 1$ if no coherence

Finite meson sizes?

Gavrilik, SIGMA 2 (2006) 074 [hep-ph/0512357]

Phase shift (a la Aharonov-Bohm) in hadron gas?

Random fields create random phase shift, on average distorts Bose-Einstein correlations

Csanad et al., Gribov-90 (2021) 261-273 [arXiv:2007.07167]

Test of core-halo model / coherence

Recall: $\kappa_3 = 1$ in pure core-halo model, $\kappa_3 \neq 1$ if coherence

