INVESTIGATION OF THE TWO-PARTICLE SOURCE FUNCTION AT $\sqrt{s_{NN}} = 2.76$ TEV WITH EPOS

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DAY OF FEMTOSCOPY

2023, GYÖNGYÖS

arXiv:2212.02980 Phys. Lett. B (2023)

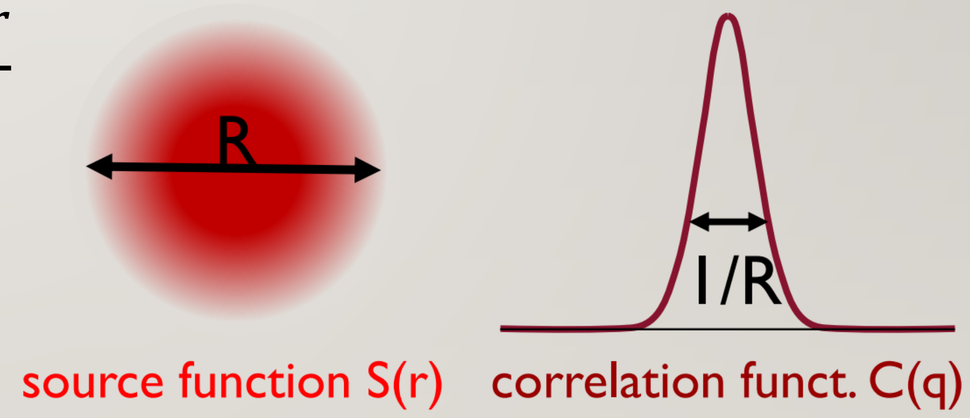
2 /16 FEMTOSCOPY – THE TWO-PARTICLE SOURCE

relative coordinate, average momentum, single-particle phase-space density

- Two-particle (pair) source: $D(r,K) = \int S\left(\rho + \frac{r}{2}, K\right) S\left(\rho - \frac{r}{2}, K\right) d^4\rho$

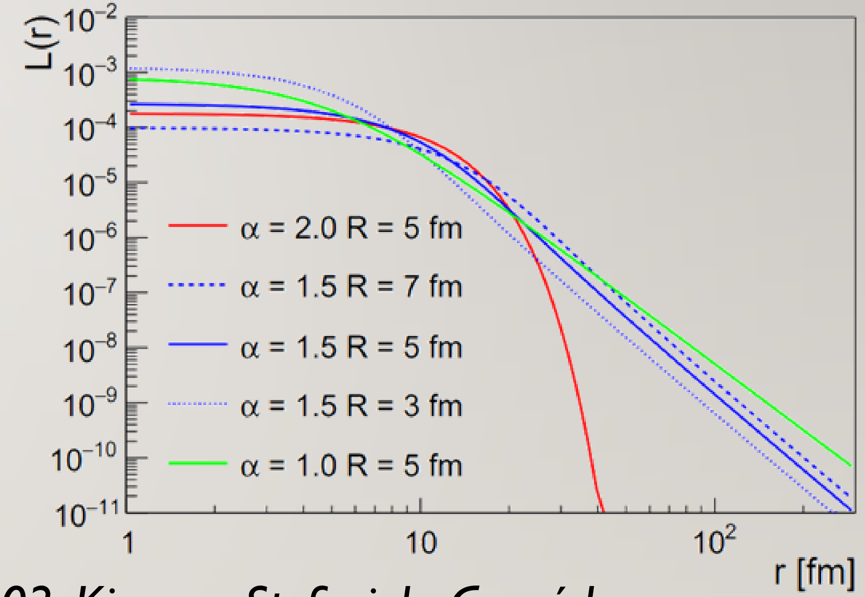
relative momentum, pair wave function

- Correlation function: $C(q,K) = \frac{\int D(r,K)\left|\Psi_q(r)\right|^2 d^4r}{\int D(r,K)\, d^4r}$
- Experiments – no direct access to pair-source
  - Assume given source shape and wave function
  - Calculate the correlation function
  - Test the assumptions on the measured correlation
- Event generator models (like EPOS) – direct access to pair-source!



LÉVY DISTRIBUTIONS IN HEAVY ION PHYSICS

- Measurements suggest phenomena beyond Gaussian distribution
- Lévy-stable distribution: $L(\boldsymbol{r};\alpha,R) = (2\pi)^{-3}\int d^3\boldsymbol{q}e^{i\boldsymbol{q}\boldsymbol{r}}e^{-\frac{1}{2}|\boldsymbol{q}R|^{\alpha}}$
  - α: Lévy stability index
  - R: Lévy scale parameter
- 1-D projection: $L(r;\alpha,R) = (2\pi^2 r)^{-1}\int dqe^{-\frac{1}{2}(qr)^{\alpha}}\sin(qr)q$



- Some possible causes:
  - Event averaging *(Cimerman et al., Phys.Part.Nucl. 51 (2020) 282)*
  - Resonance decays *(Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002; Kincses, Stefaniak, Csanád, Entropy 24 (2022) 308)*
  - Hadronic rescattering, anomalous diffusion *(Braz.J.Phys. 37 (2007) 1002; Entropy 24 (2022) 308)*

THE EPOS MODEL

- EPOS = **E**nergy conserving quantum mechanical multiple scattering approach, based on **P**artons (parton ladders), **O**ff-shell remnants, and **S**aturation of parton ladders *K.Werner et al., PRC82 (2010) 044904, PRC89 (2014) 064903*
- Monte-Carlo based phenomenological model
- Stages of the evolution:
  - Initial stage – parton based Gribov-Regge theory
  - Core-corona separation
  - 3+1D viscous hydrodynamic evolution
  - Hadronic rescattering – UrQMD
- Dataset: EPOS3 2.76 TeV PbPb, 800k events

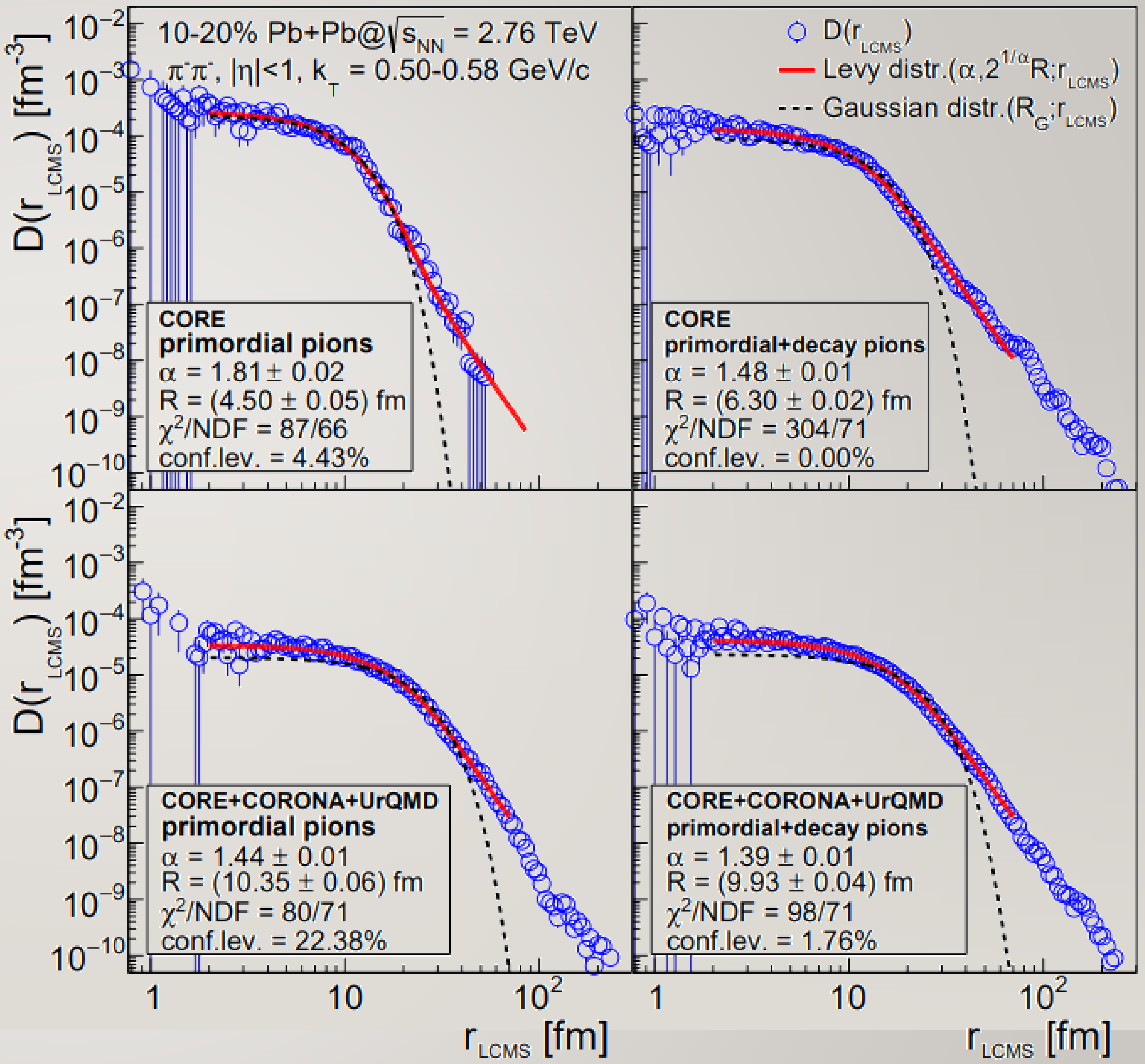
5/16 RECONSTRUCTING THE TWO-PARTICLE SOURCE

- Source spherically symmetric in the LCMS *(PHENIX coll.,Phys. Rev. Lett. 93 (2004), 152302)*
- $\boldsymbol{r}_{LCMS} = \left(x_1 - x_2,\ y_1 - y_2,\ \frac{z_1 - z_2 - \beta(t_1 - t_2)}{\sqrt{1-\beta^2}}\right),\ \beta = \frac{p_{z,1} + p_{z,2}}{E_1 + E_2}$
- Calculate $D(r_{LCMS})$ event-by-event!
- Average transverse momentum (k_T) classes
- Investigated cases:
  - Pions:
    - CORE, primordial
    - CORE, primordial+decay
    - CORE+CORONA+UrQMD, primordial
    - CORE+CORONA+UrQMD, primordial+decay
  - Kaons: CORE+CORONA+UrQMD, primordial+decay
  - Protons: CORE+CORONA+UrQMD, primordial+decay

LÉVY FITS TO THE TWO-PARTICLE SOURCE

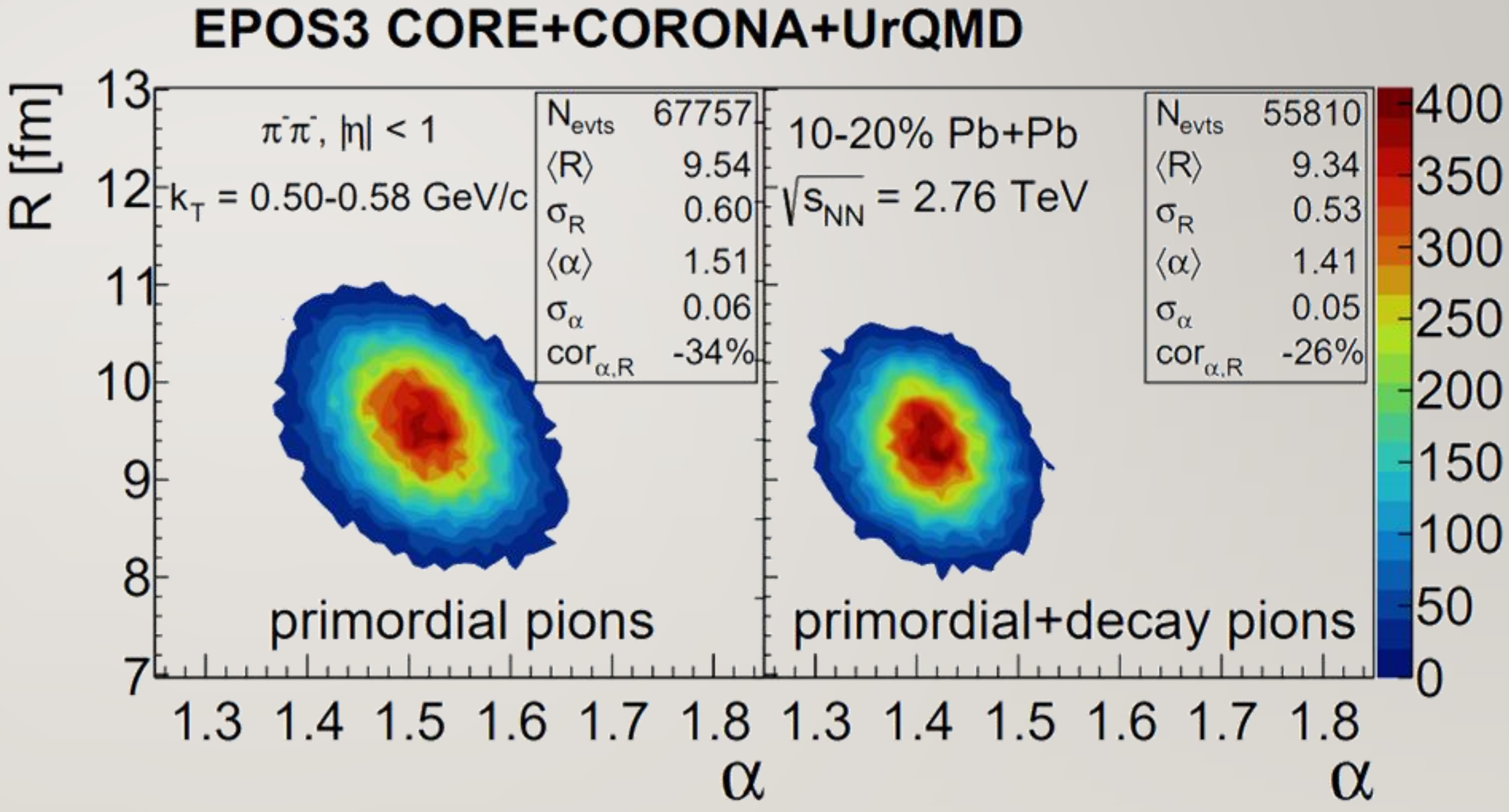
- Event-by-event Lévy fits
- Without decays and UrQMD → close to Gaussian
- After decays or UrQMD → far from Gaussian
- Lévy shape appears in single events!
- Similar fits for kaons and protons
- Only keep fits with CL > 0.1%

EPOS3 single event



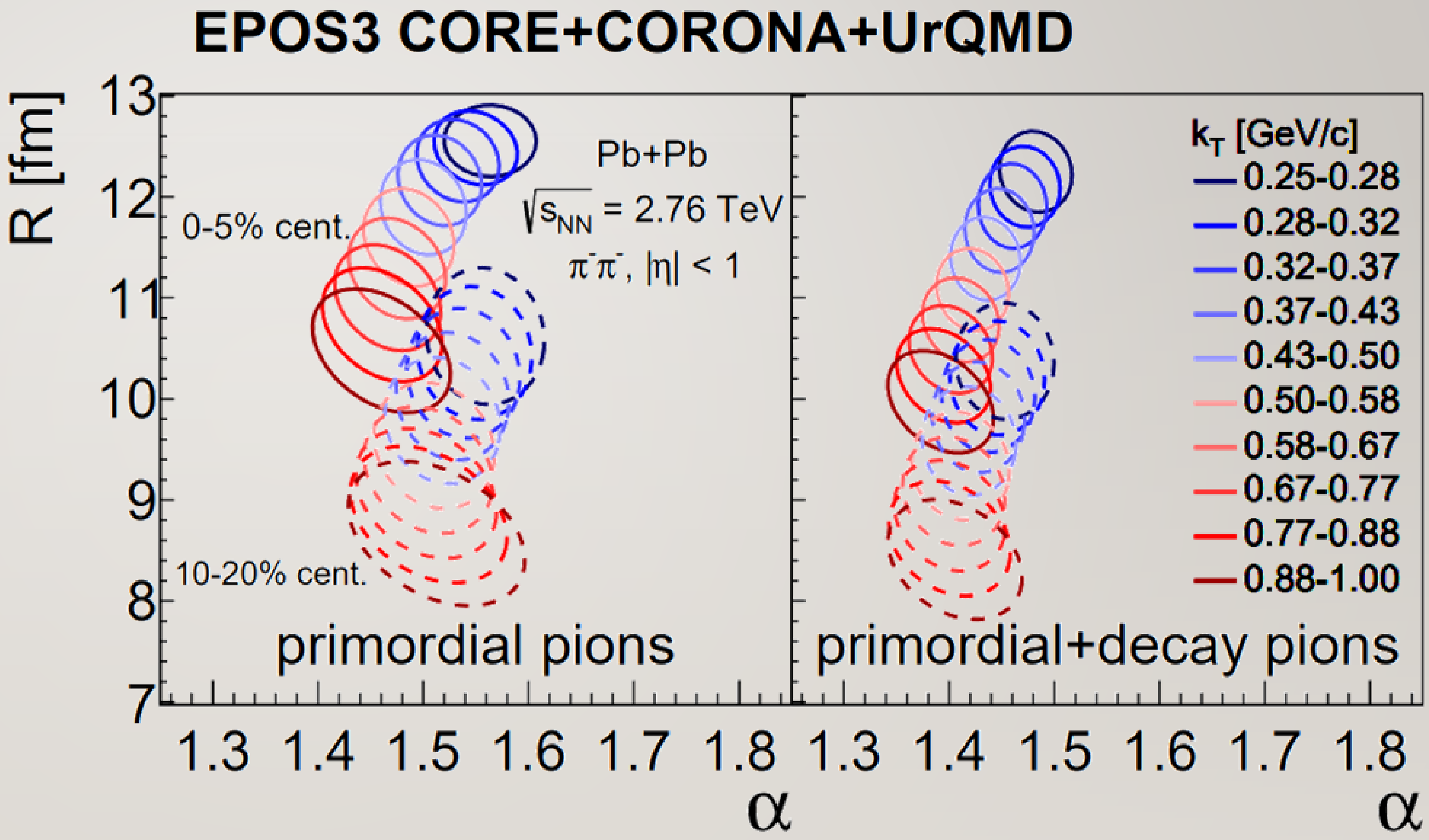
7/16 DISTRIBUTION OF THE SOURCE PARAMETERS

- Collect all fit results in R vs α histograms
- Similar figures for each centrality, k_T and for kaons or protons
- Extract average values $\langle R\rangle$ and $\langle\alpha\rangle$
- Extract standard deviations
- Investigate centrality and k_T dependence



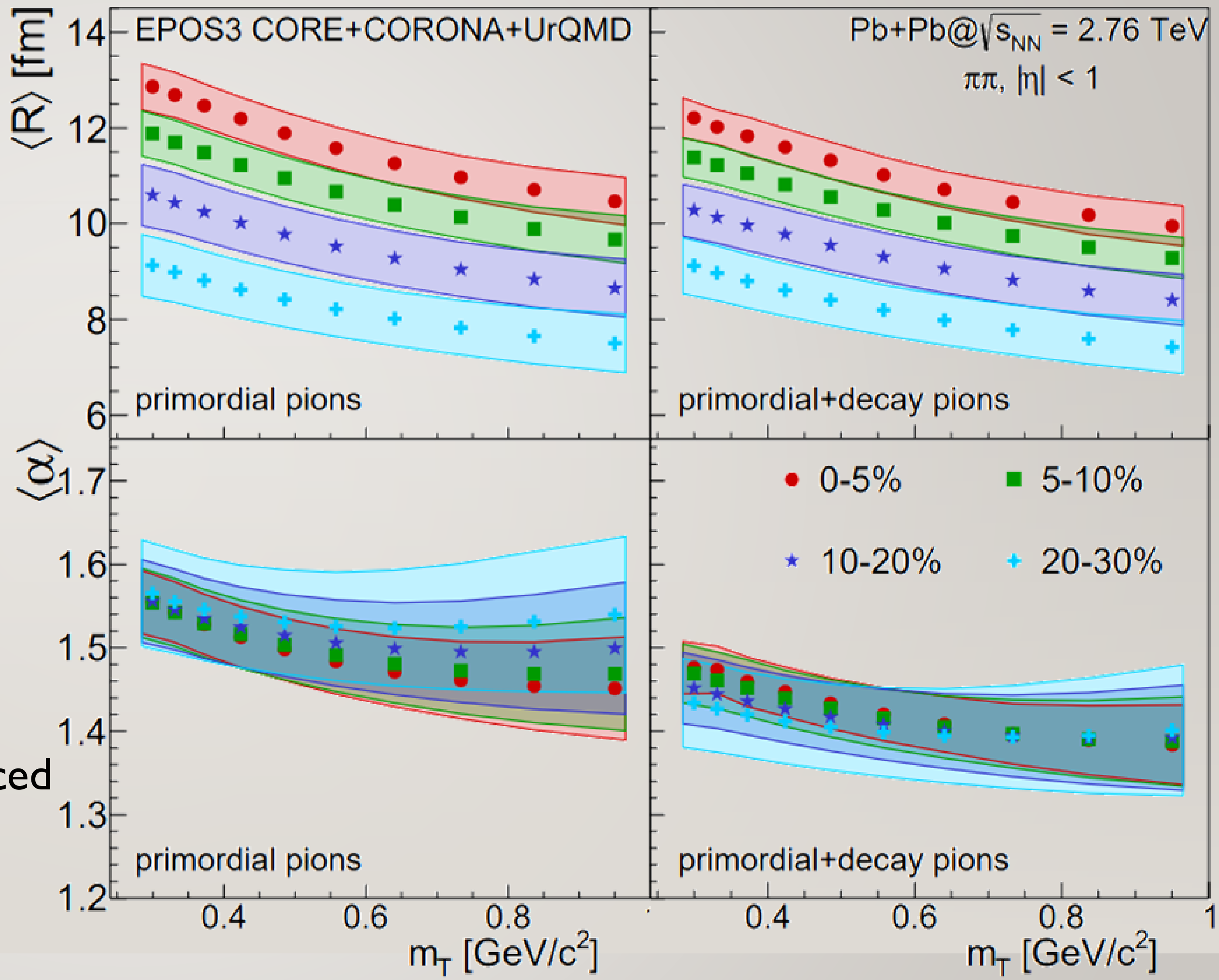
CONTOURS OF THE R VS α DISTRIBUTIONS

- 1σ contours for all k_T classes
  - Ellipses from σ_α, σ_R and $cor_{\alpha,R}$
  - Only 2 centralities in one figure for clarity
- $\alpha - R$ anti-correlation
- Illustrates centrality and k_T dependence

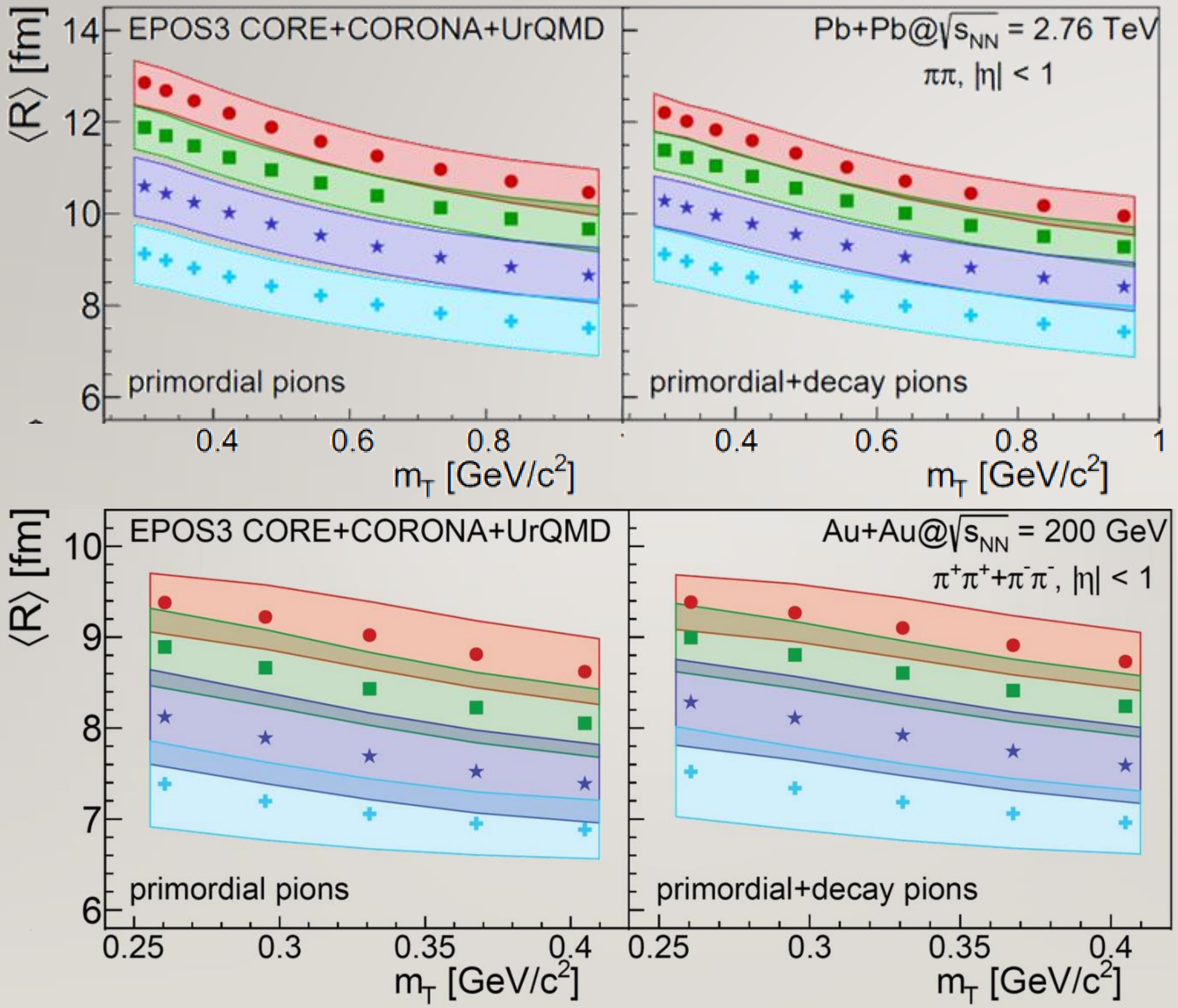


9/16 PION SOURCE PARAMETERS

- Transverse mass: $m_T = \sqrt{k_T^2 + m^2}$
- Lévy scale parameter (R):
  - Larger in central collisions → spatial scale
  - Decreases with m_T → hydrodynamic scaling
  - Small effect of decay products
- Lévy stability index (α):
  - Weak centrality dependence
  - Small decrease with m_T
  - Smaller after decays → source shape influenced
- Error bands = standard deviation of $R/\alpha \neq$ statistical uncertainty of $\langle R\rangle/\langle\alpha\rangle$



COMPARISON TO DATA AND LOWER ENERGY EPOS



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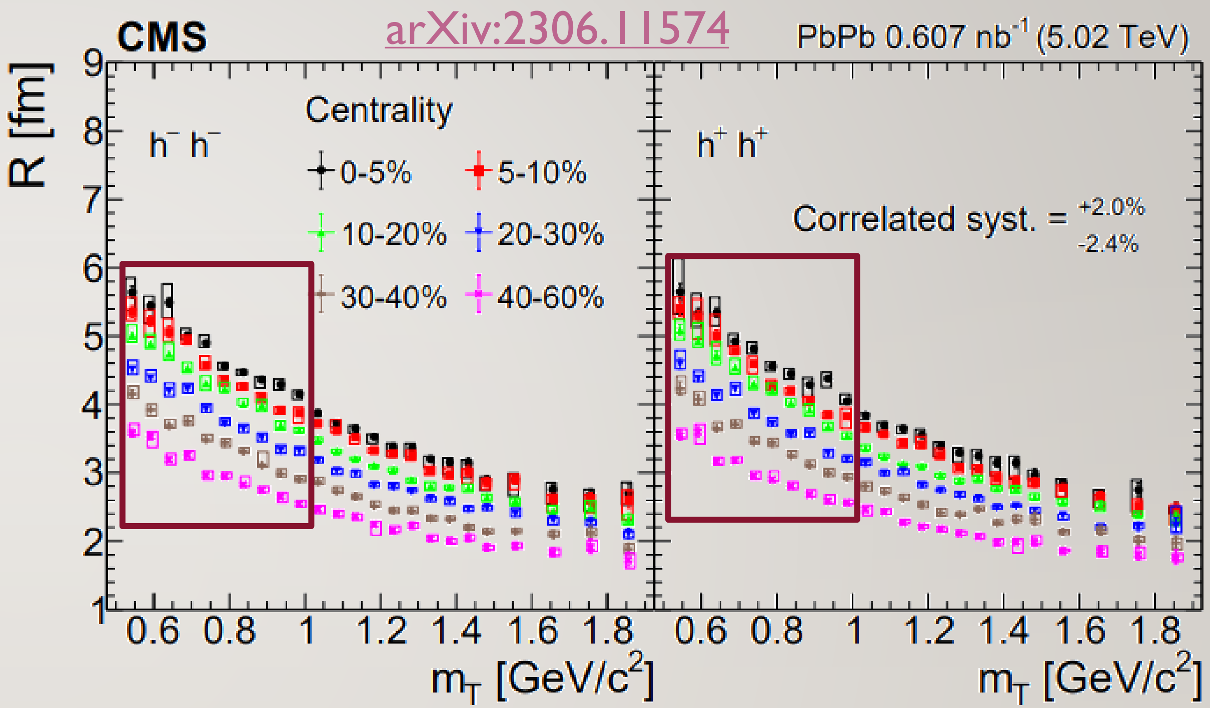
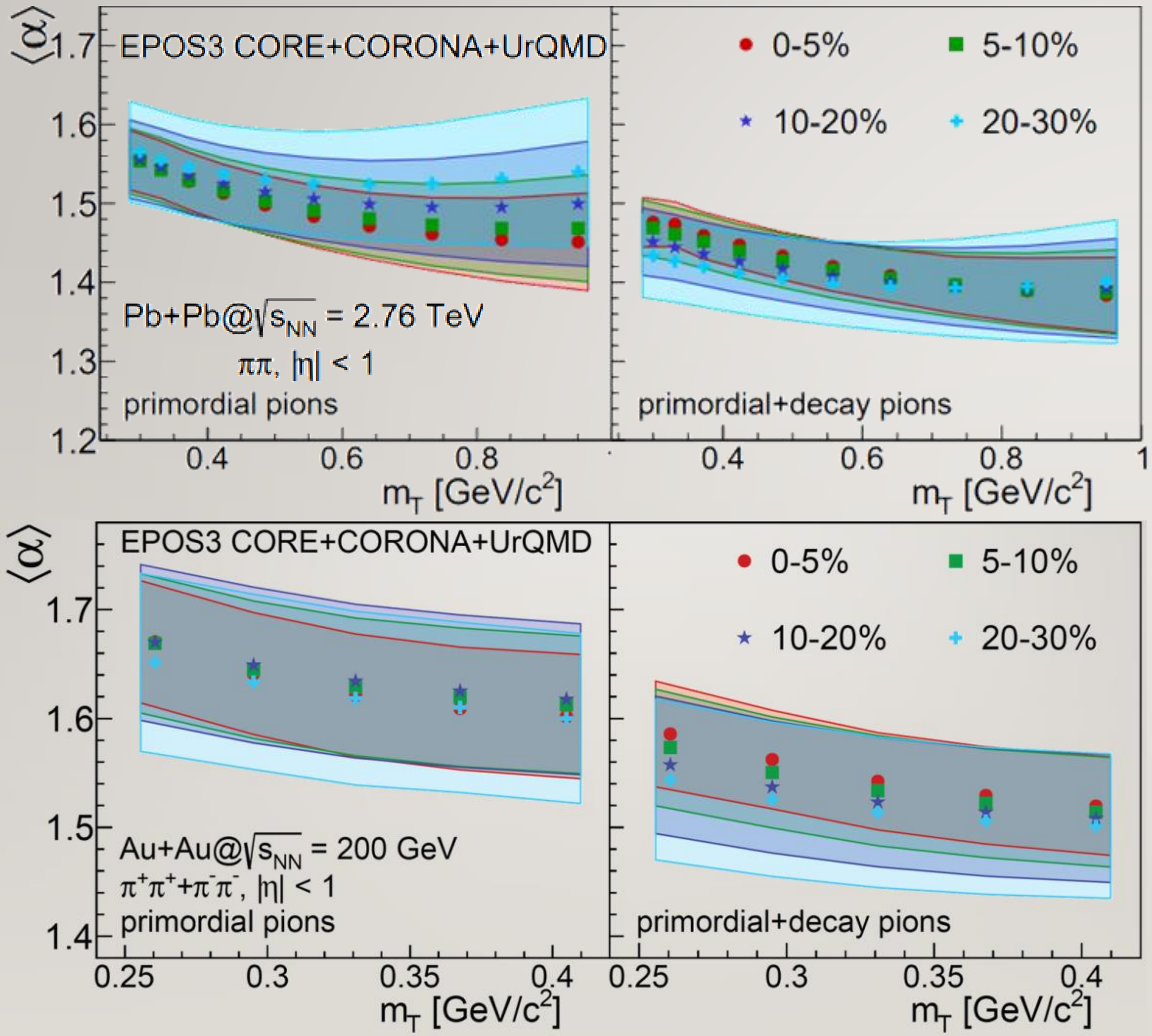


- Similar centrality and m_T dependence
- $\langle R \rangle$(2.76 TeV EPOS) > $\langle R \rangle$(200 GeV EPOS)
- $\langle R \rangle$(2.76 TeV EPOS) > R(5.02 TeV data) ?

11/16 COMPARISON TO DATA AND LOWER ENERGY EPOS



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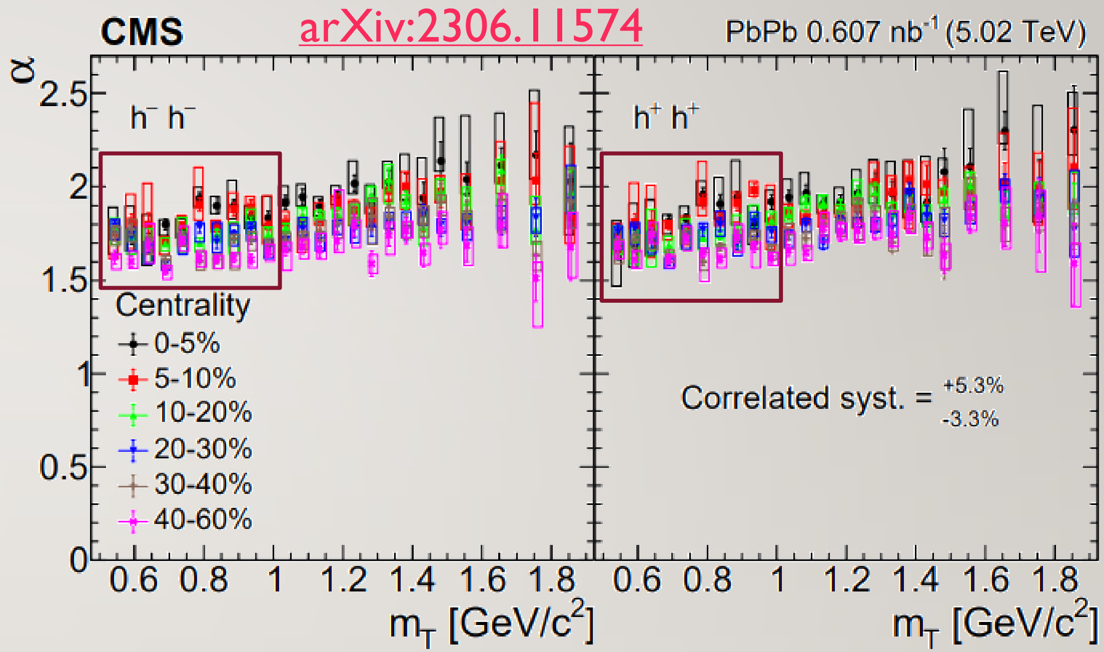
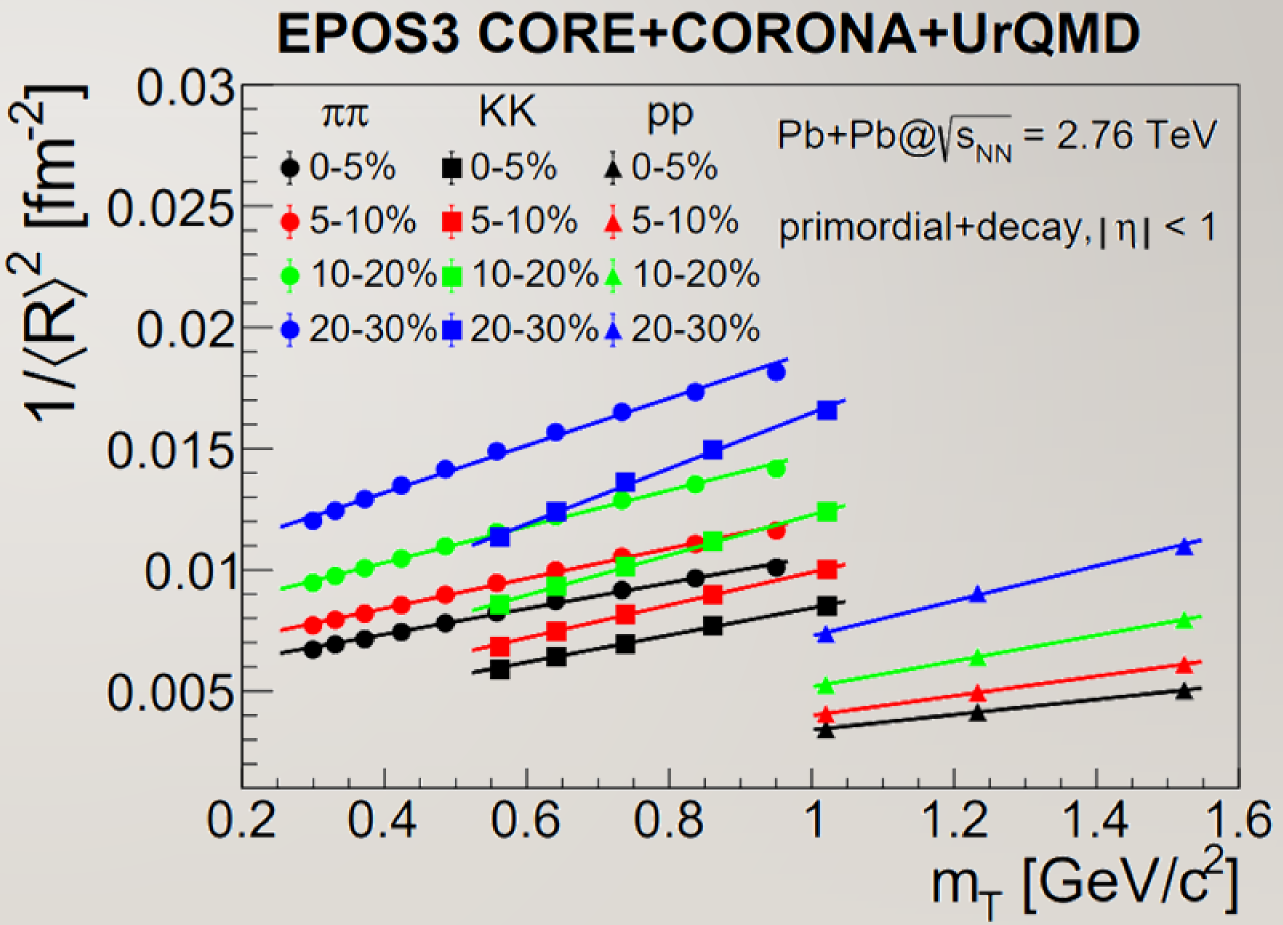


- Similar centrality and m_T dependence
- $\langle\alpha\rangle$(2.76 TeV EPOS) $<$ $\langle\alpha\rangle$(200 GeV EPOS)
- $\langle\alpha\rangle$(2.76 TeV EPOS) $<$ α(5.02 TeV data)

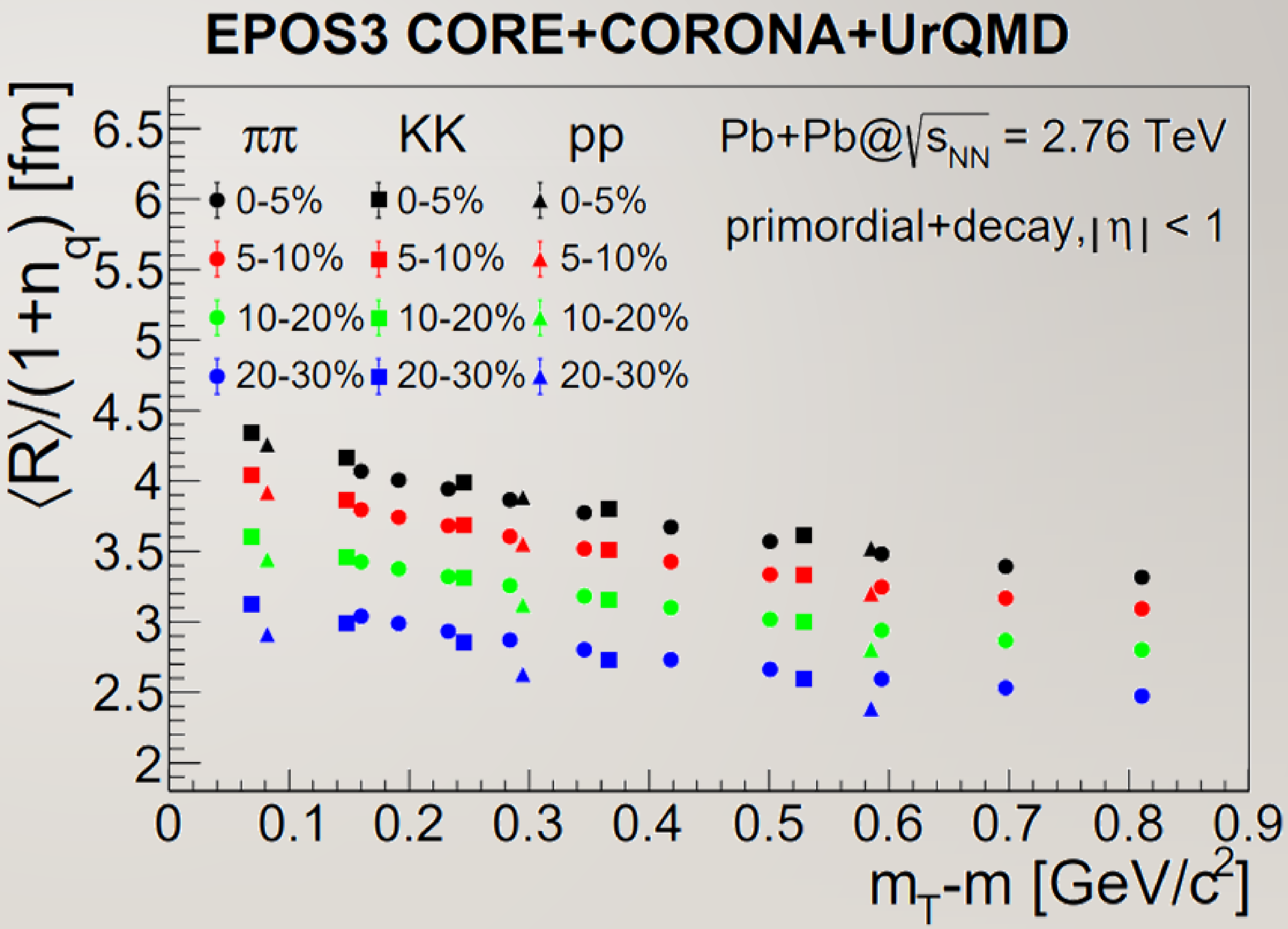
12/16 PION, KAON, PROTON LÉVY SCALE PARAMETER

- Similar trends
- Hydrodynamics + Gaussian source → $\frac{1}{R^2} \sim m_T$ particle independent scaling
- EPOS → R depends on the particle type
- No universal m_T scaling in EPOS
- For given species scaling is approximately fulfilled
- Stat. uncertainties smaller than markers



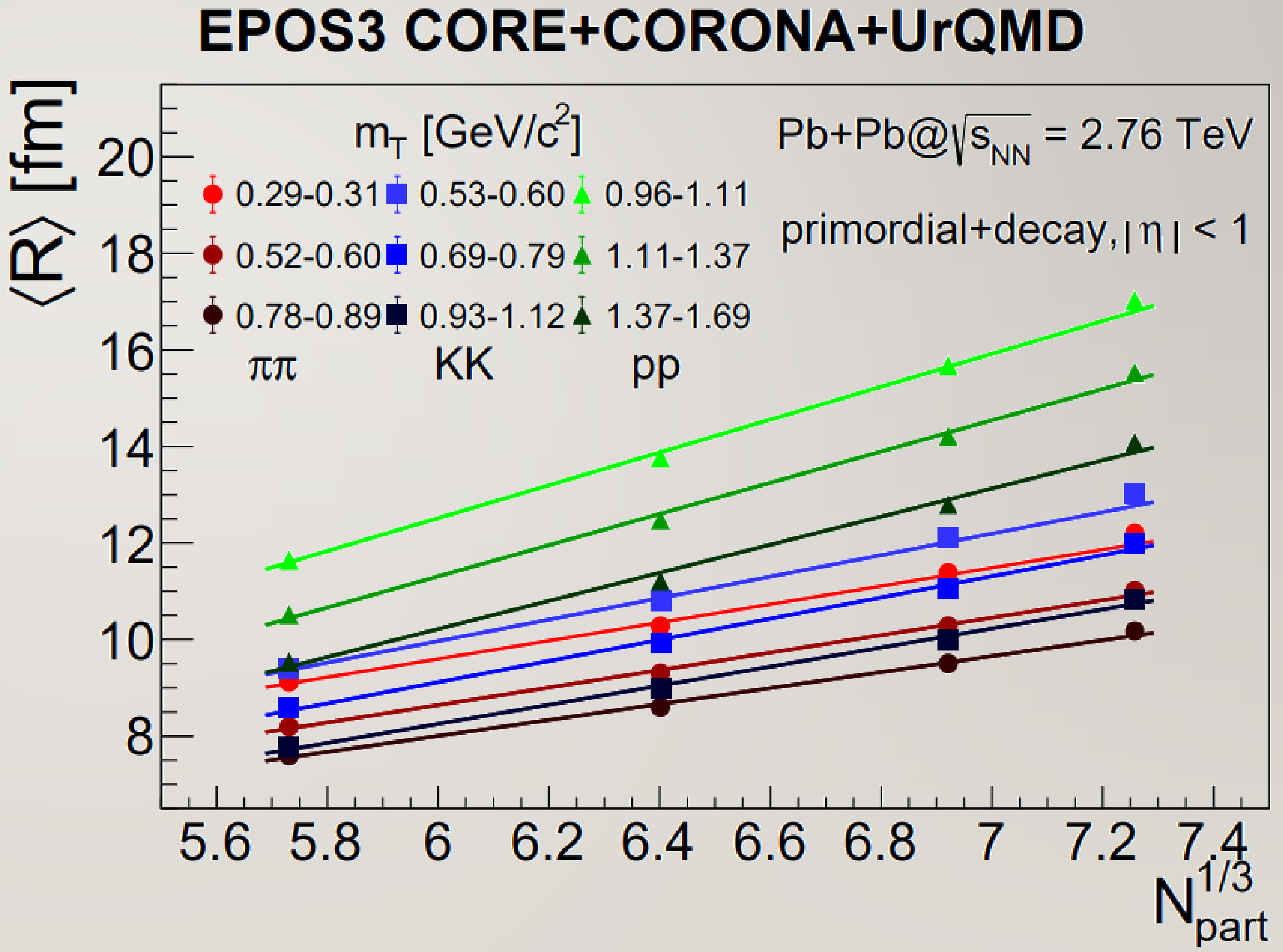
13/16 INTERESTING SPECIES INDEPENDENT SCALING OF *R*

- *R* vs. $(m_T - m)$ → same curve for pions and kaons
- Divide R with one plus the number of valence quarks → same curve for protons
- Unknown reasons and interpretation



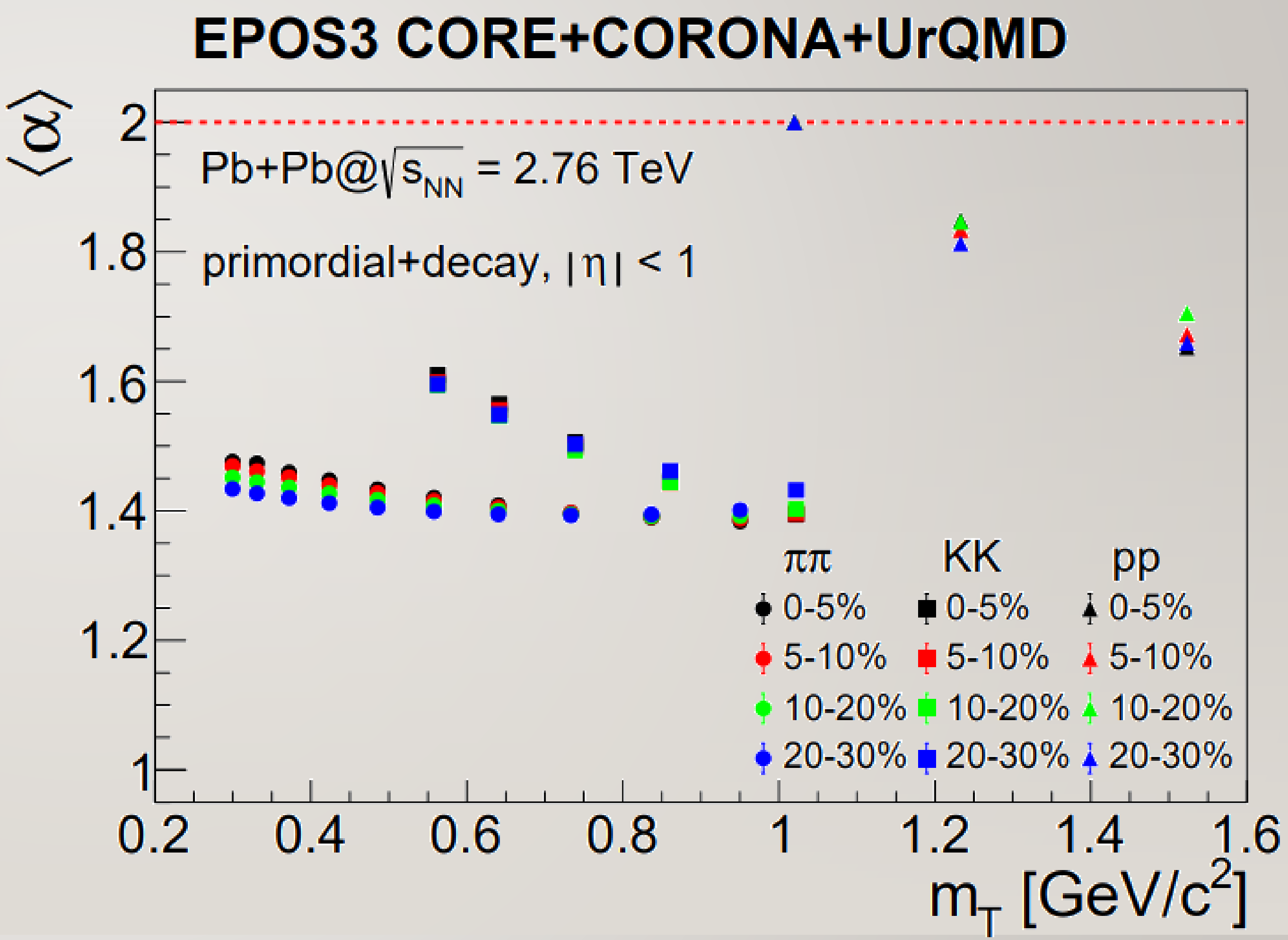
LÉVY SCALE PARAMETER VS N_{part}

- N_{part} : average number of participating nucleons
- $N_{part}^{1/3} \sim$ one-dimensional initial size
- Approximately linear scaling → geometric interpretation
- Super small statistical uncertainties: $\frac{\sigma_R}{\sqrt{N_{evts}}} \approx 0.01\%$



PION, KAON, PROTON LÉVY STABILITY INDEX

- Source deviation from Gaussian ($\alpha = 2$)
- In case of anomalous diffusion:
  - Smaller cross-section → larger mean free path → longer power-law tail → smaller α
- Prediction: $\alpha_K < \alpha_\pi < \alpha_p$
- Only partially fulfilled!
- Anomalous diffusion cannot be the only reason for the Lévy shape



SUMMARY

- Analysis steps:
  - Event-by-event reconstruction of the two-particle source in EPOS 2.76 TeV PbPb
  - Single event Lévy fits – event-by-event Lévy shape
  - Extract mean Lévy parameters $\langle R \rangle$ and $\langle \alpha \rangle$
- Results:
  - Hydrodynamic-like and geometric scaling of $\langle R \rangle$ } pions
  - $\langle \alpha \rangle$ affected by decays } pions
  - Similar trends to experiment, but different magnitudes } pions
  - Particle species dependent $\langle R \rangle$
  - Partially fulfilled predictions of anomalous diffusion
  - Preprint: arXiv:2212.02980 (accepted at Phys. Lett. B)

Supported by the NKFIH OTKA grants K-133046, K-128713, and K-138136. Supported by the ÚNKP-22-2 New National Excellence Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund.

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THANK YOU FOR YOUR ATTENTION!

BACKUP SLIDES

19 KAON AND PROTON EXAMPLE FIT