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

Based on a recent talk at the EuNPC conference

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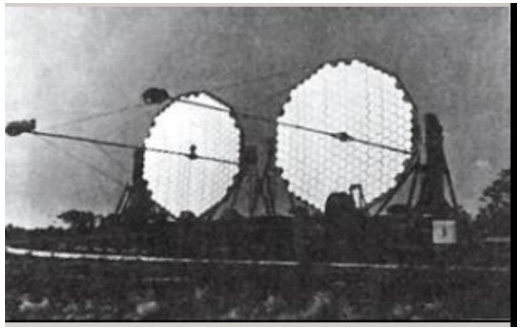
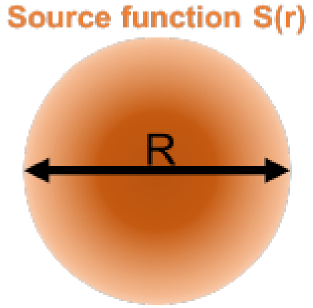
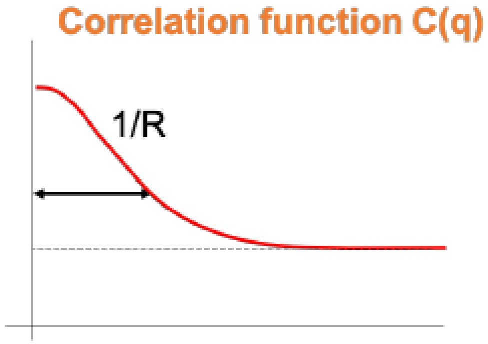
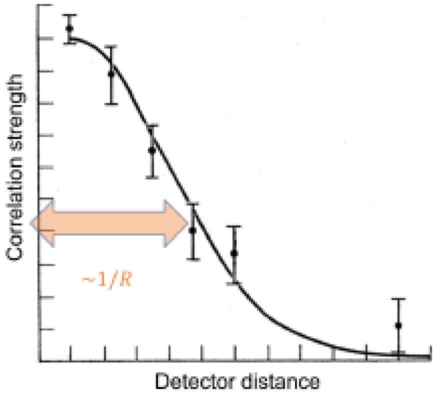
The HBT-effect in Femtoscopy



- **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*):**
    $C(q) \cong 1 + \left|\tilde{S}(q)\right|^2$, **where $\tilde{S}(q)$ is Fourier transform of *S*(*q*).**

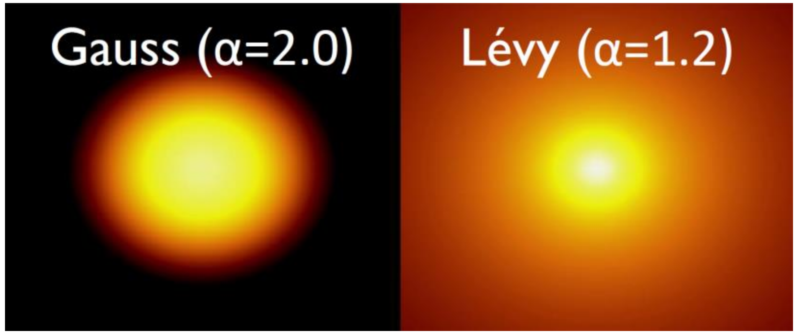






Lévy Distributions in Heavy Ion Physics

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



- **Shape of the correlation functions with Lévy source:**

  $C_2(q)=1+\lambda\cdot e^{-|qR|^{\alpha}}$; α=2:Gaussian; α=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

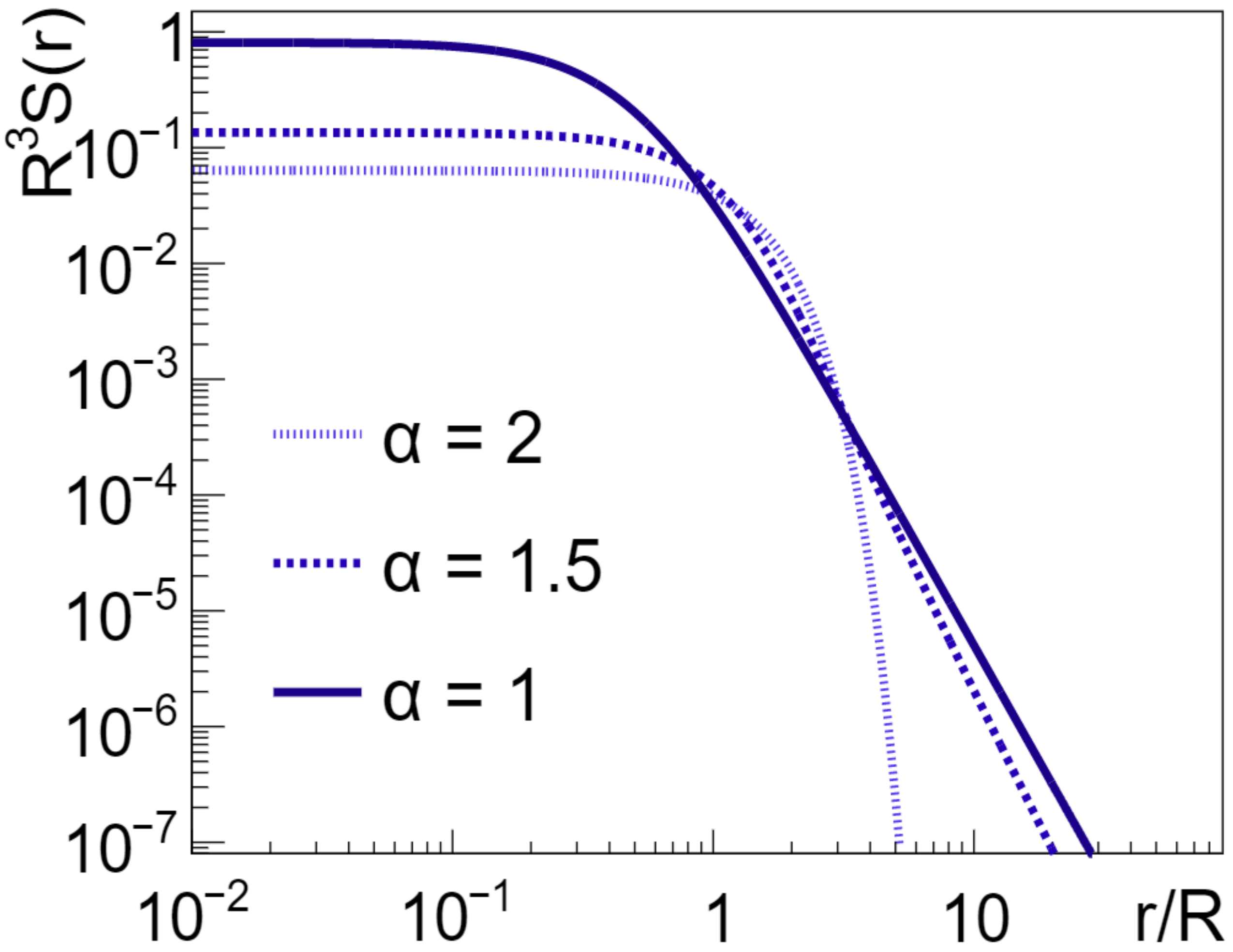
- **No tail if α=2, power law if α<2; tail strength depends on α**
- **If *S*(*r*) Lévy, the distance distribution *D*(*r*) also Lévy with same α and *R* → $2^{1/\alpha}R$**
- **Critical spatial correlation:**

$$\sim r^{-(d-2+\eta)}$$

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

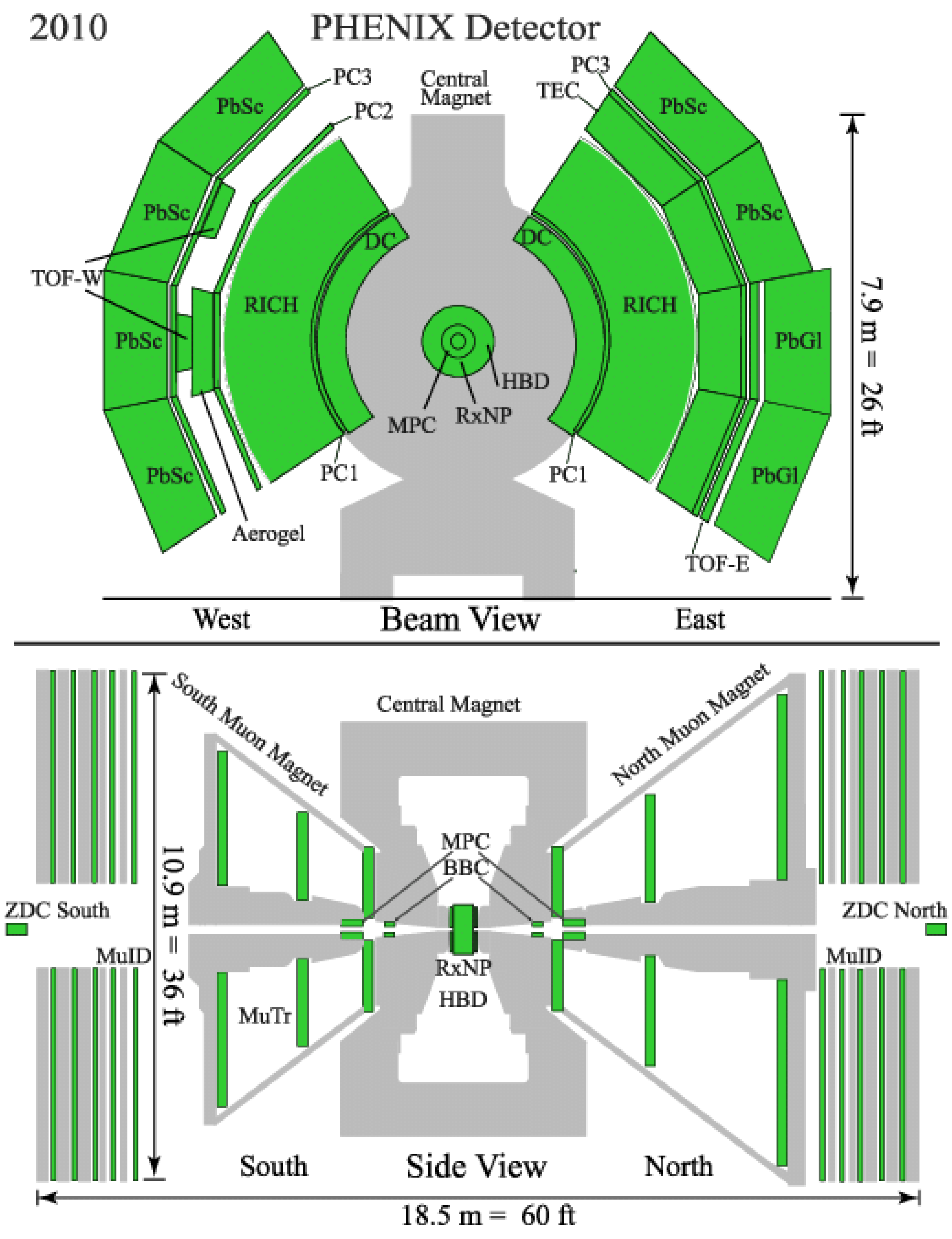
Csörgő, Hegyi , Zajc , Eur.Phys.J . C36 (2004)

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 Fligth 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: √sNN = 130 GeV, 200 GeV



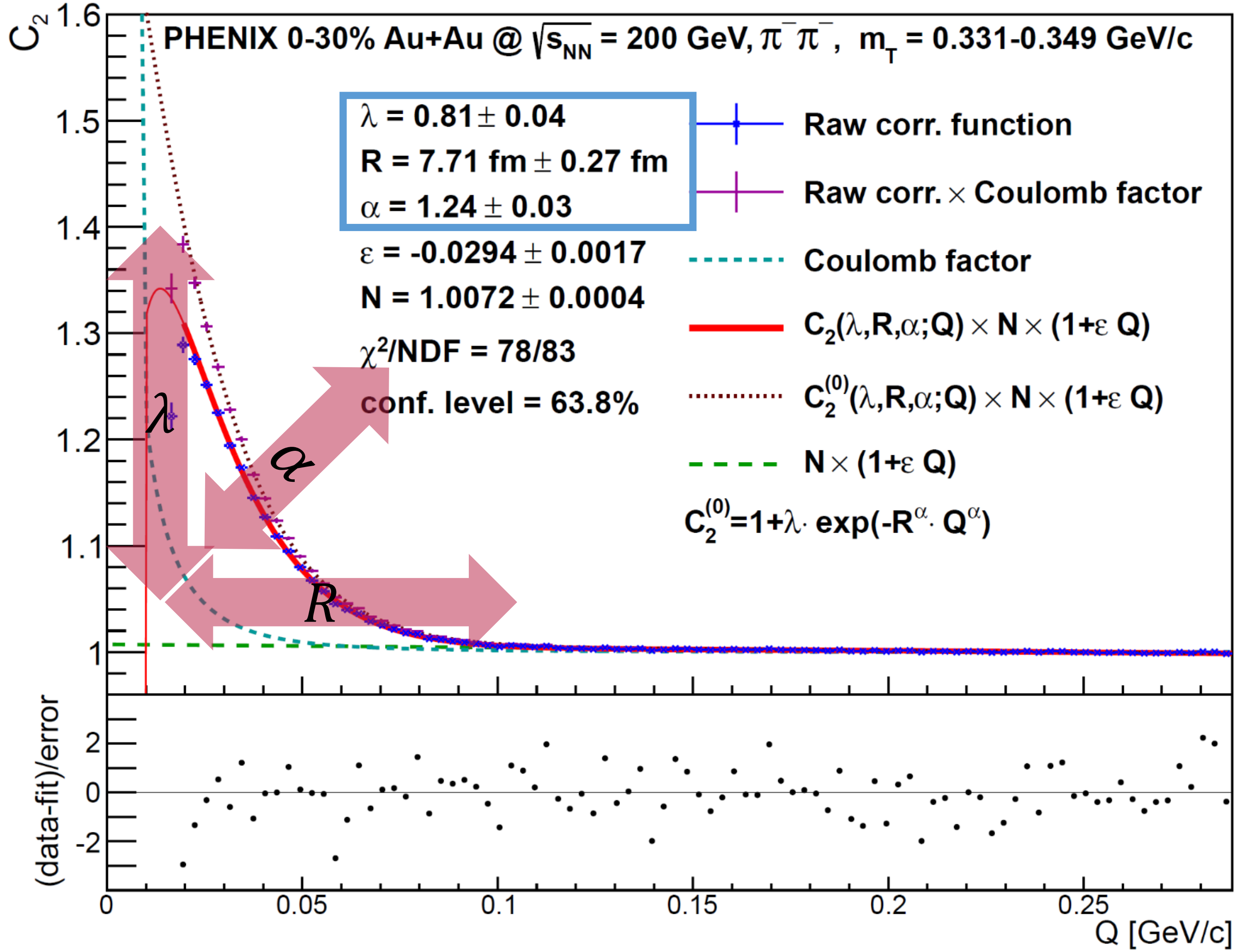
PHENIX Lévy-HBT Analysis Overview

- **Data set:** $\sqrt{s_{NN}}$= **200, 62, 39 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

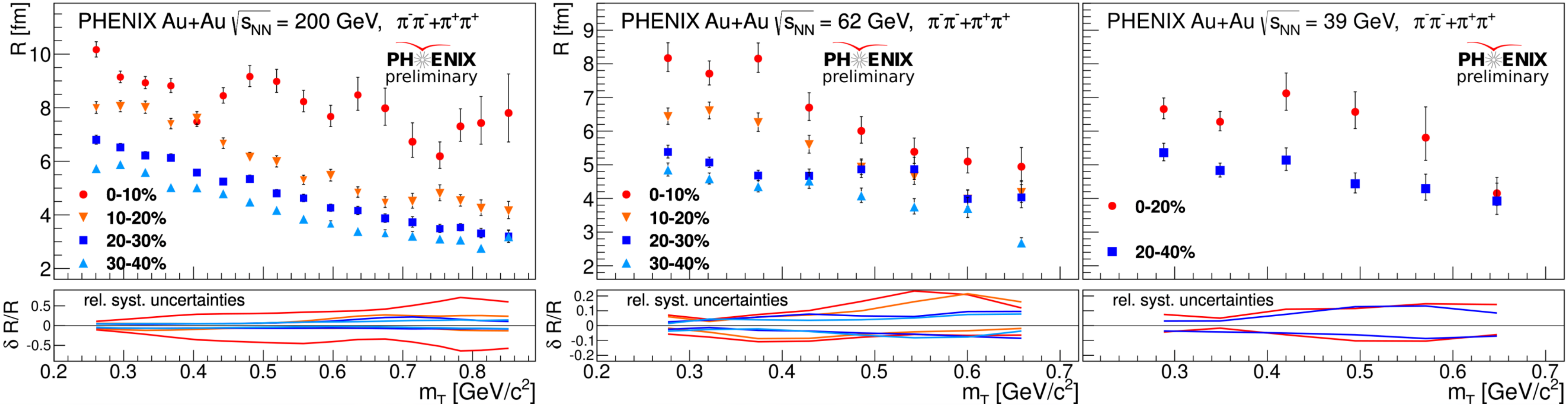
- **Fit with calculation based on Lévy distribution**
- **Physical parameters: *R, α, λ* measured versus pair m_T**
- ***R*: homogeneity length, dynamics, sizes**
- ***α*: shape, criticality, anomalous diffusion**
- ***λ*: particle creation mechanisms, in-medium mass modification**

Lévy works well



R – Centrality and m_T dependence

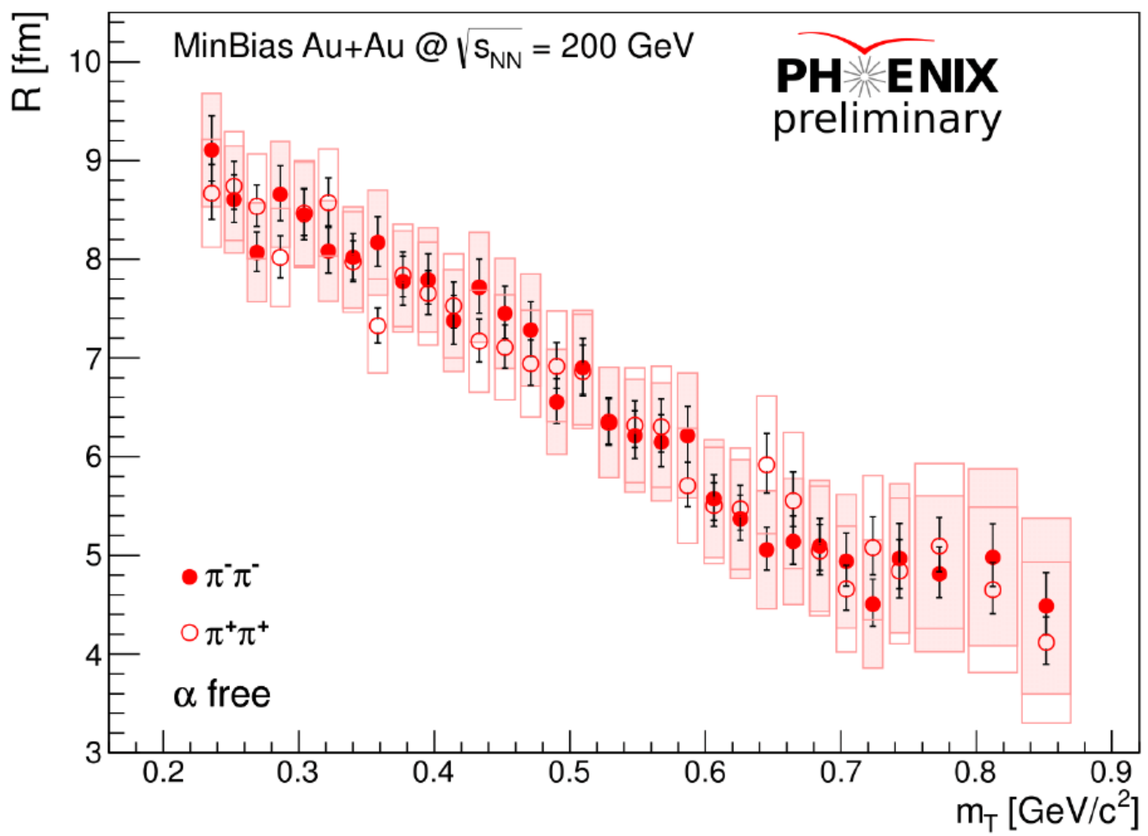
D. Kincses, Universe 4 (2018) 11

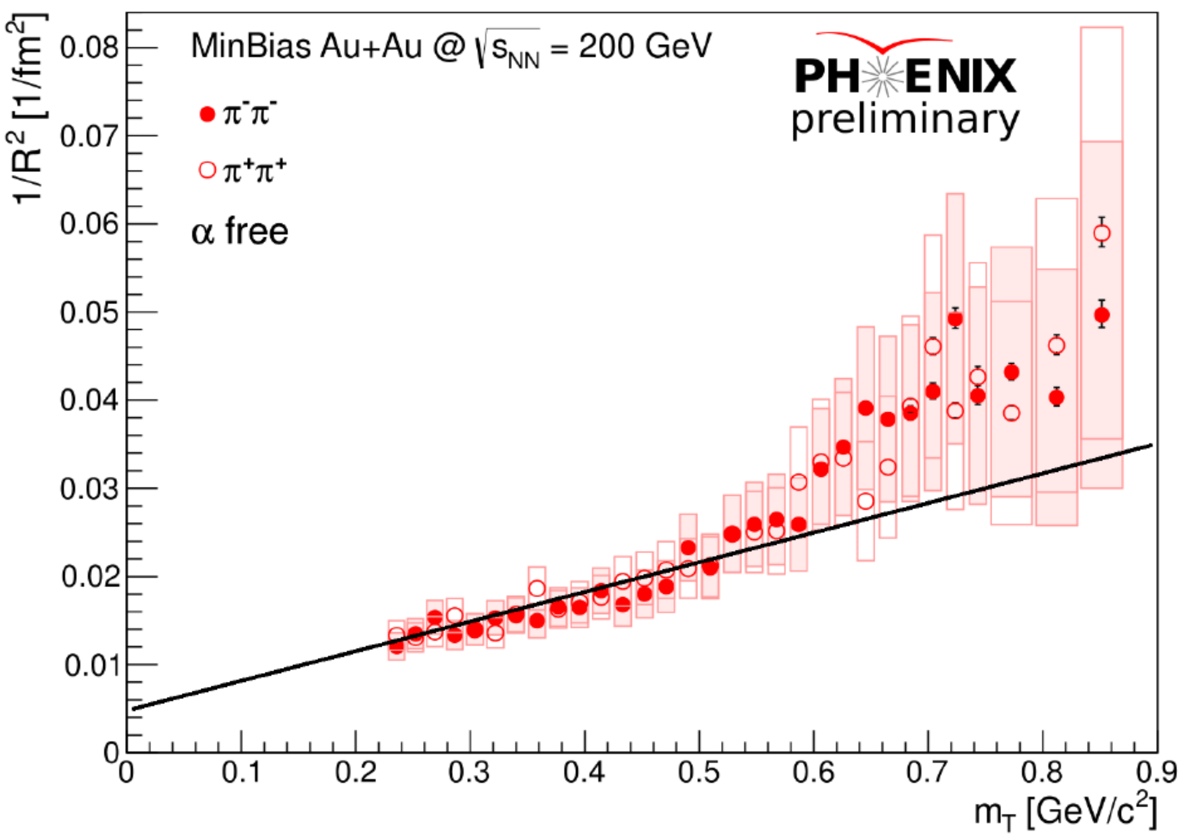


- **Geometrical centrality dependence**
- **Usual decrease with m_T is present**

Lévy scale parameter - *R*

Phys. Rev. C **97**, 064911

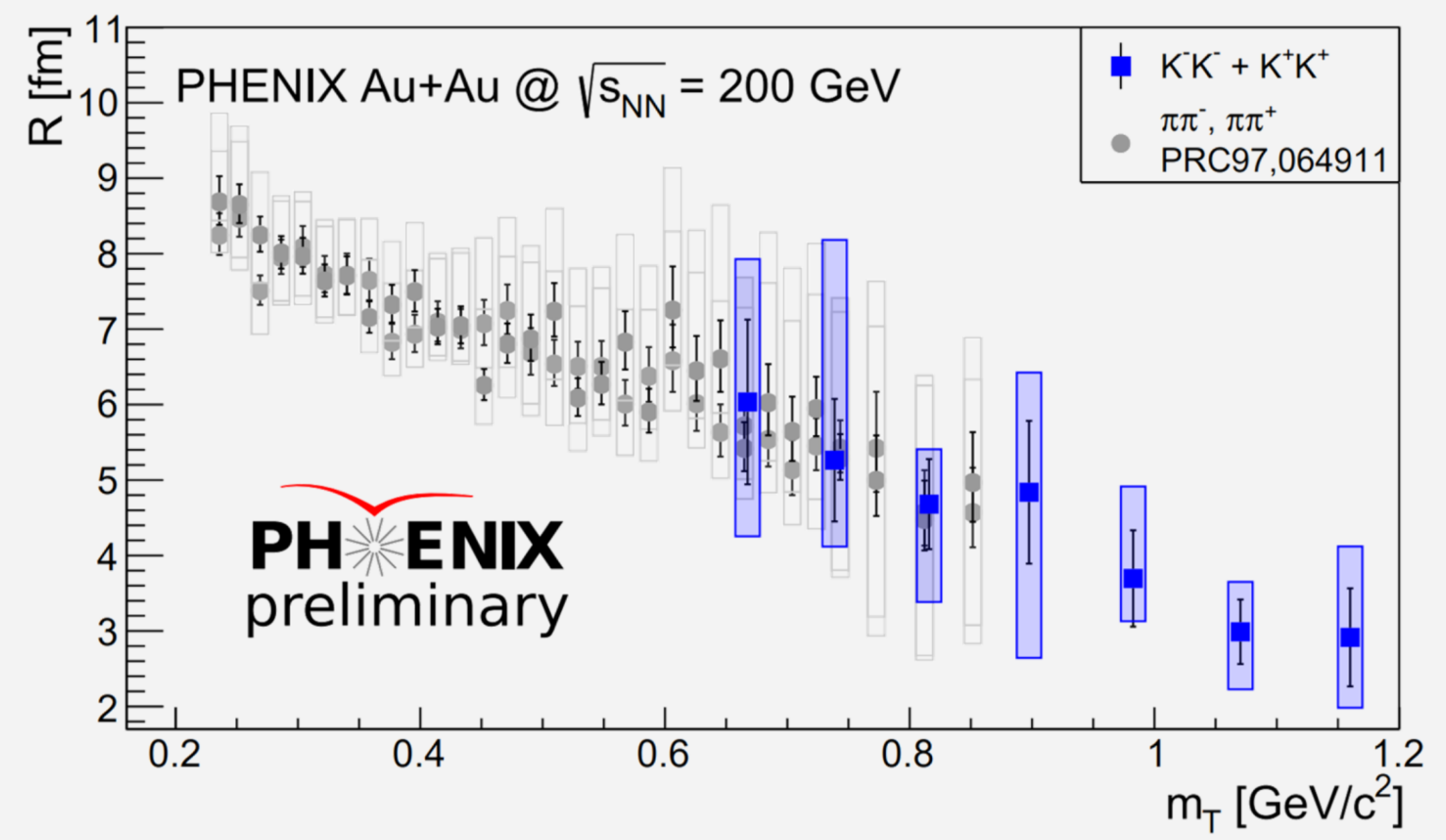




- **Hydro calculations for Gaussian radii → $1/R^2 \sim m_T$**
- **In case of low m_T, the linear scaling of $1/R^2$ holds**

Kaon Lévy Scale - *R*

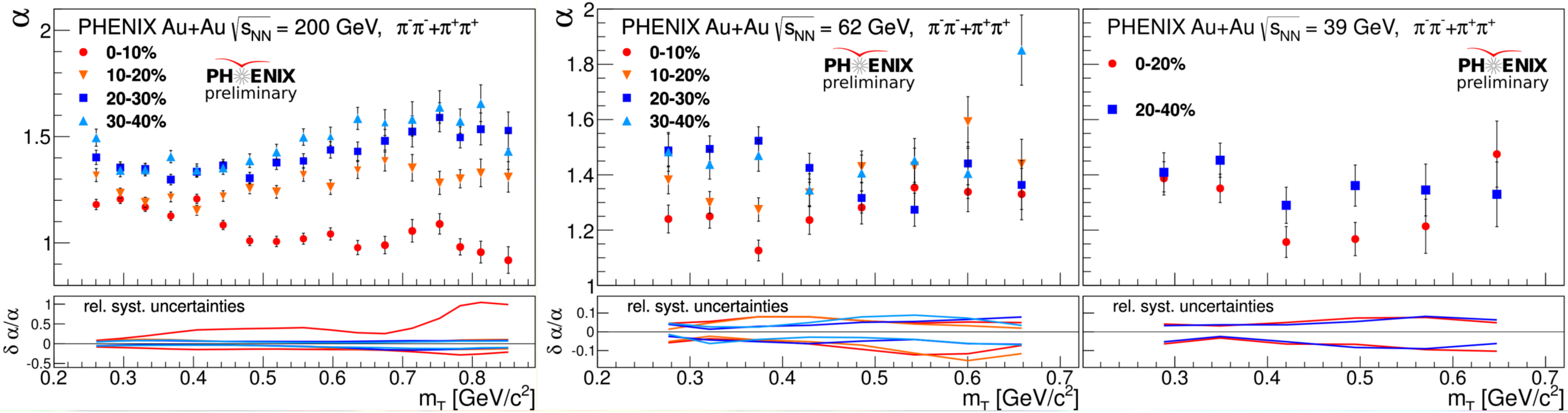
Talk of L. Kovács, WPCF 2022



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

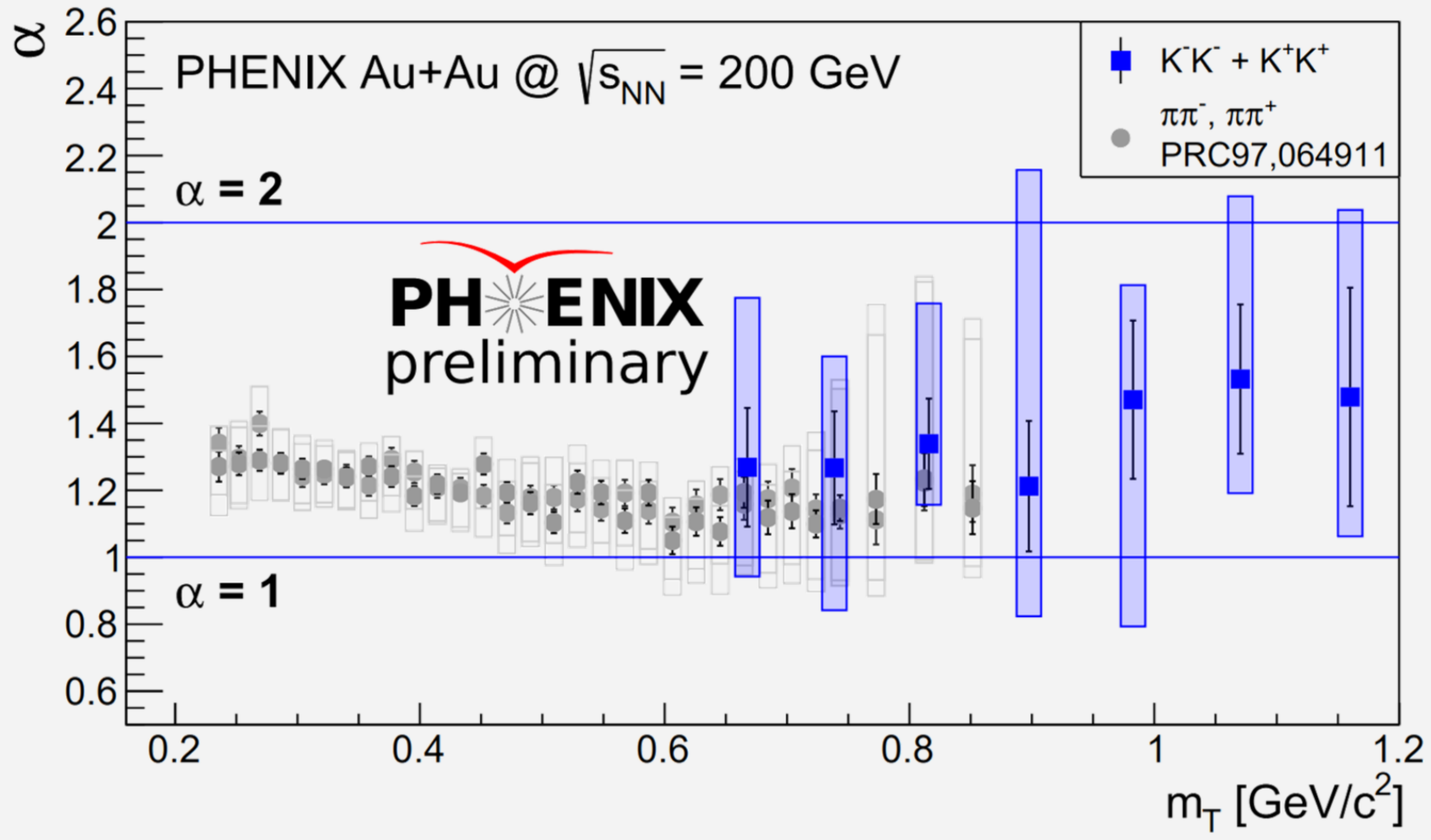
α – Centrality and m_T dependence

D. Kincses, Universe 4 (2018) 11



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

Kaon Lévy shape - α



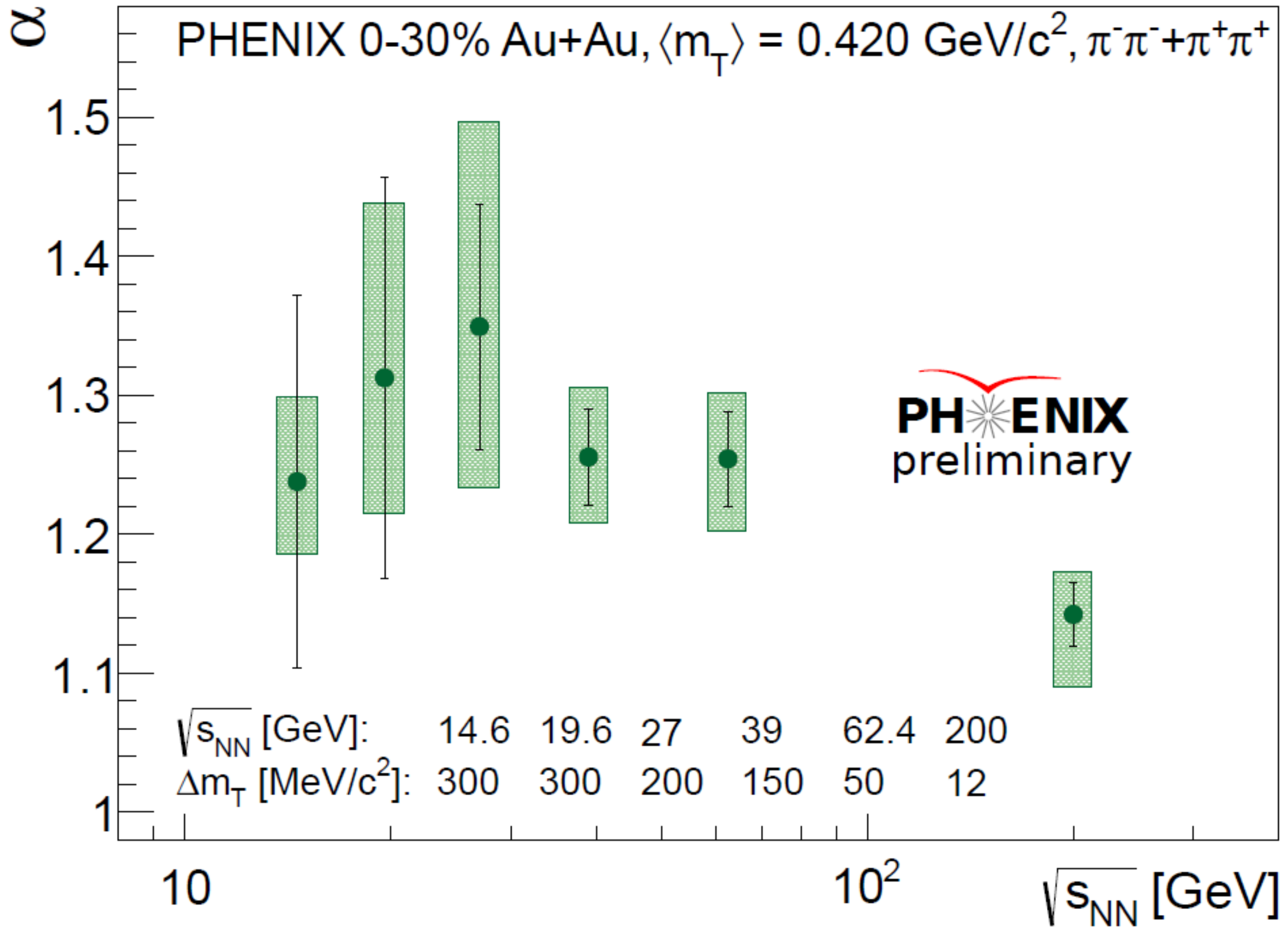
- Does not exhibit strong dependence on transverse mass
- Kaon α consistent with pions, weak $\alpha(K) \geq \alpha(\pi)$ indication
- Anomalous diffusion suggests $\alpha(K) < \alpha(\pi)$

  [M. Csanád, T. Csörgő, M. Nagy, Braz.J.Phys. 37 (2007) 1002]

Collision Energy Dependence

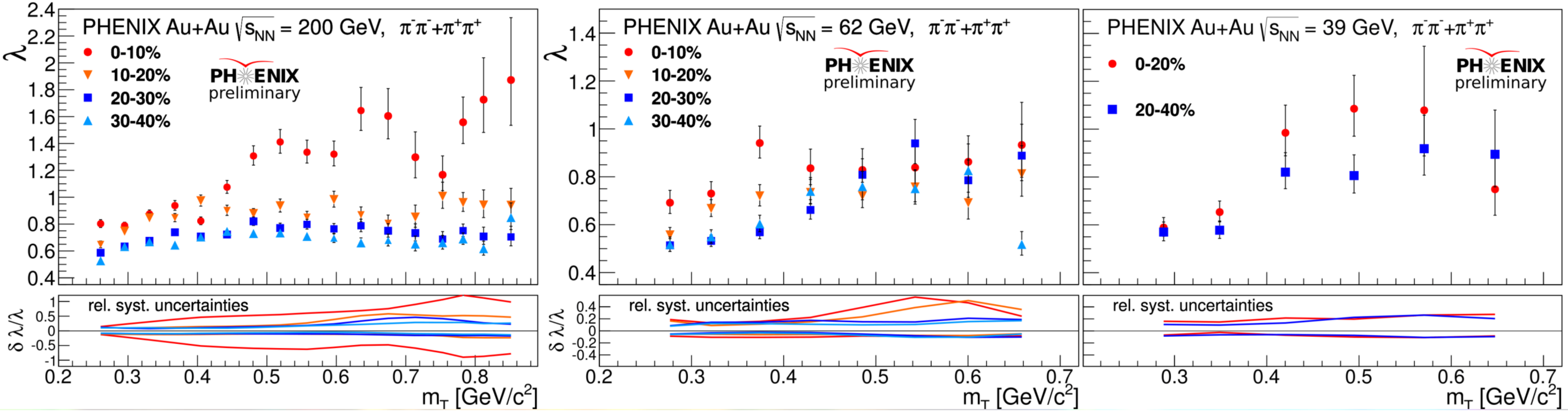
S. Lökös, Universe 4 (2018) 31

- **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**



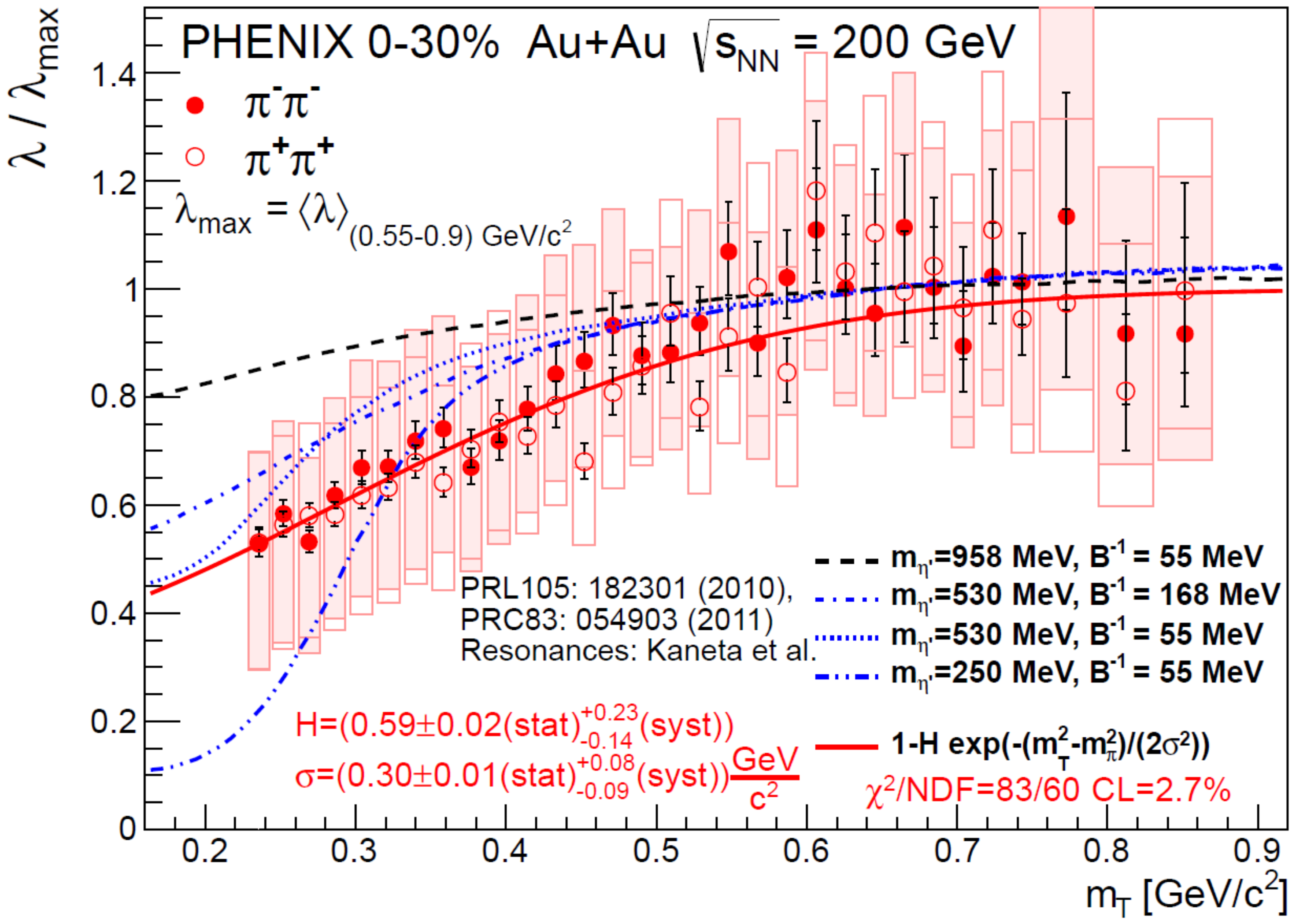
λ – Centrality and m_T dependence

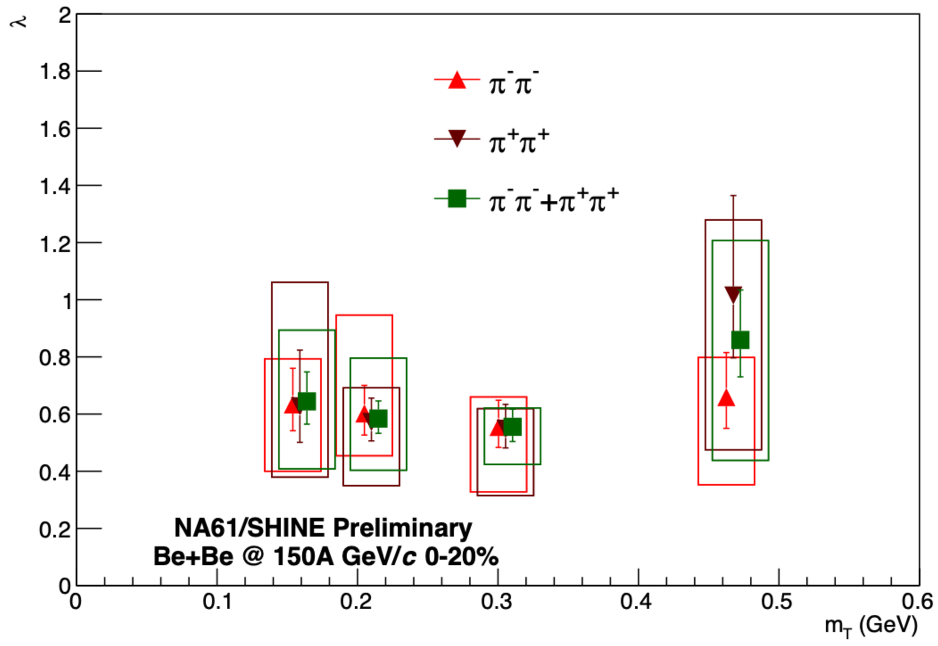
S. Lökös, Universe 4 (2018) 31

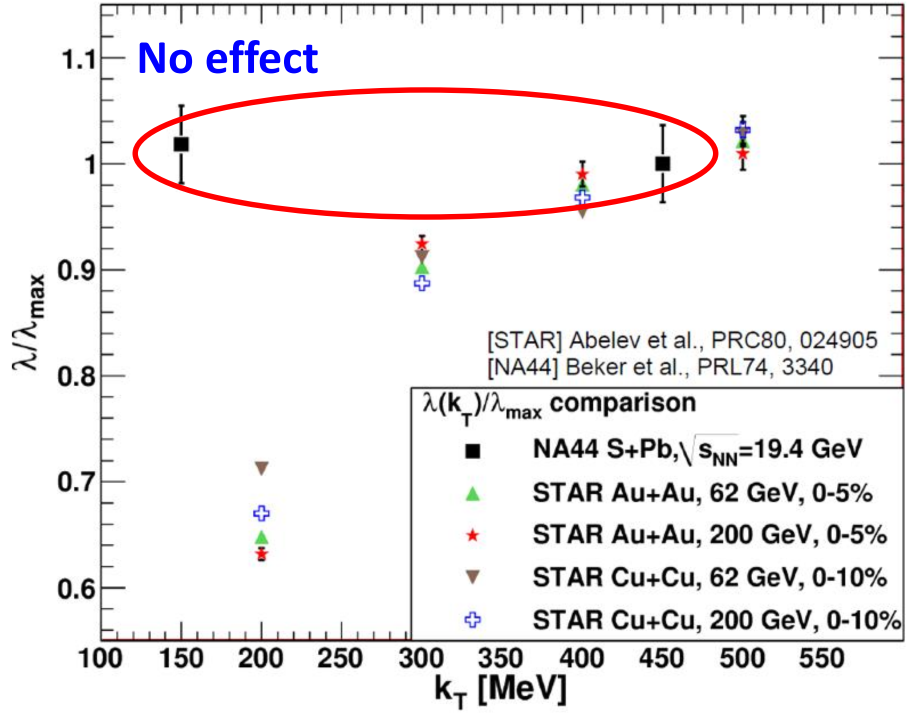


- **From the Core-Halo model, measure the core-halo fraction: $\lambda = \left(\frac{N_C}{N_C+N_H}\right)^2$**
- **Observed suppression at small m_T increase of halo fraction**

Hole in λ (m_T): λ / λ_{max}





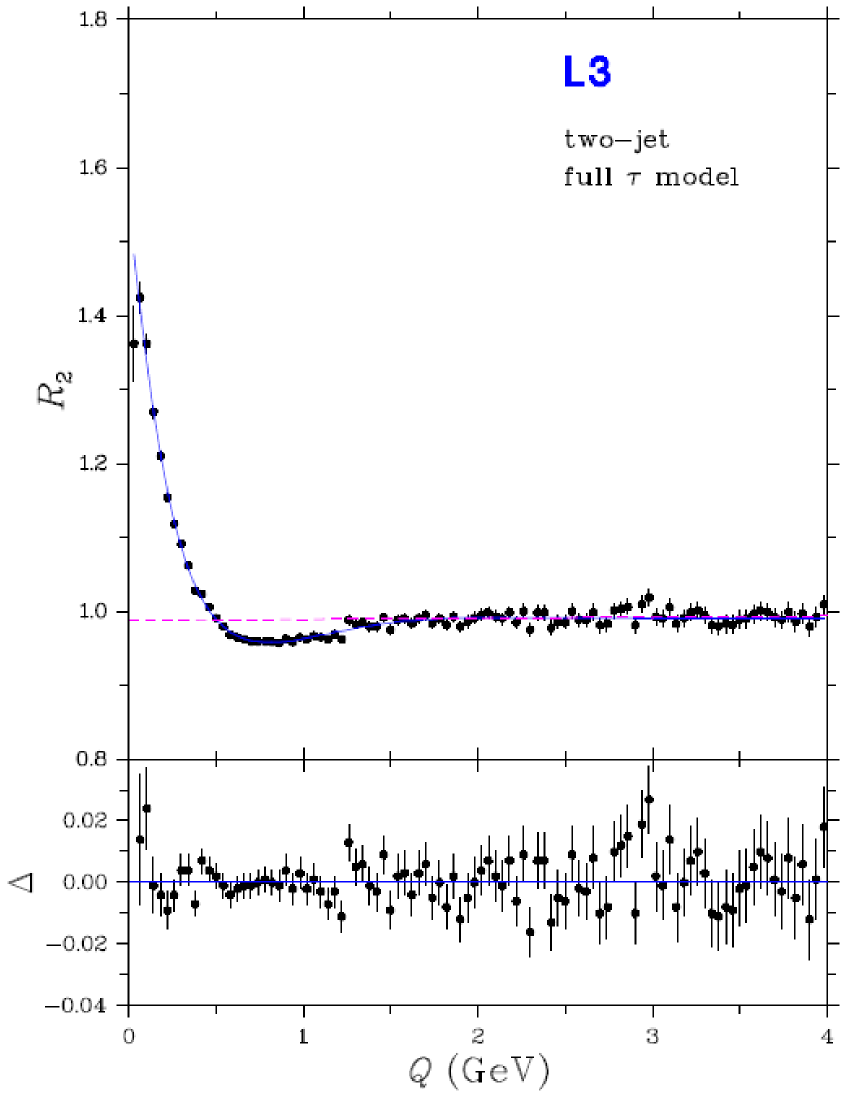


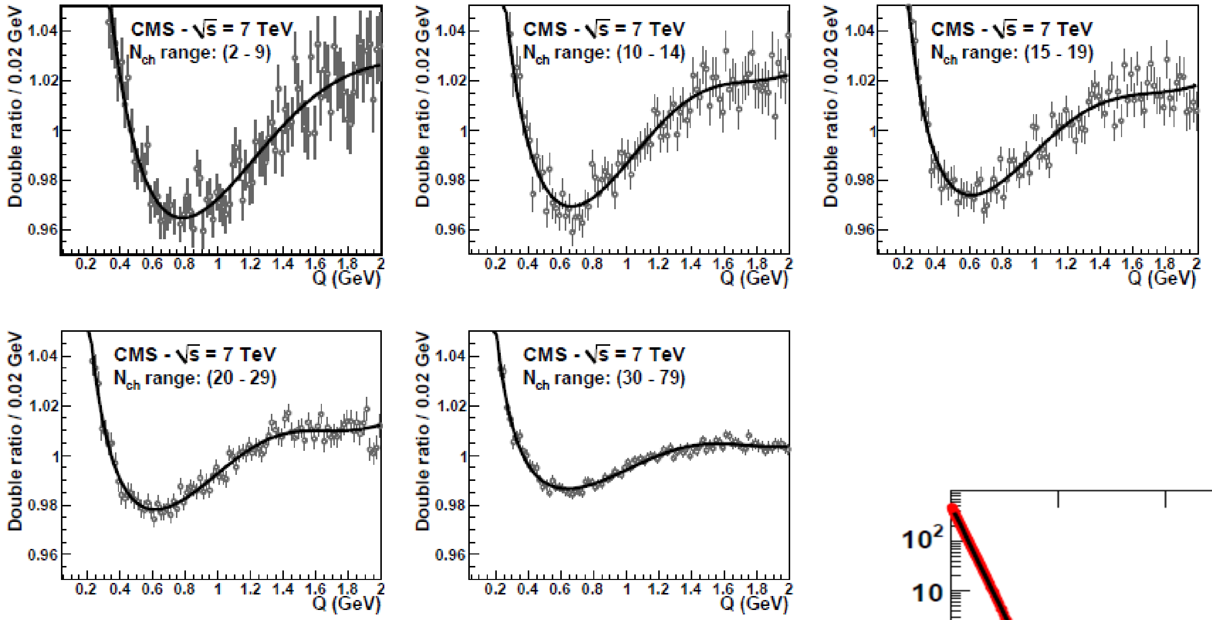
Summary and outlook

- **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**

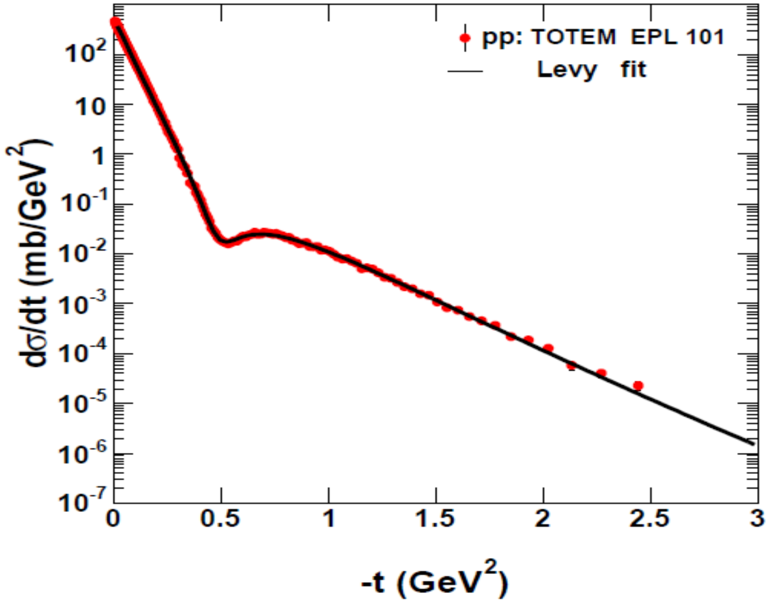
Thank you for your attention!

Earlier Experimental Applications of Lévy



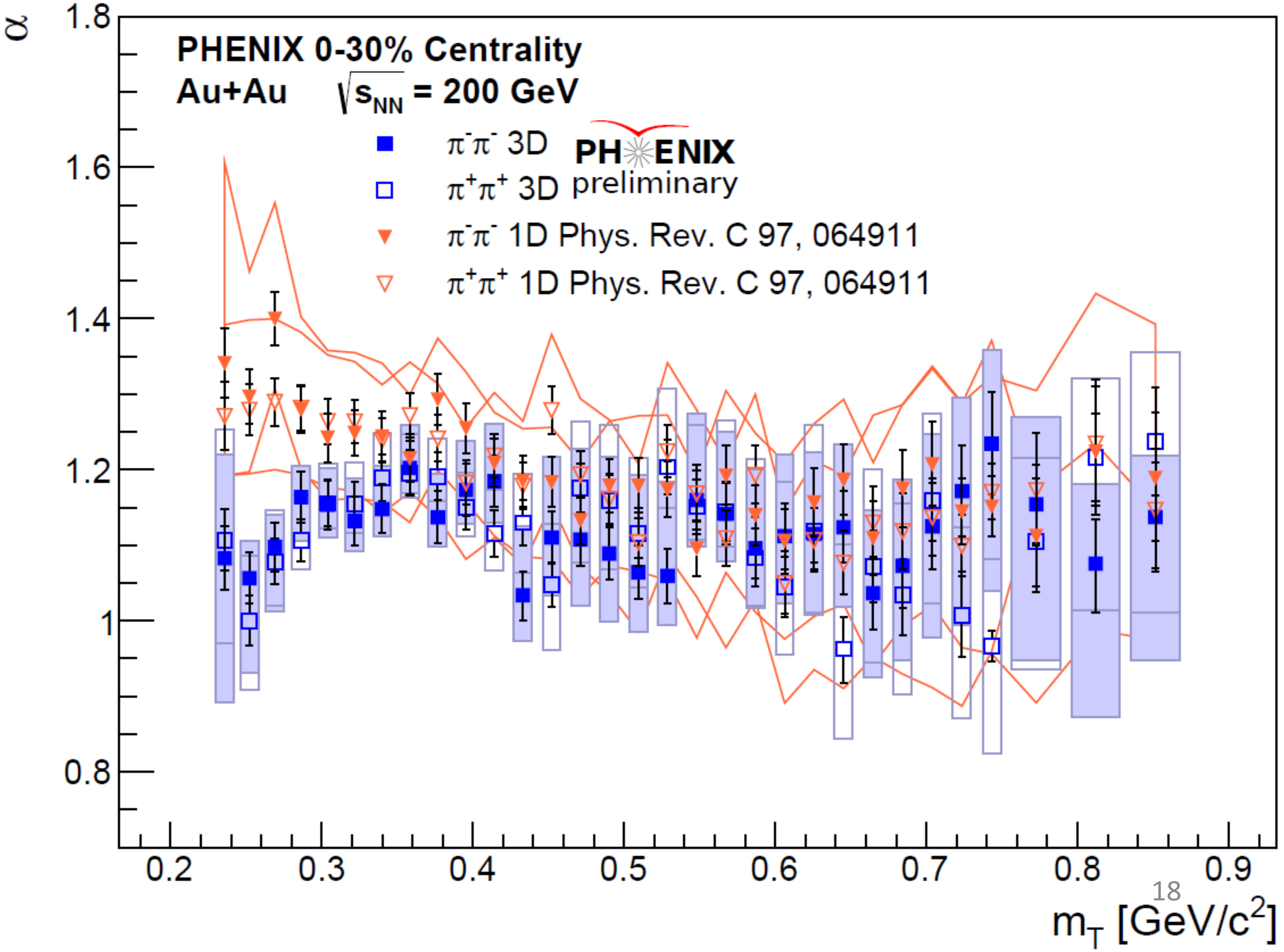


- **Three experimental results:**
  - **L3 e+e-at LEP**
  - **CMS pp at LHC**
  - **TOTEM at LHC**



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. Kurgyis, arXiv:2007.10173



Coherence with three-pion Lévy

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

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):

$$\lambda_2 = f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$
$$\lambda_3 = 2f_C^3[(1-p_C)^3 + 3p_C(1-p_C)^2] + 3f_C^2[(1-p_C)^2 + 2p_C(1-p_C)]$$

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?

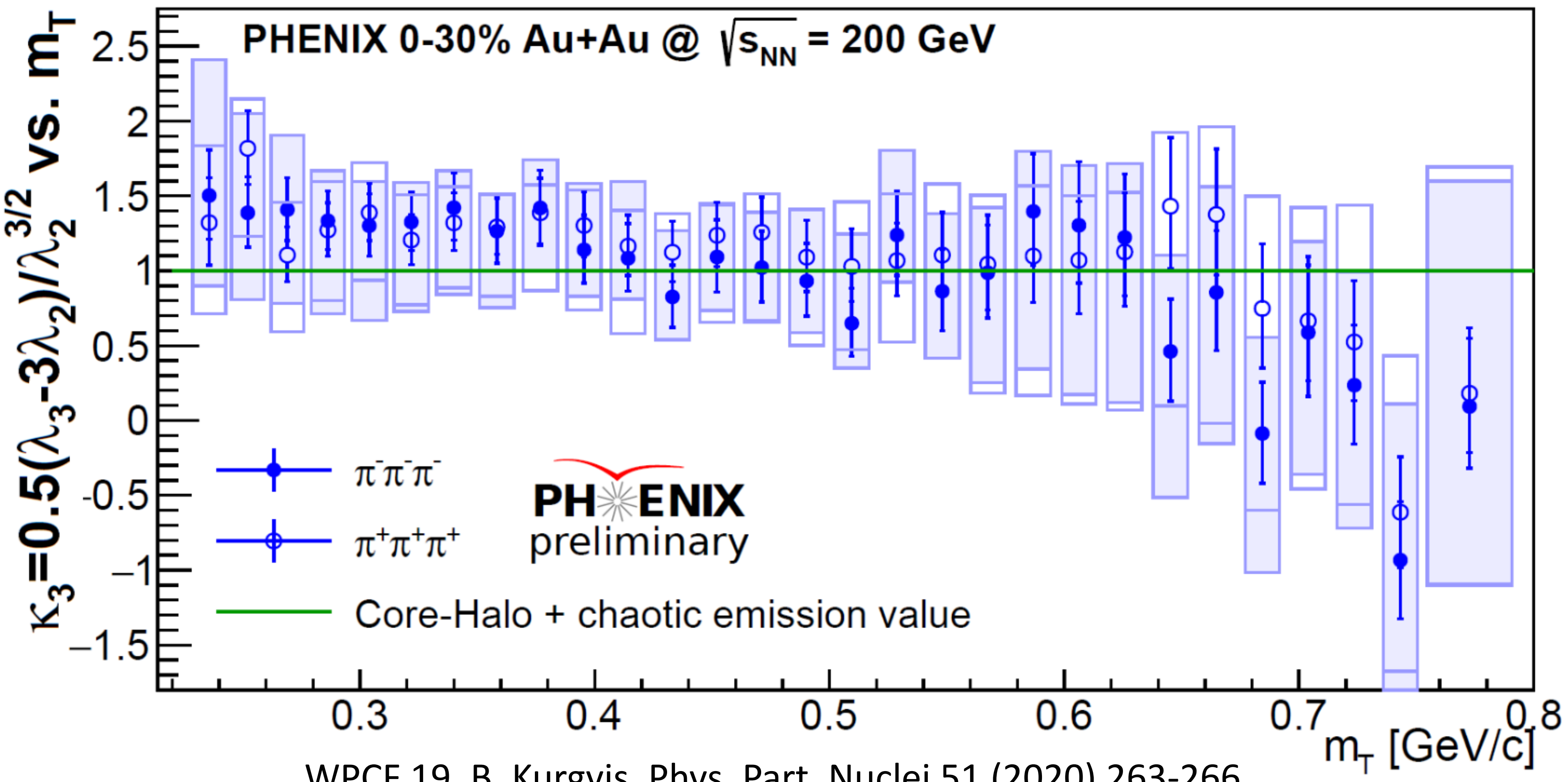
- Gavrilik, SIGMA 2 (2006) 074 [hep-ph/0512357]

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

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



WPCF 19, B. Kurgyis, Phys. Part. Nuclei 51 (2020) 263-266