Event-by-event investigation of the kaon and pion two-particle source function with EPOS

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The correlation function

- Correlation function: $C_2(p_1, p_2) = \frac{N_2(p_1,p_2)}{N_1(p_1)N_1(p_2)}$
- Single particle distribution: $N_1(p) = \int S(r, p\ )|\Psi_p(x)|^2\ d^4x$
- Pair momentum distribution:

$$N_2(p_1, p_2) = \int \underbrace{S(x_1, p_1)S(x_2, p_2)}_{\text{Phase-space density}} \underbrace{|\Psi_{p_1-p_2}(x_1 - x_2)|^2}_{\text{Symmetrized pair wave function}}\ \underbrace{d^4x_1 d^4x_2}_{\text{Space-time coordinates}}$$

Phase-space density
What shape?
Exploring via femtoscopy!

Symmetrized
pair wave
function

Space-time
coordinates

Pair source distribution

- Under some assumptions: $C_2(Q,K) \cong 1 + \left|\int S(r,K) e^{iQr} dr\right|^2$
- $S(r,K)$ can be reconstructed from $C_2(Q,K)$
- The pair source distribtuion

$$D(r,K) = \int S\left(\rho + \frac{r}{2}, K\right) S\left(\rho - \frac{r}{2}, K\right) \mathrm{d}^4\rho$$

- *r*: Relative space-time coordinate
- *ρ*: Average space-time coordinate
- *K*: Average pair momentum*
- Q: Relative pair momentum

- Bose-Einstien correlation function:

$$C_2(Q,K) = \int D(r,K) |\psi_Q(r)|^2 d^4 r \cong 1 + \int D(r,K) e^{iQr} dr$$

Experiment

*Instead of *K*, m_T is often used

The shape of the source

- Lévy-stable distribution:

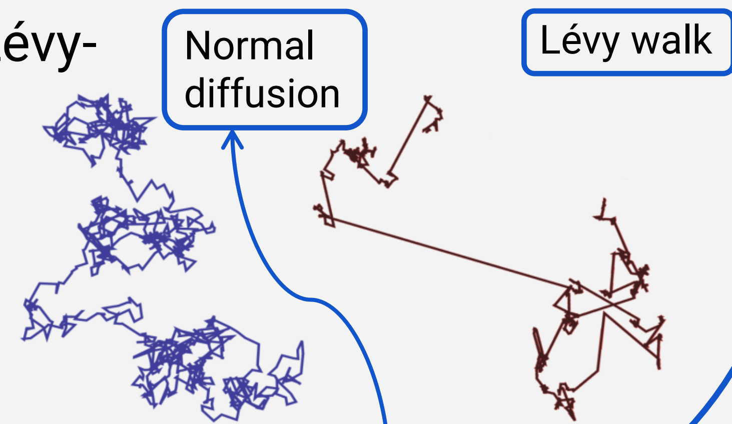
$$S(\boldsymbol{r},K) = \mathcal{L}(\alpha,R;\boldsymbol{r}) = (2\pi)^{-3}\int d^3\boldsymbol{q}\, e^{i\boldsymbol{q}\boldsymbol{r}} \mathrm{e}^{-\frac{1}{2}|\boldsymbol{q}R|^{\alpha}}$$

Retains the same α under convolution:

$$S(\boldsymbol{r}) = \mathcal{L}(\alpha,R;\boldsymbol{r}) \Longrightarrow D(\boldsymbol{r}) = \mathcal{L}(\alpha, 2^{\frac{1}{\alpha}}R;\boldsymbol{r})$$

α = 2 ⟹ Gaussian
α = 1 ⟹ Cauchy

- Possible reasons for the appearance of Lévy-type sources:
  - Closeness to the critical point
  - Lévy walk
  - Jet fragmentation
  - Event averaging



- Generalized central limit theorem:
  - Constant mean free path, finite variance ⟹ Gaussian (α = 2)
  - Increasing mean free path, infinite variance ⟹ Lévy (0 < α < 2)
    - Power-law tail
    - In a rapidly expanding system

R. Metzler, E. Barkai, J. Klafter, Phys. Rev. Lett. 82, 3563 (1999)
T. Csörgő, S. Hegyi, W.A. Zajc, Eur. Phys. J. C36, 67 (2004)
M. Csanád, T. Csörgő, M. Nagy, Braz. J. Phys. 37, 1002 (2007)

The aim of the analysis

- Experimental indications – Lévy source for pion pairs
  - RHIC (PHENIX, STAR), LHC (CMS), SPS (NA61/SHINE)
    Phys.Rev.C 97 (2018) no.6, 064911; Universe 10 (2024) 3, 102
    Phys.Rev.C 109 (2024) 2, 024914; Eur.Phys.J.C 83 (2024) 10, 919
    See talks of S. Lökös, S. Bhosale, and B. Pórfy
- In case of elastic scattering dominating Lévy walk:

smaller cross-section → larger mean free path → heavier power-law tail → $\alpha(\mathrm{K})<\alpha(\pi)$

M. Csanád, T. Csörgő, M. Nagy, Braz.J.Phys. 37 (2007) 1002
Humanic, Int.Jour.Mod.Phys. E 15 (2006) 197

Relation?

$\alpha(\mathrm{K}^{\pm})$ ⟷ $\alpha(\pi^{\pm})$

The EPOS model

- The model is based on Monte-Carlo techniques
- Core-Corona division (based on energy density)
- The three stages of evolution:
  - **Initial interactions: parton-based Gribov-Regge theory** (PBGRT)
  - **Viscous Hydrodynamical evolution** (vHLLE 3D+1 viscous hydro)
  - **Hadronic rescattering**, based on UrQMD

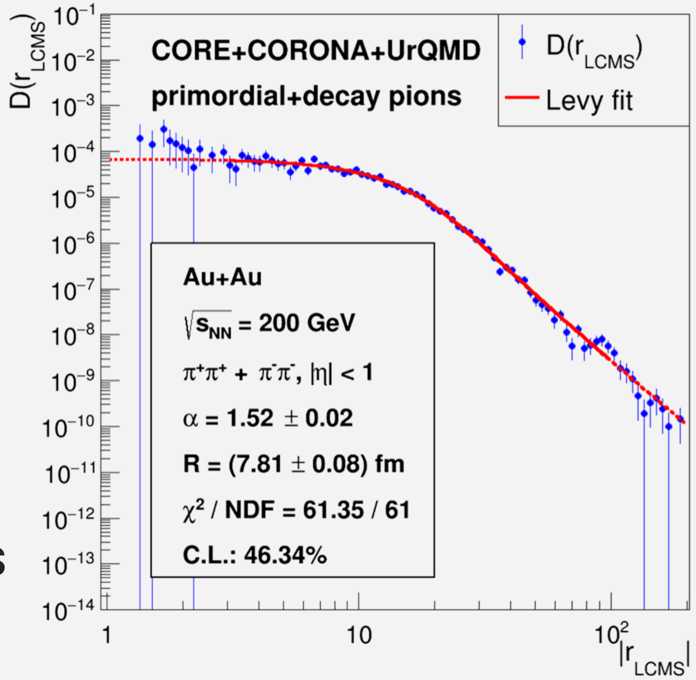
Details of the analysis

- $\sqrt{s_{\rm NN}} = 200$ GeV Au+Au collisions generated by EPOS359
- Angle-averaged one-dimensional distance distribution:

  $$\mathrm{D}(r_{\rm LCMS}) = \int D(\boldsymbol{r}_{\rm LCMS}, t)\, d\Omega_{\rm LCMS}\, dt$$

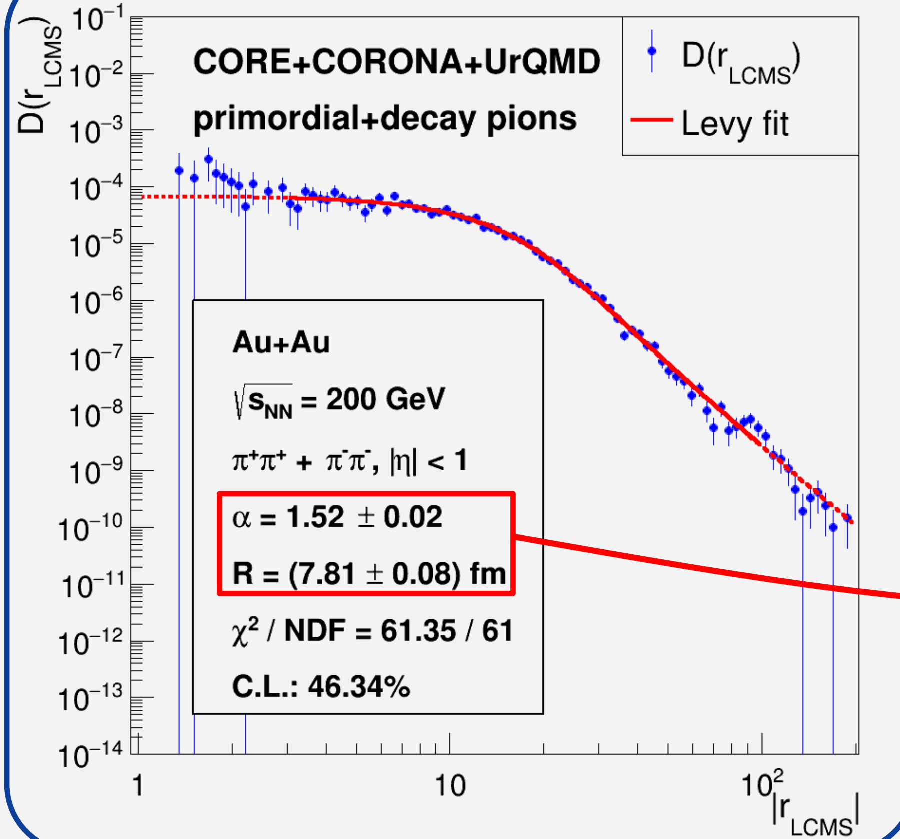
  LCMS: Longitudinal co-moving system
- Event-by-event investigation
- Lévy parameters: from 1000s of fits
- 4 centrality and 5 k_T classes for kaons,

  4 centrality and 10 k_T classes for pions

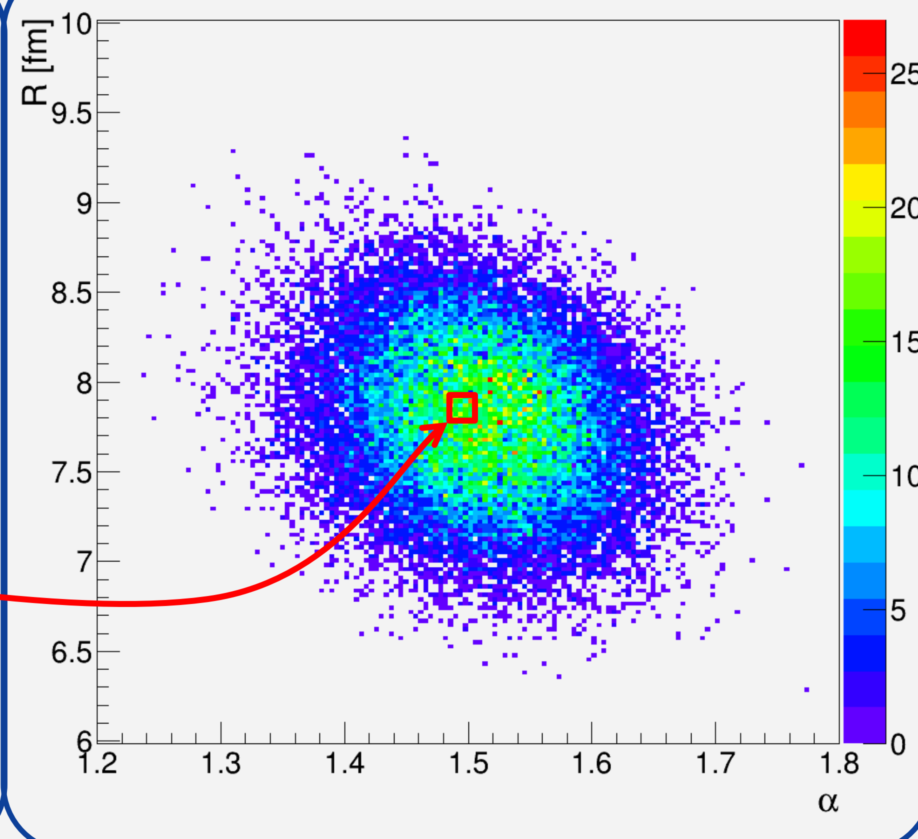


Example fit and α-R distribution

Example fit, one event

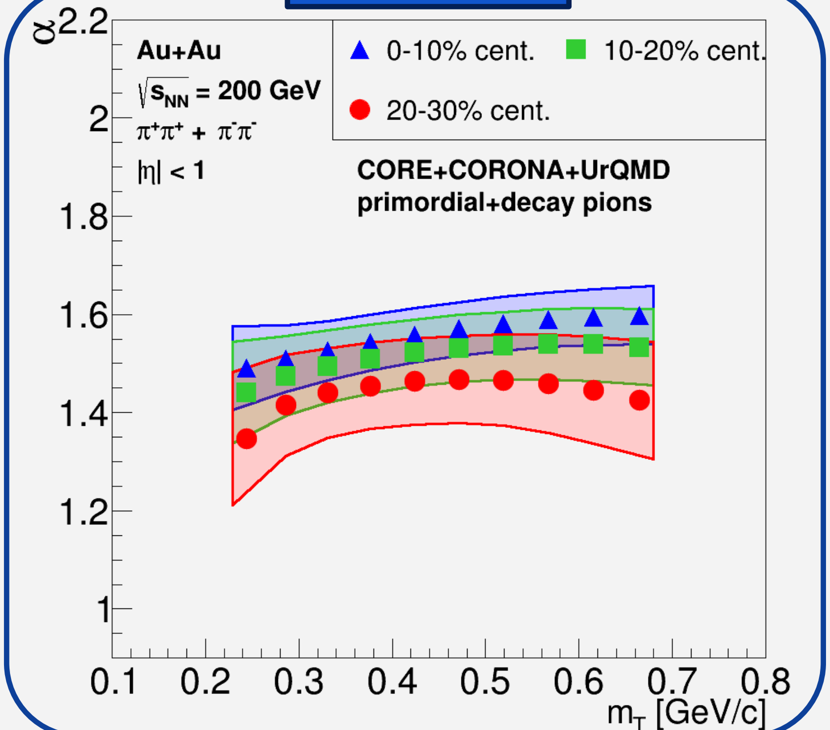


α-R distribution

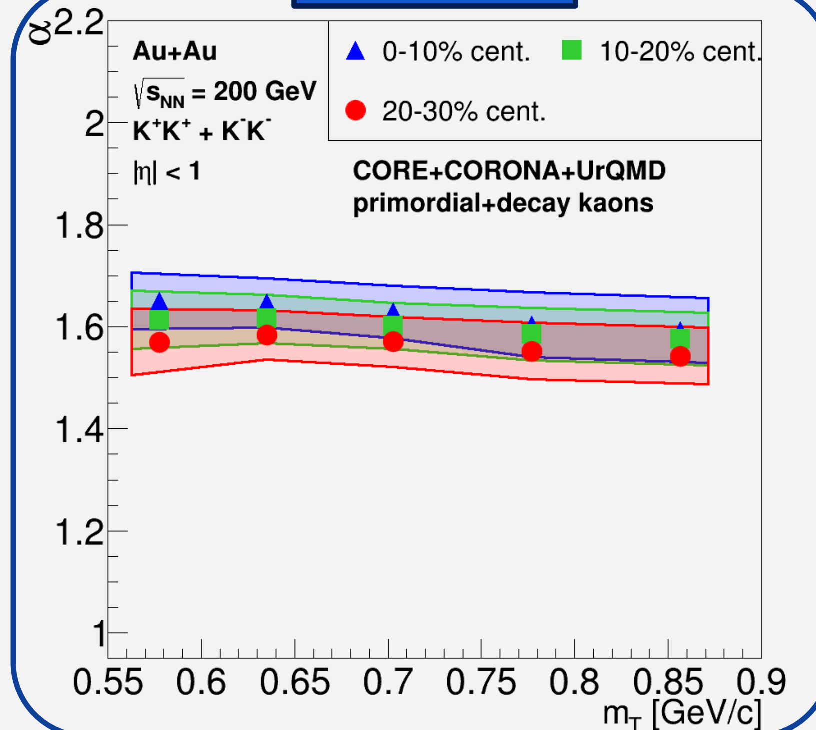


π vs K comparision – Parameter α

Pions



Kaons

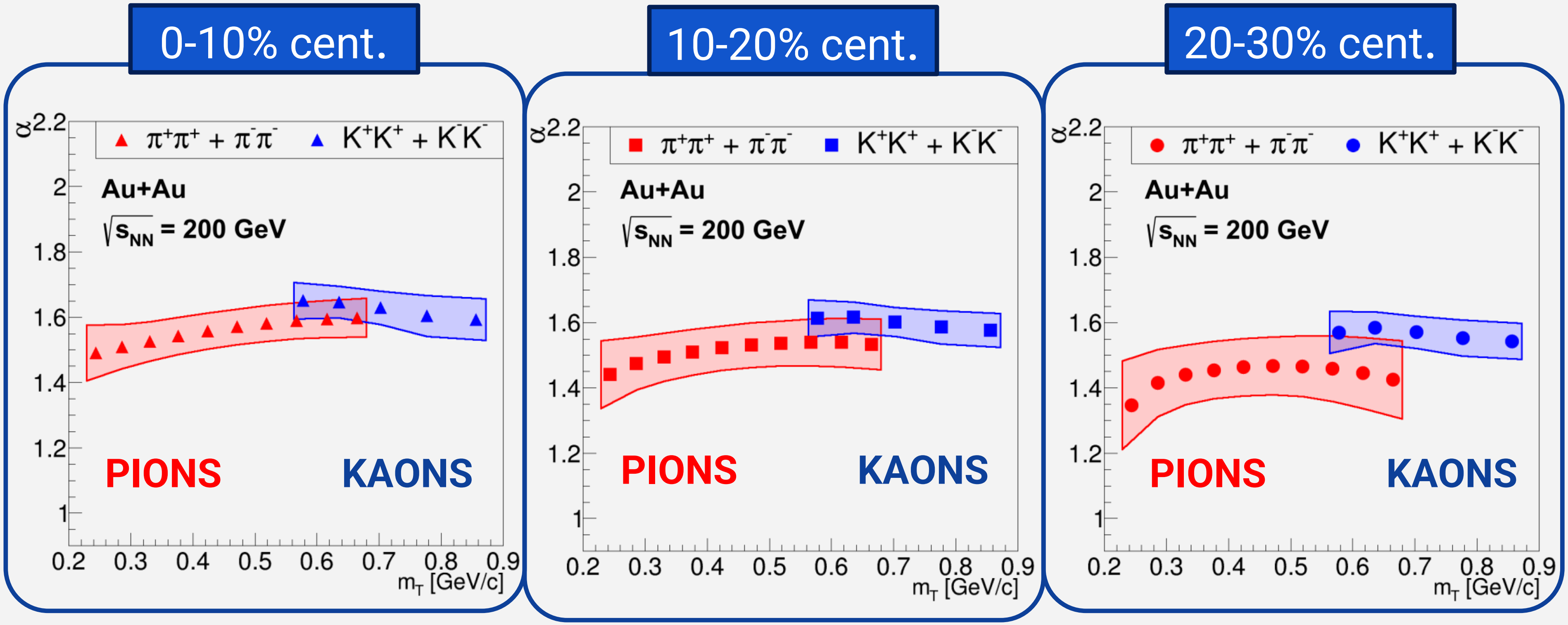


Not what expected in elastic scattering

$$\alpha(\pi^{\pm}) \leq \alpha(K^{\pm})$$

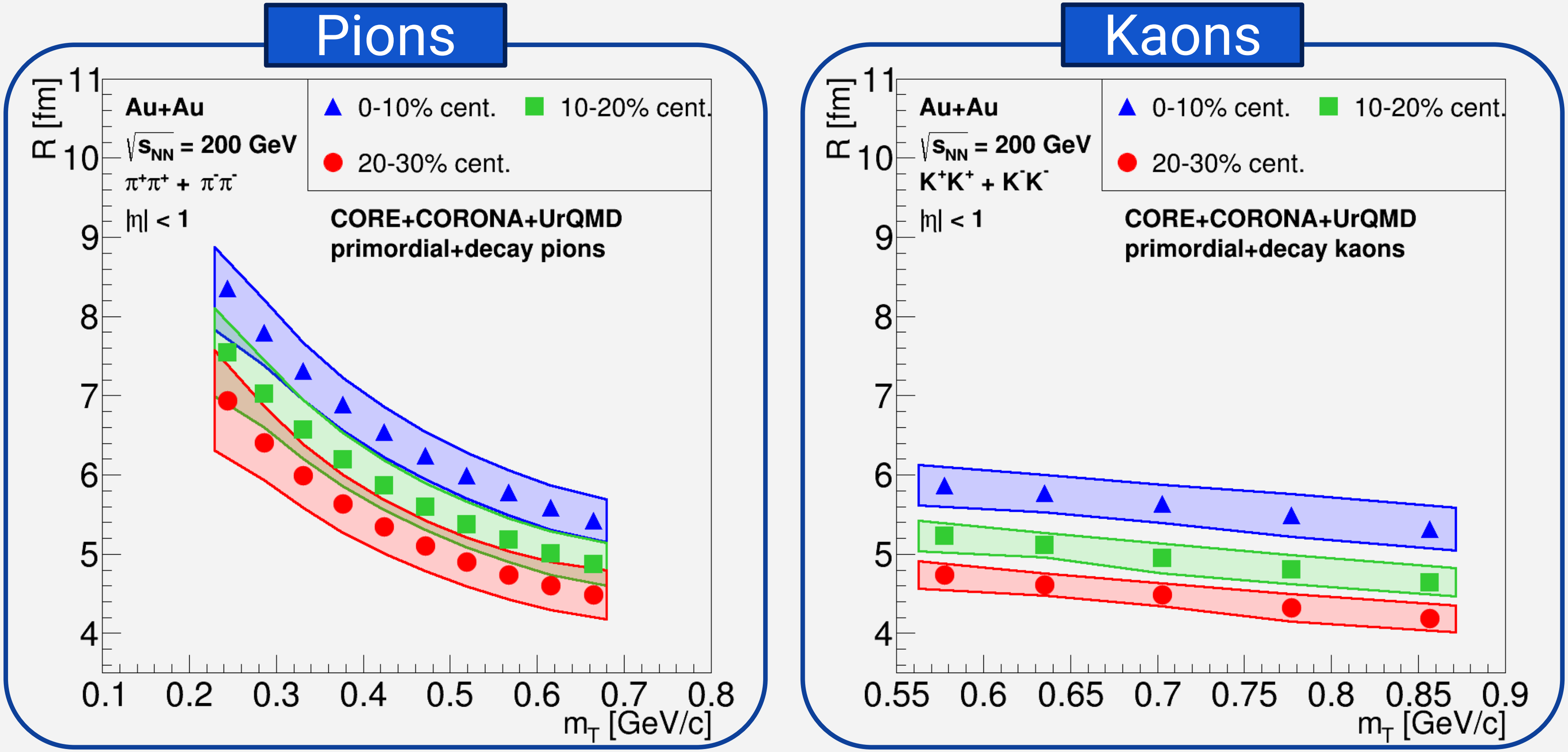
Due to resonance decays and inelastic scattering?

π vs K comparision – Parameter α



- Observation: $\alpha(\pi) \leq \alpha(K)$; approximately species-independent
- Unlike expectation for elastic scattering dominated Lévy walk
- Likely due to resonance decays and inelastic scattering

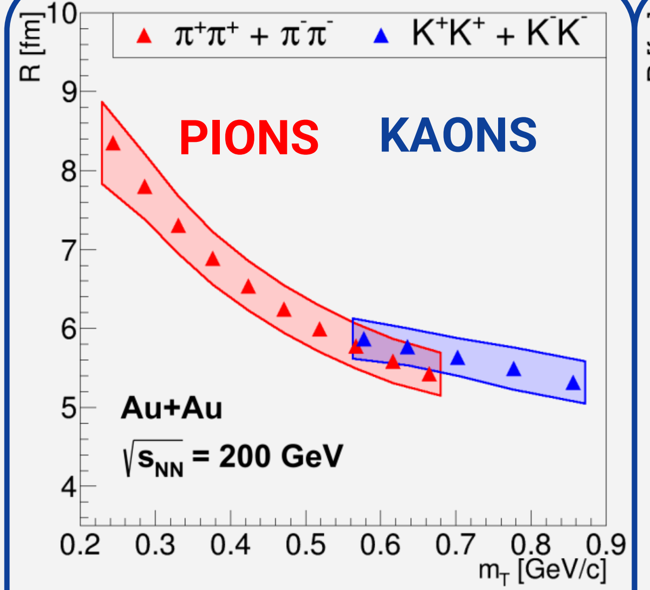
π vs K comparision – Parameter R



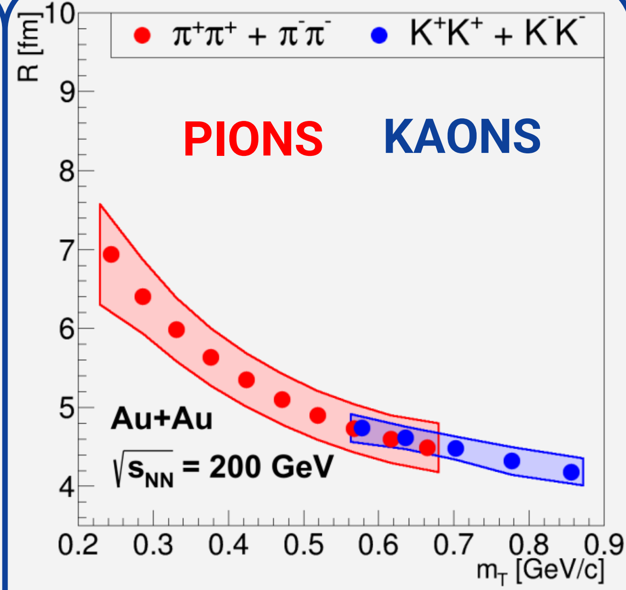
- Geometric centrality ordering of R, usual decrease with m_T due to collective flow

π vs K comparision – Parameter R

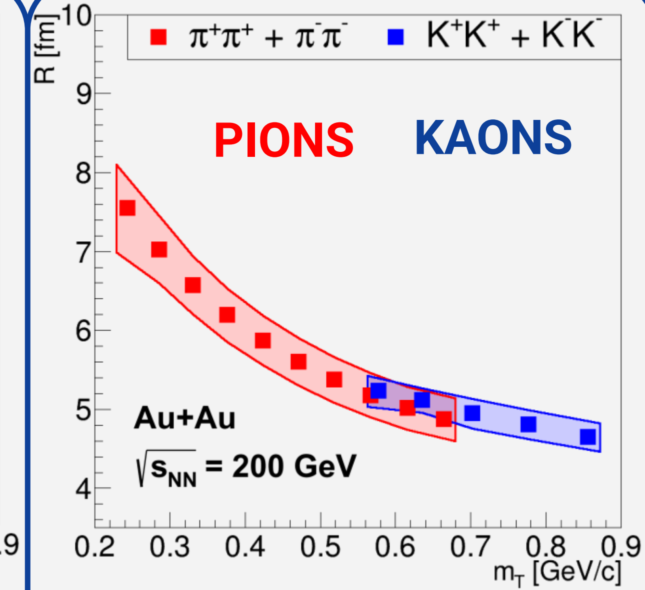
0-10% cent.



10-20% cent.

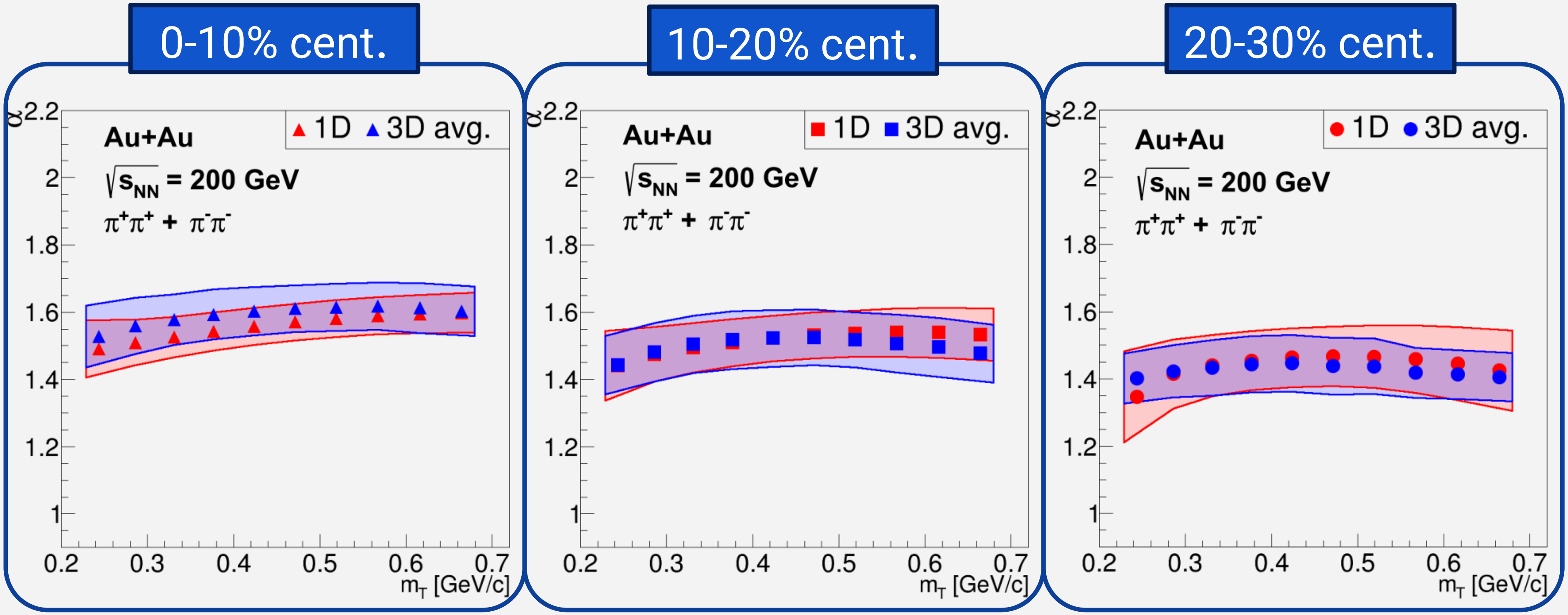


20-30% cent.



- Approximate m_T scaling holds
- Same source for pions and kaons, even after decays and scattering?

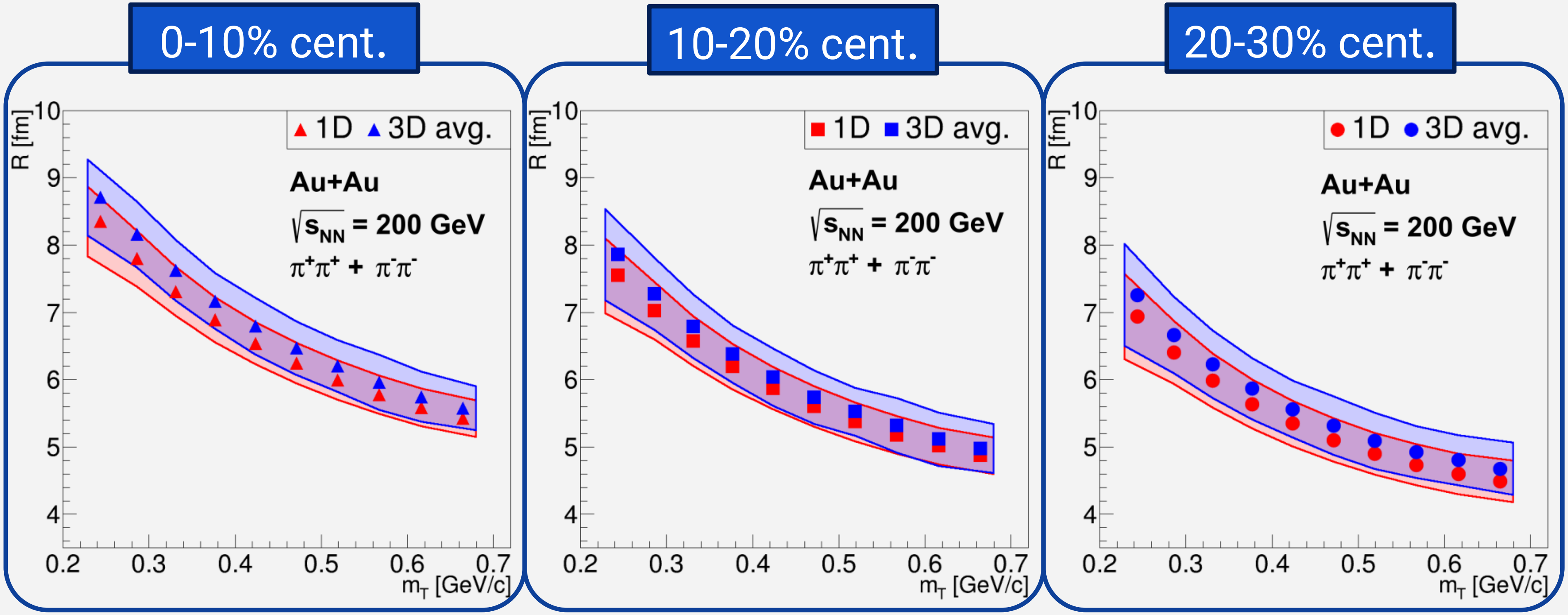
1D vs 3D analysis - Parameter α



- Good agreement with 3D results ➡ angle averaging does not change the shape!

3D analysis: see talk of E. Árpási

1D vs 3D analysis - Parameter R

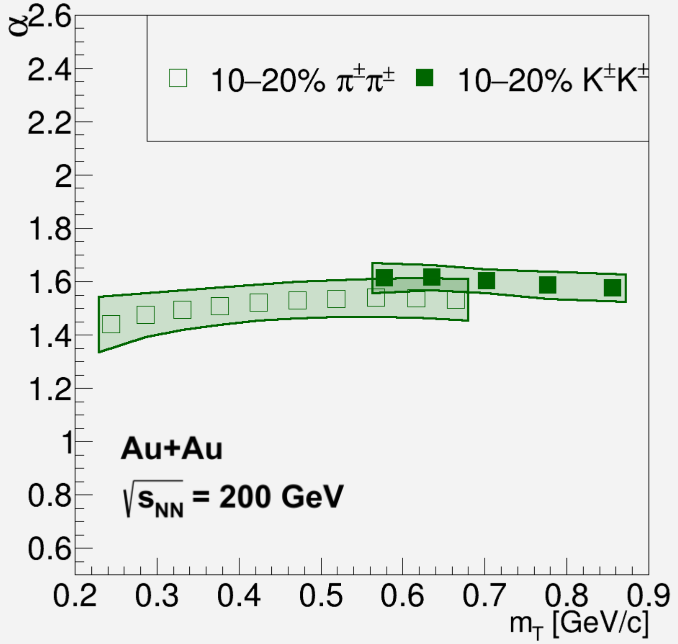


- Good agreement with 3D ⇒ angle averaging does not change the average scale!
- Slight but systematic difference between 1D and 3D, sign of asymmetry?

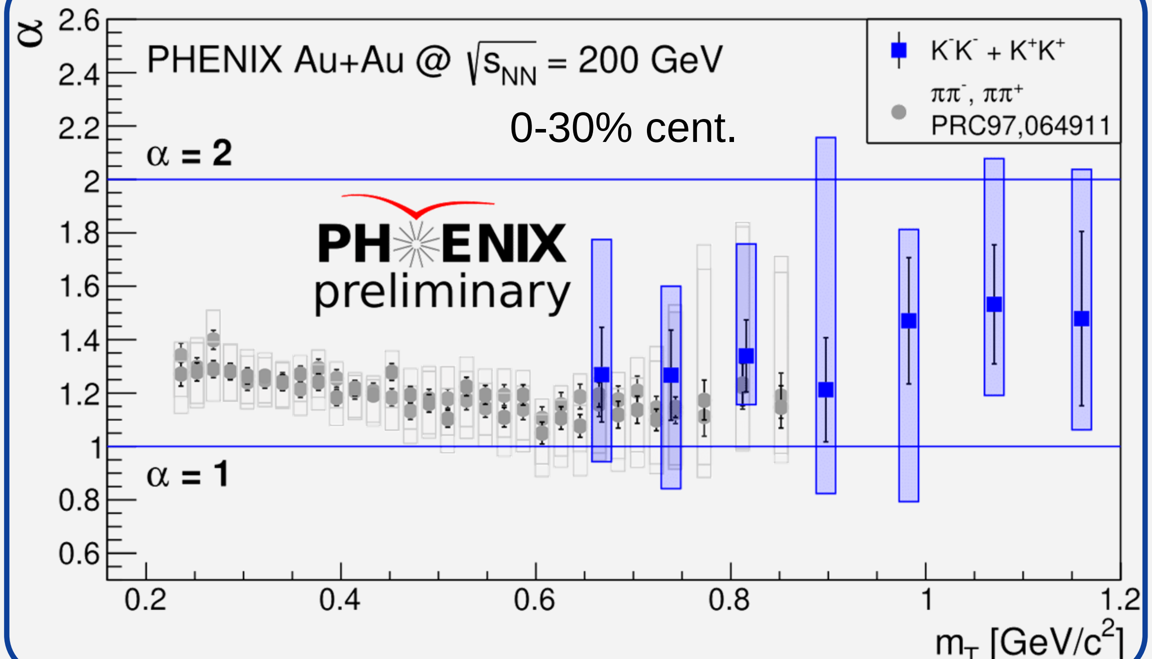
3D analysis: see talk of E. Árpási

EPOS vs experiment – Parameter α

EPOS



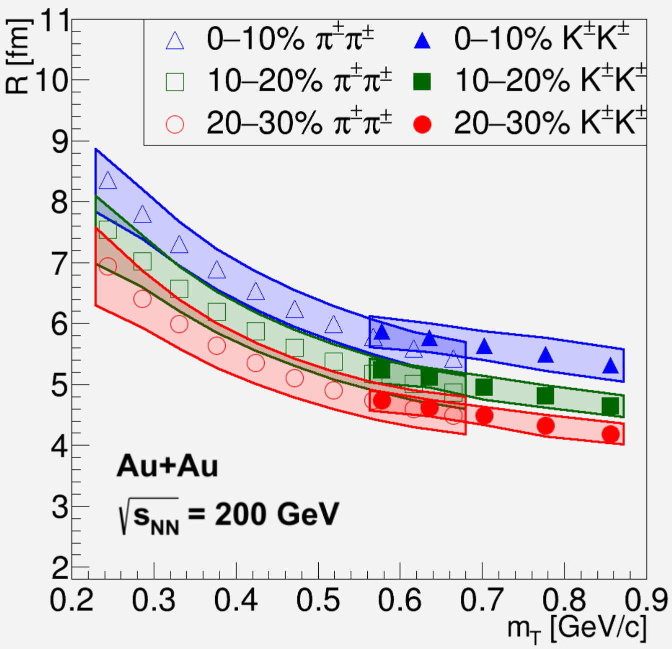
Experiment



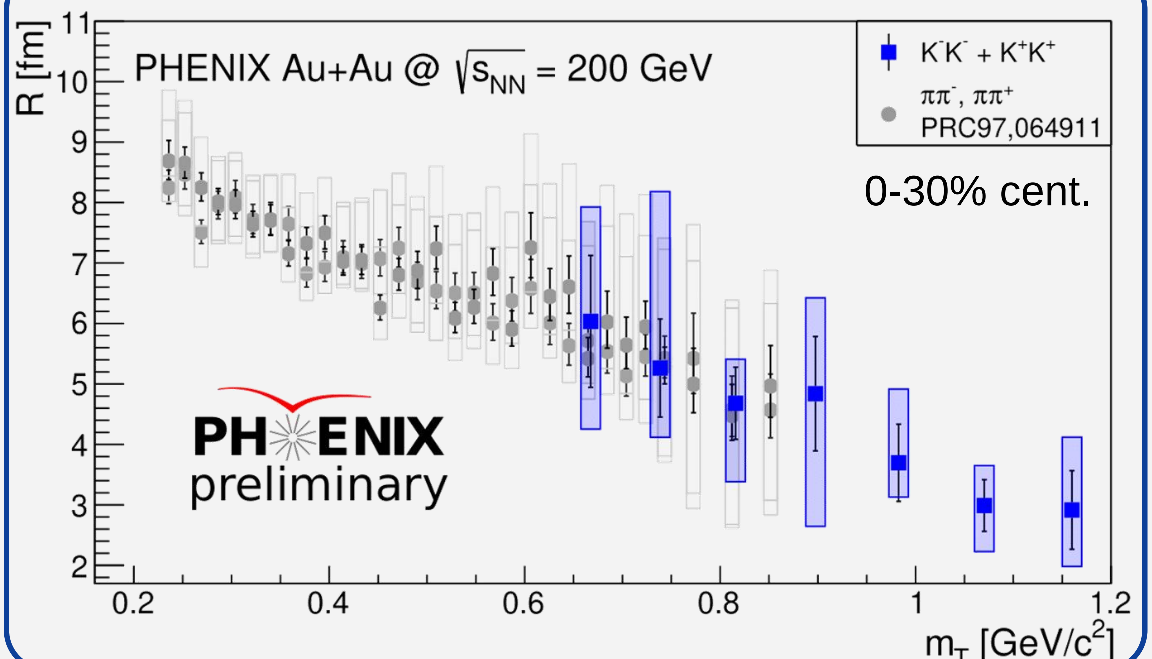
- Good agreement with preliminary experimental results, PHENIX and STAR as well

EPOS vs experiment - Parameter R

EPOS



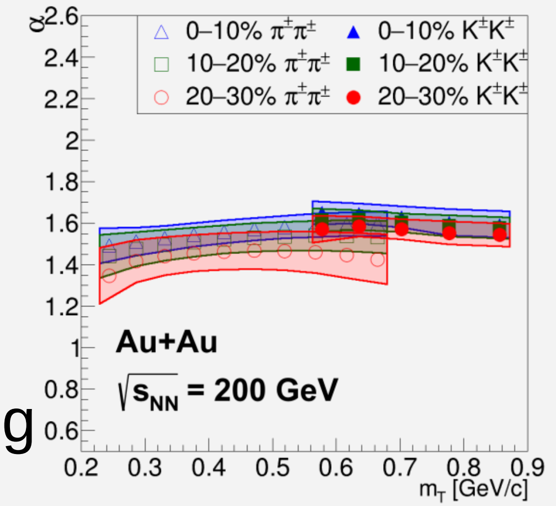
Experiment

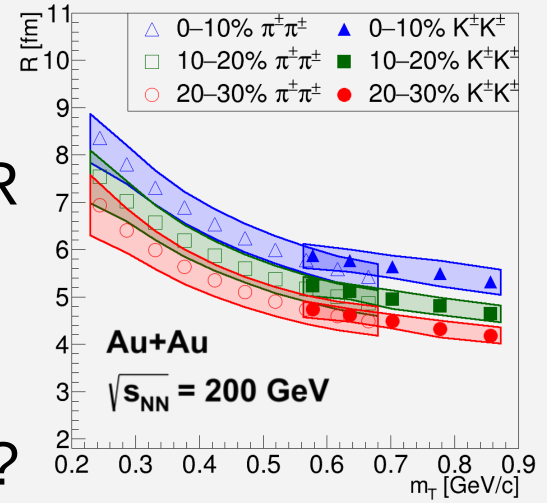


- Good agreement with preliminary experimental results, PHENIX and STAR as well

Summary

- π & K pair source investigated in EPOS
- Expected result based on elastic scattering: $\alpha(\pi) > \alpha(K)$
- EPOS results: $\alpha(\pi) \leq \alpha(K)$, likely due to resonance decays and inelastic scattering
- Parameter *R*: preserved m_T scaling
- 1D and 3D analyses show agreement
- Good agreement with PHENIX and STAR preliminary results
- Common Lévy source, shared collective system even after decays and scattering?





Thank you for your attention!

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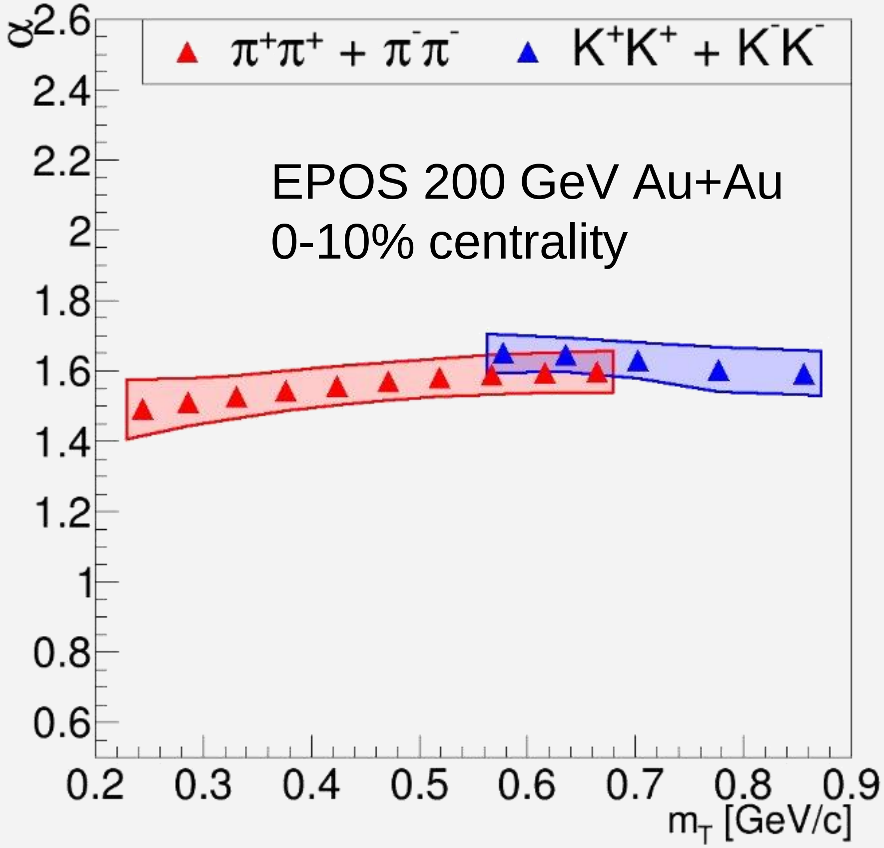
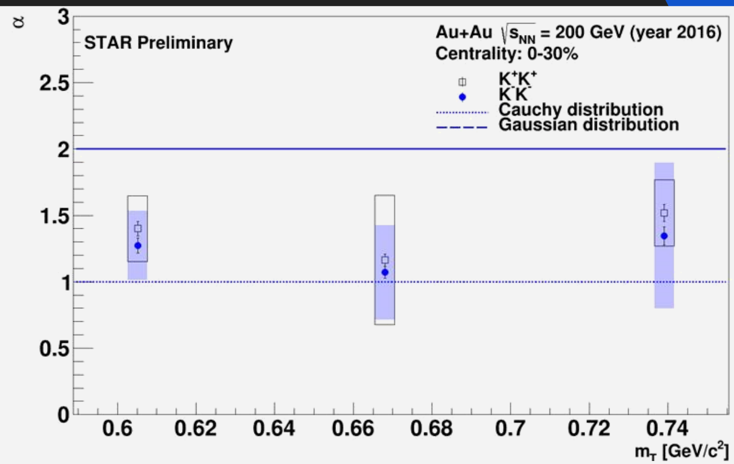
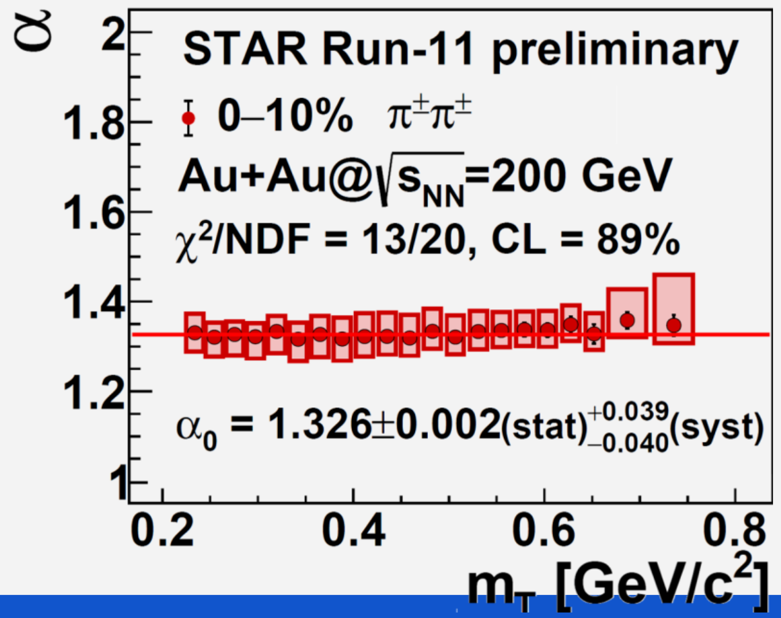
STAR comparision







STAR comparision