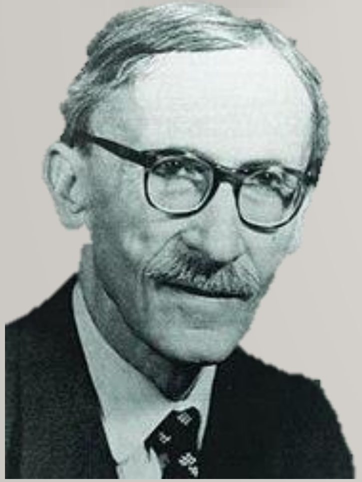
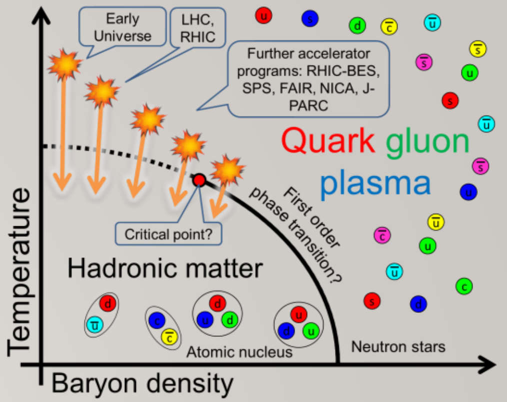




PION FEMTOSCOPY WITH LÉVY-STABLE SOURCES IN THE BES

MÁTÉ CSANÁD (EÖTVÖS U) FOR THE STAR COLLABORATION

BES-II WORKSHOP, DECEMBER 2024

BROOKHAVEN NATIONAL LABORATORY

Partially funded by

U.S. DEPARTMENT OF ENERGY

Office of Science

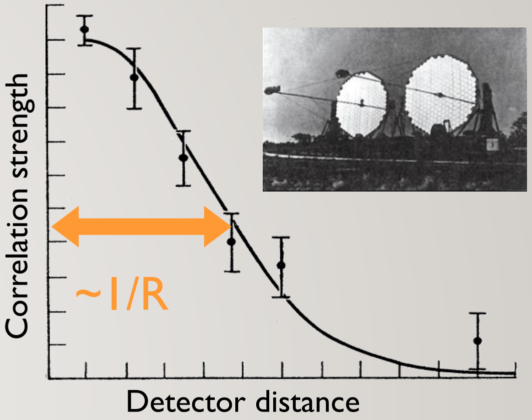
HBT OR FEMTOSCOPY IN HIGH ENERGY PHYSICS

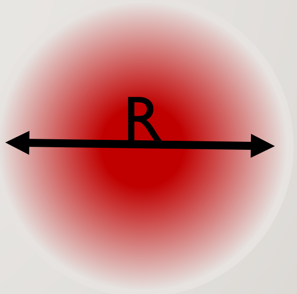
- R. Hanbury Brown, R. Q. Twiss - observing Sirius with radio telescopes
  - Intensity correlations vs detector distance ⇒ source size
  - Measure the sizes of apparently point-like sources!
- Goldhaber et al: applicable in high energy physics
- Understanding: Glauber, Fano, Baym, …
  Phys. Rev. Lett.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

    $$C(q) \cong 1 + \left|\int S(r) e^{iqr} dr\right|^2$$

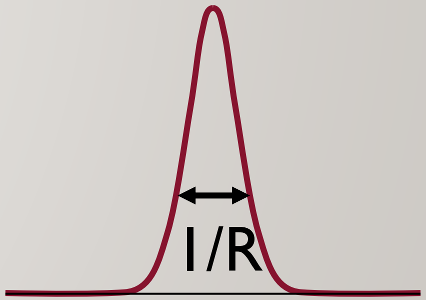
    (under some assumptions)
  - Also with distance distribution $D(r)$:

    $$C(q) \cong 1 + \int D(r) e^{iqr} dr$$
  - Neglected: pair reconstruction, final state interactions, multi-particle correlations, coherence, …
- What is the source shape? Can be explored via femtoscopy





source function S(r)



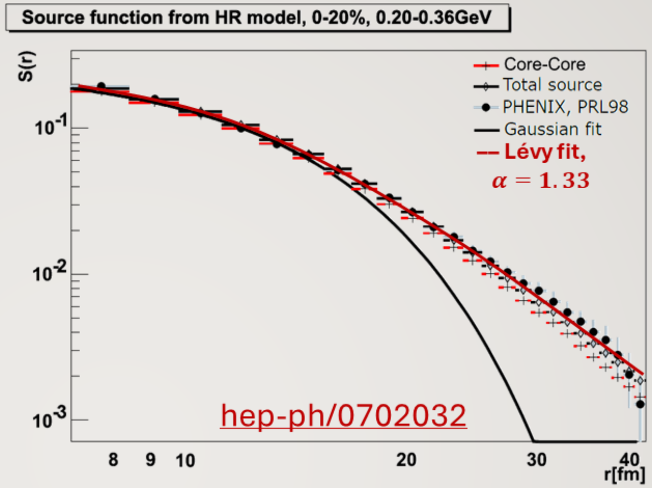
correlation funct. C(q)

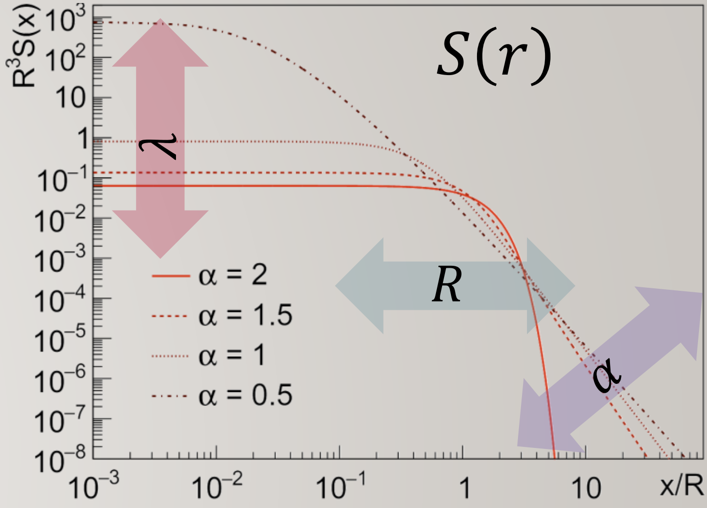
LÉVY DISTRIBUTIONS IN HEAVY ION PHYSICS

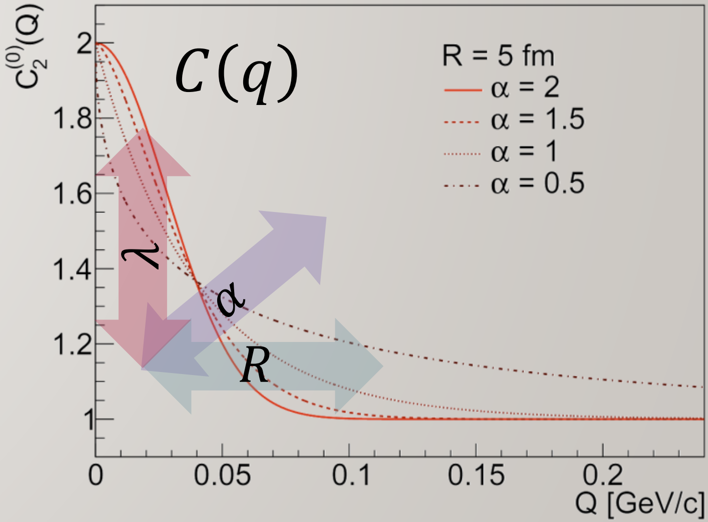
- Central limit theorem, diffusion, and thermodynamics lead to Gaussians
- Measurements suggest phenomena beyond Gaussian distribution
- Lévy-stable distribution:

$$\mathcal{L}(\alpha, R; r) = \frac{1}{2\pi}\int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$$

  - 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
- Lévy source seen & exponent measured from SPS through RHIC to LHC
  NA61 [EPJC83(2023)919], PHENIX [PRC97(2018)064911,PRC(2024)], CMS [PRC109(2024)024914]

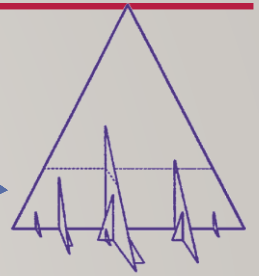


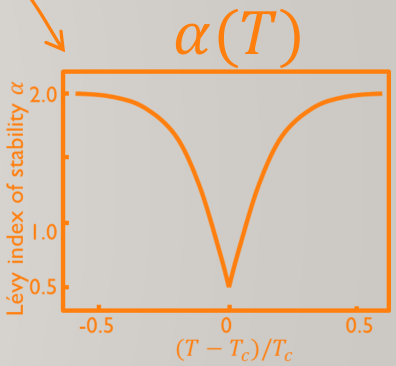


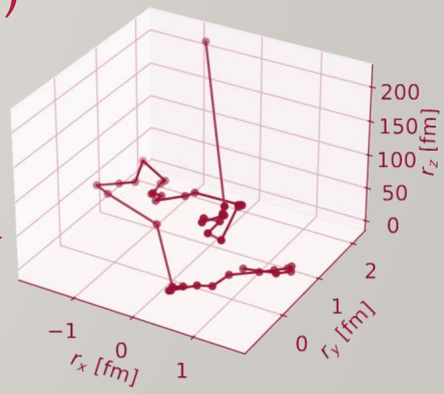


WHY DO LÉVY SHAPES APPEAR, WHY IS IT IMPORTANT?

- A more comprehensive list of possible reasons:
  - Jet fragmentation (Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon. B36 (2005) 329-337)
    - See also Caucal, Mehtar-Tani, JHEP 09 (2022) 023
    - Important in e^+e^-, see L3 Collaboration, Eur.Phys.J.C 71 (2011) 164
  - Critical phenomena (Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828 (2006) no.1, 525-532)
    - Role in the few GeV region? Affected by finite size effects?
  - Directional or event averaging (Cimerman et al., Phys.Part.Nucl. 51 (2020) 282)
    - Ruled out by event-by-event and 3D analyses
  - Lévy walk (BJP37(2007); PRB103(2021), Entropy24(2022); PLB847(2023); arXiv:2409.10373)
    - Only plausible explanation at high energies and large systems
- Importance of utilizing Lévy sources, leaving α as parameter:
  - Measuring α and R: quark-hadron transition, critical point, etc
  - Measuring λ: In-medium mass modification, coherent pion production





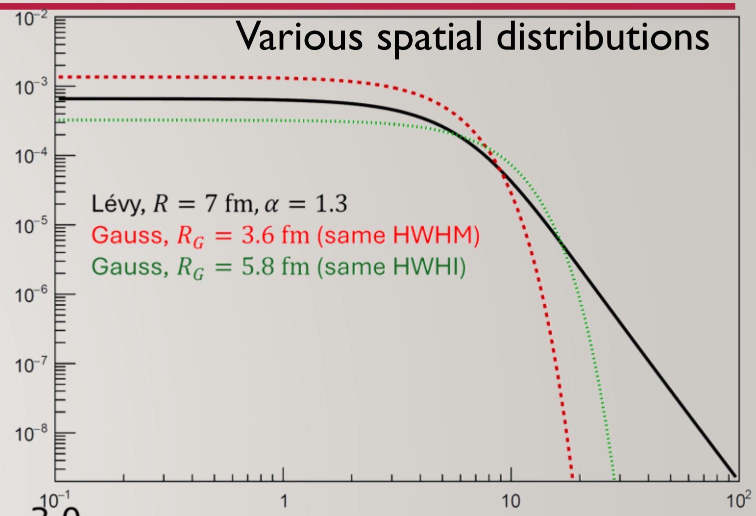


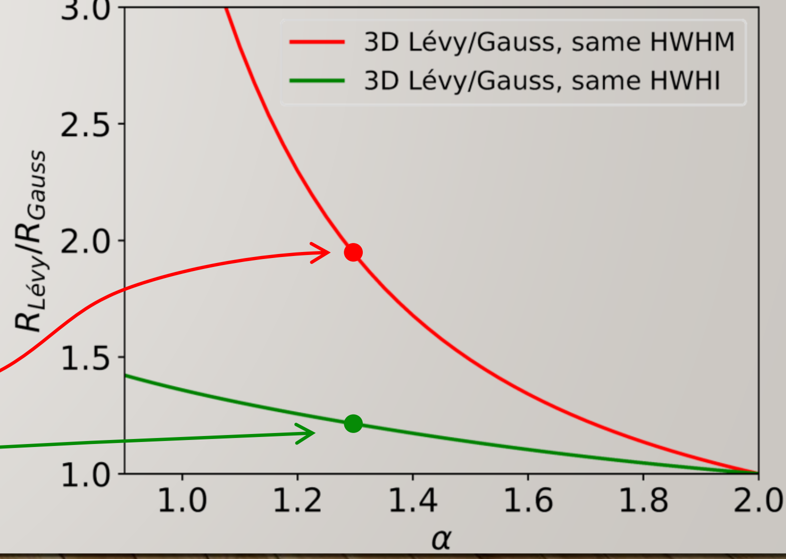
SOURCE SIZE MEASURE CHANGE WITH α

- No tail if $\alpha = 2$, power law and RMS $= \infty$ if $\alpha < 2$: depends on cutoff
- What do Gaussian HBT radii mean? Important also w.r.t. CEP search
- Alternative measures (see arXiv:2401.01249 for details)
    - HWHM: (half) width at half maximum
    - HWHI: (half) width at half integral
    - Width (normalized by R) nontrivially depends on α
- Relations for 3D Gauss: HWHM $\approx 1.17 \cdot R_G$, HWHI $\approx 1.54 \cdot R_G$
- For (e.g.) Lévy $\alpha = 1.3$: HWHM $\approx 0.61 \cdot R_L$, HWHI $\approx 1.27 \cdot R_L$
- **Thus (e.g.) $\boldsymbol{\alpha = 1.3}$ and $\boldsymbol{R_L = 7}$ fm "means":**
    - Same HWHM Gaussian: $R_G \approx 3.61$ fm
    - Same HWHI Gaussian: $R_G \approx 5.77$ fm

$R_{Gauss} \approx R_{Lévy}/1.94$

$R_{Gauss} \approx R_{Lévy}/1.21$





LÉVY PROCESSES IN NATURE AND IN SCATTERING

- Lévy walk and Lévy flight: known in ecology, climatology, etc.
  - If step size distribution has no finite width: generalized central limit theorem, Lévy-stable limiting distributions
- In HIC: increasing mean free path, step size increases
  - Seen in expansion under Coulomb potential in solid-state physics
- Observed in UrQMD [arXiv:2409.10373]
  - Scatterings, decays, coalescence (no Coulomb scattering)

E. I. Kiselev, Phys. Rev. B 103, 235116 (2021)

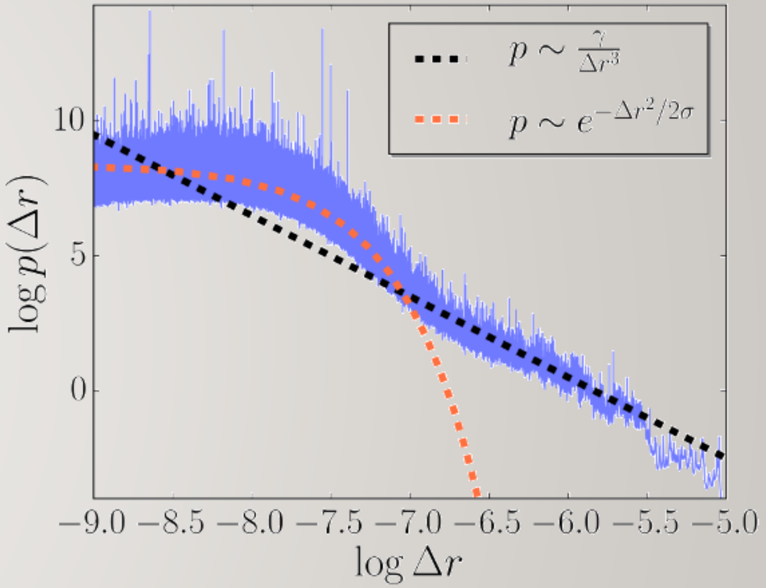
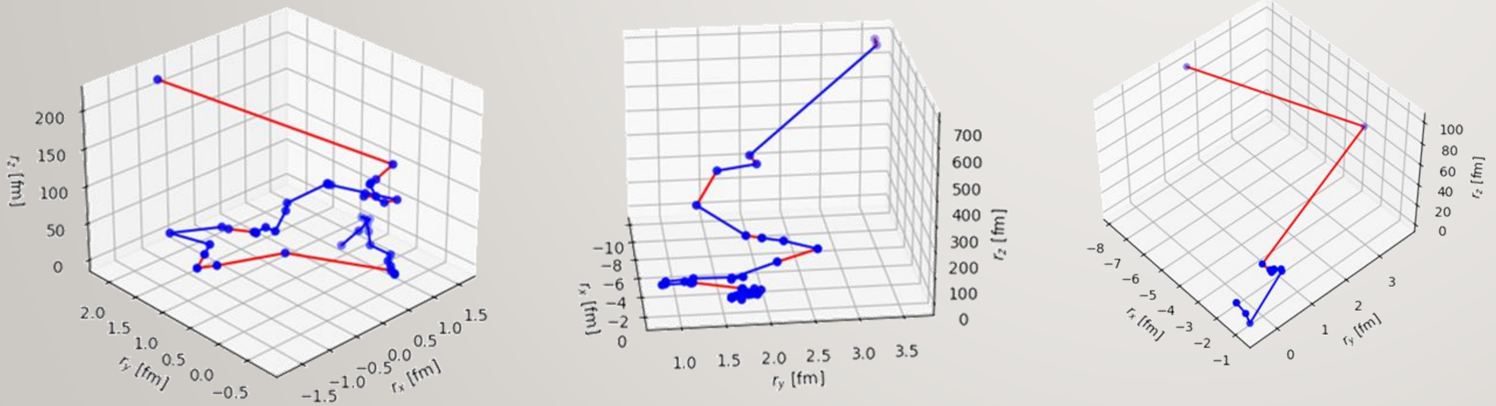


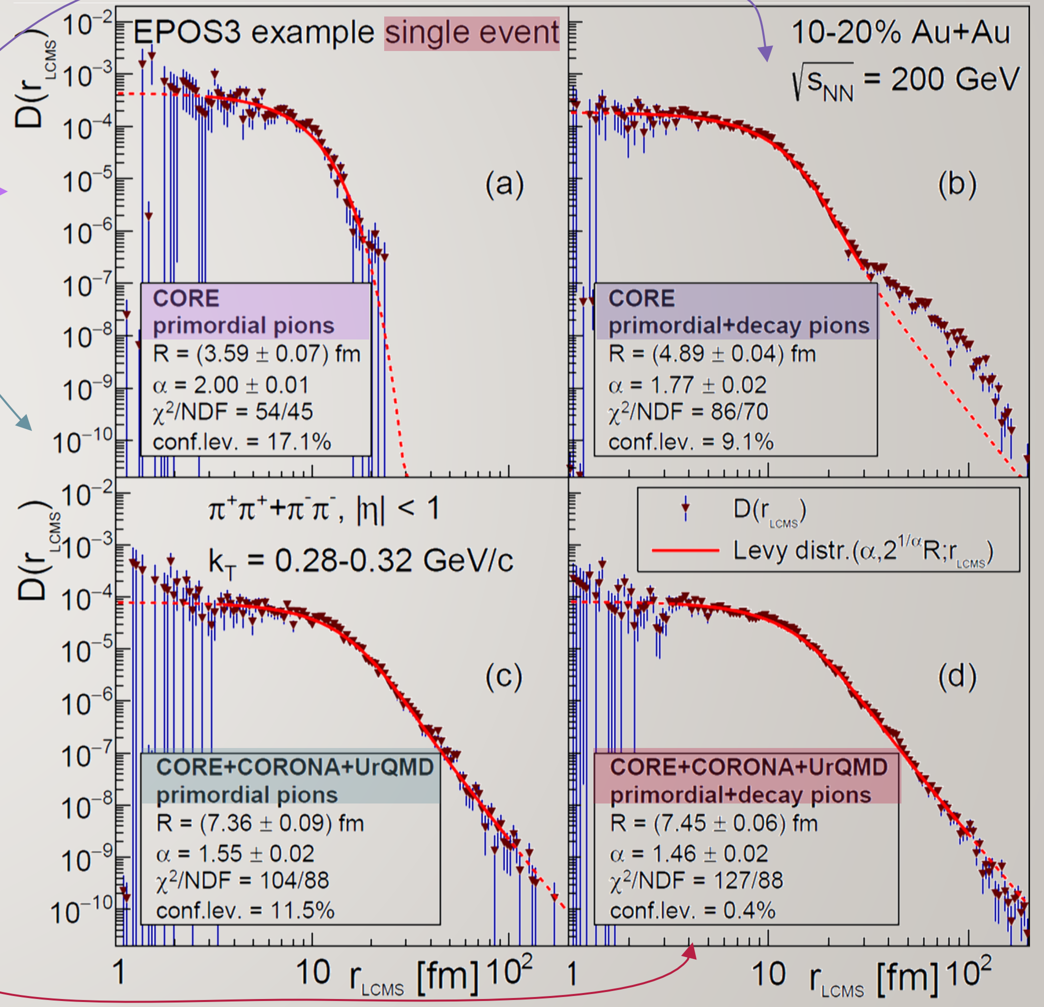
Figure 1. The Figure shows the step size distribution $p(\Delta r)$ of a random walk as performed by Coulomb interacting, diffusing particles in two dimensions. At large step sizes, the distribution clearly follows the $p \sim \Delta r^{-3}$ power-law which leads to the superdiffusive dynamics described by Eq. (1). The data was obtained by integrating the system of coupled Langevin equations of Eq. (56).



LÉVY SHAPES IN SINGLE EPOS EVENTS, 1D

- EPOS model: parton-based Gribov-Regge theory (PBGRT)
  - Werner et al., PRC82 (2010) 044904, PRC89 (2014) 064903, …
- Source observed in four stages:
  a) CORE, primordial pions: close to Gaussian
  b) CORE, with decay products: power-law structures
  c) CORE+CORONA+UrQMD, primordial pions: Lévy shape
  d) CORE+CORONA+UrQMD, with decay products: Lévy shape
  - Radii in the four stages (one example event)
    3.59 fm → 4.89 fm → 7.36 fm → 7.45 fm
  - Shape (α) change: 2.00 → 1.77 → 1.55 → 1.46
- **Scattering stage needed for Lévy shaped sources**
- Can one relate the observed HBT radii to the hydro phase homogeneity lengths?

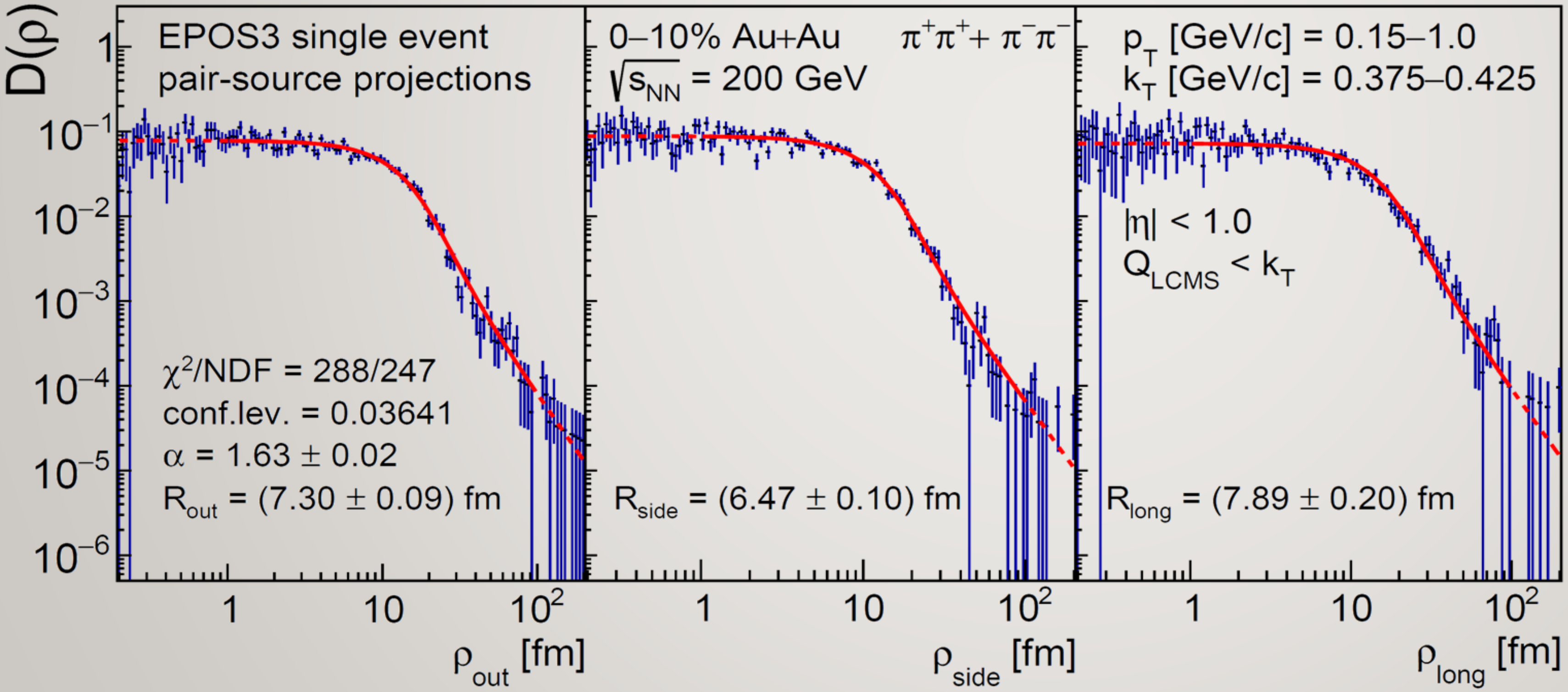
arXiv:2201.07962

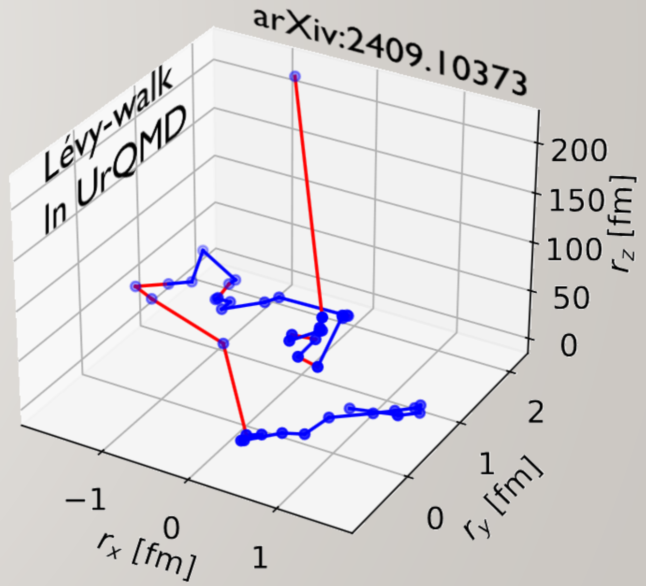


LÉVY SHAPES IN SINGLE 3D EPOS EVENTS, 3D

- What if the Lévy shapes appeared only because of directional averaging?
- Let's check 3D event shapes in EPOS! → Also Lévy, with similar α and radii (as those in 1D)
- Clear physical reason: Lévy walk

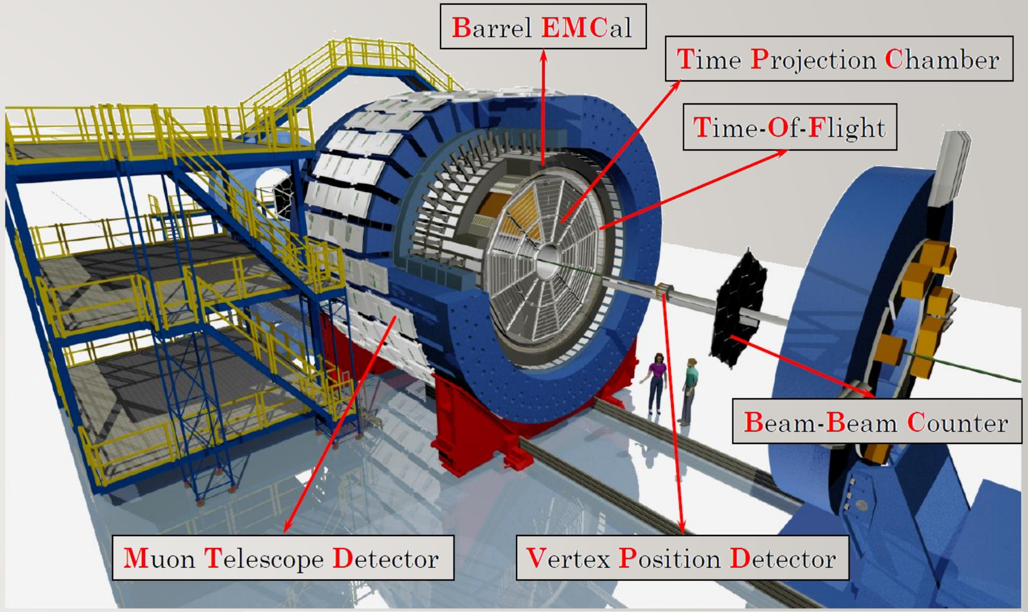
arXiv:2409.10373

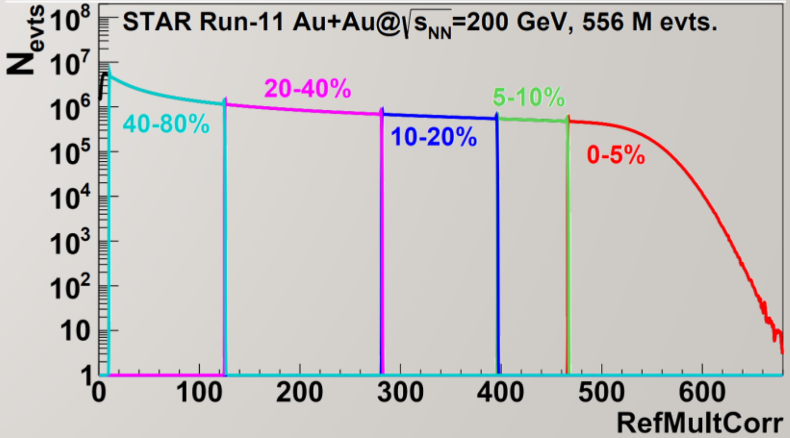




STAR FEMTOSCOPY ANALYSIS SETUP

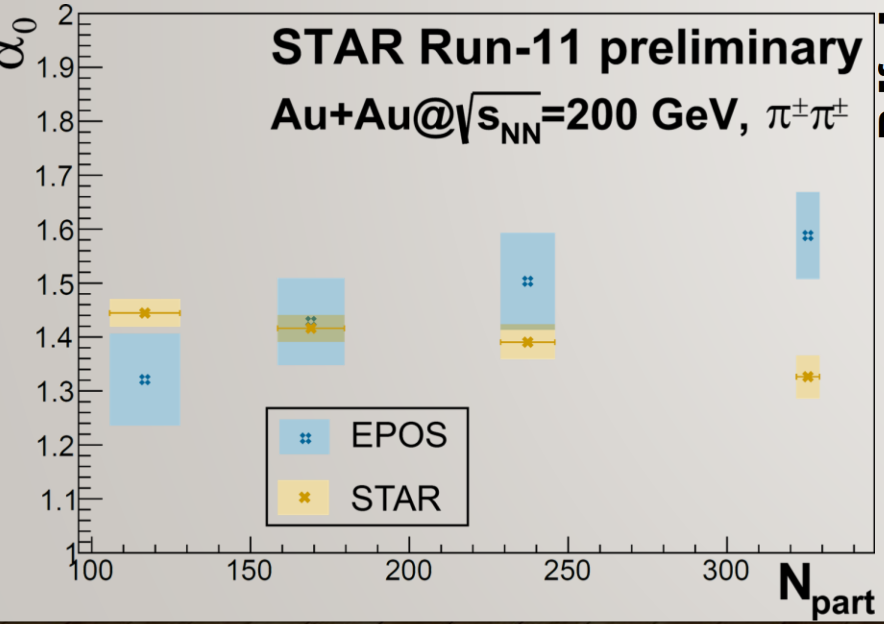
- Detectors used for the analysis:
  - BBC, TPC, VPD: centrality, vertex position
  - TPC: tracking, dE/dx Particle Identification (PID)
  - TOF: time-of-flight PID
- Event selection:
  - Vertex cuts on v^{TPC} and v^{VPD}
  - Pile-up removal using TOF vs. TPC multiplicity
- Track selection:
  - Combined PID using TPC and TOF
  - Momentum selection: $p_T = 0.15 - 1.0$ GeV/c
  - Rapidity selection: $|\eta| < 0.75$
  - Quality cuts on TPC number of hits and DCA
- Pair selection: Splitting Level and Fraction of Merged Hits cuts
  - Additional cut on average pair separation in TPC pad rows

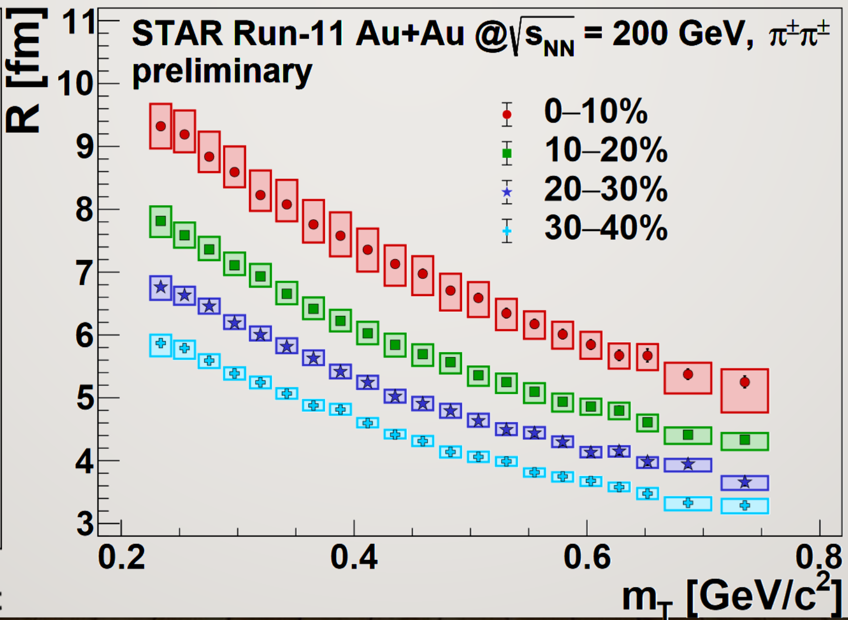


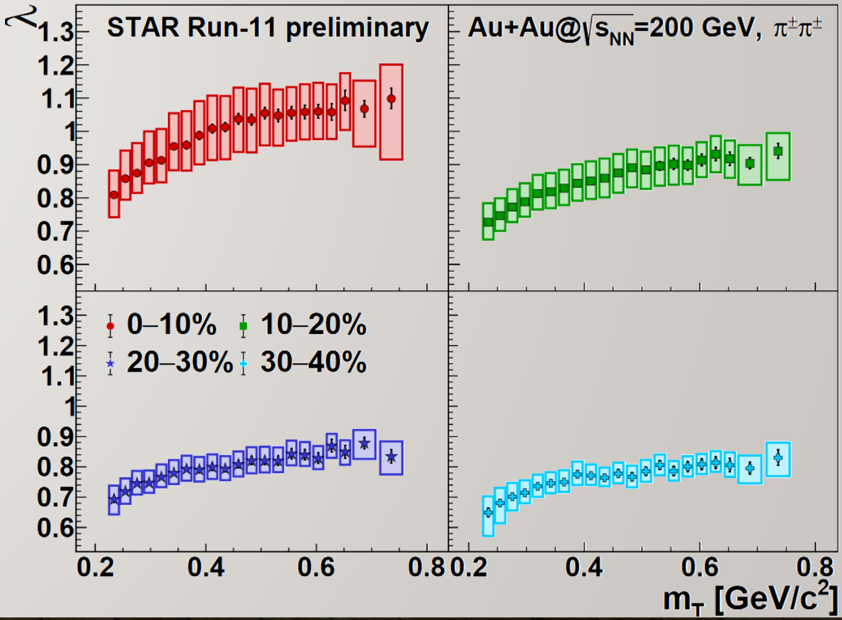


CENTRALITY DEPENDENCE AT 200 GEV

- Lévy scale R: decreasing trend with m_T and with centrality
  - Connection to flow and initial geometry, similarly to Gaussian radii
- Lévy exponent α: EPOS quantitatively close, largest discrepancy for central collisions
  - Effect of Coulomb scattering? PRB103(2021)235116, arXiv:2410.15525
- Correlation strength λ: increase from low to high m_T and from peripheral to central collisions
  - m_T dependence: might attributed to modified in-medium η' mass? PRL81(1998)2205, PRL105(2010)182301, arXiv:2407.08586

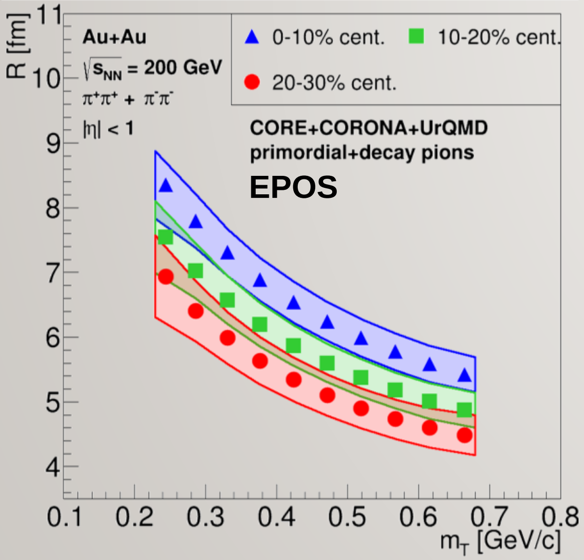


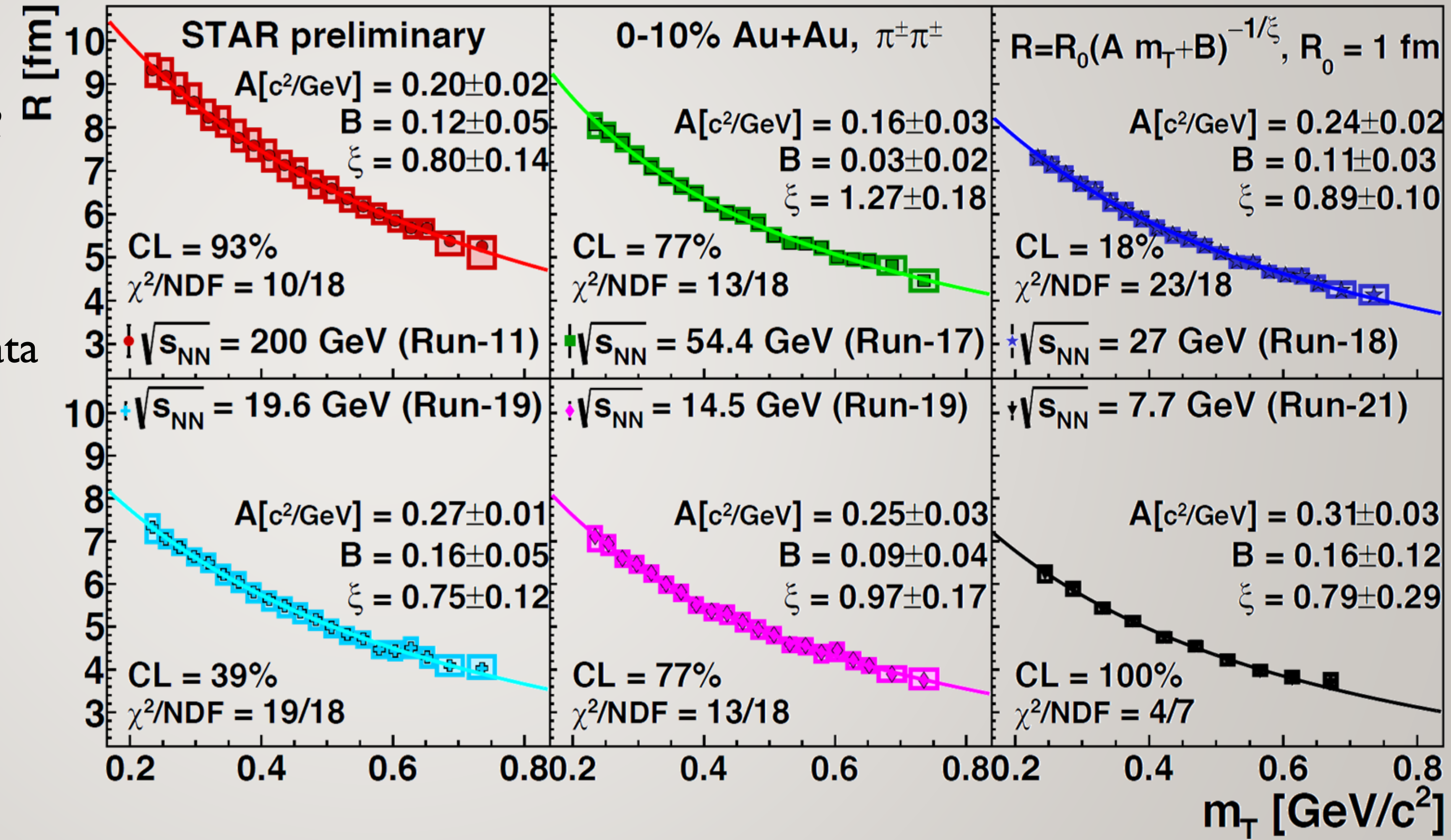




RESULTS AT COLLIDER ENERGIES: 7.7 TO 200 GEV

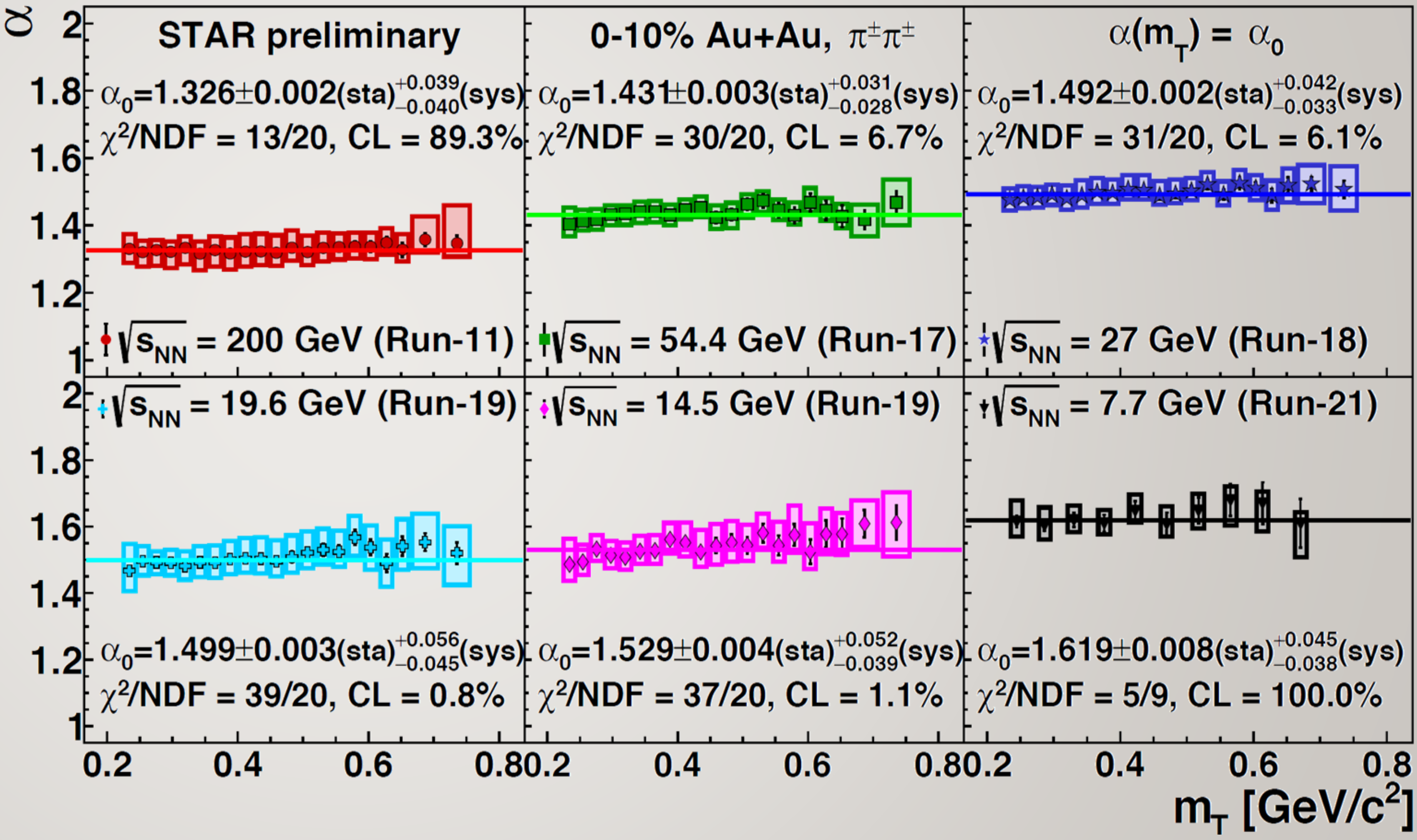
- Slow decrease with $\sqrt{s_{NN}}$ from 200 to 7.7 GeV
  - Same trend as Gaussian R
- Decrease in R with m_T
  - Connection to flow
- 200 GeV: EPOS close to data





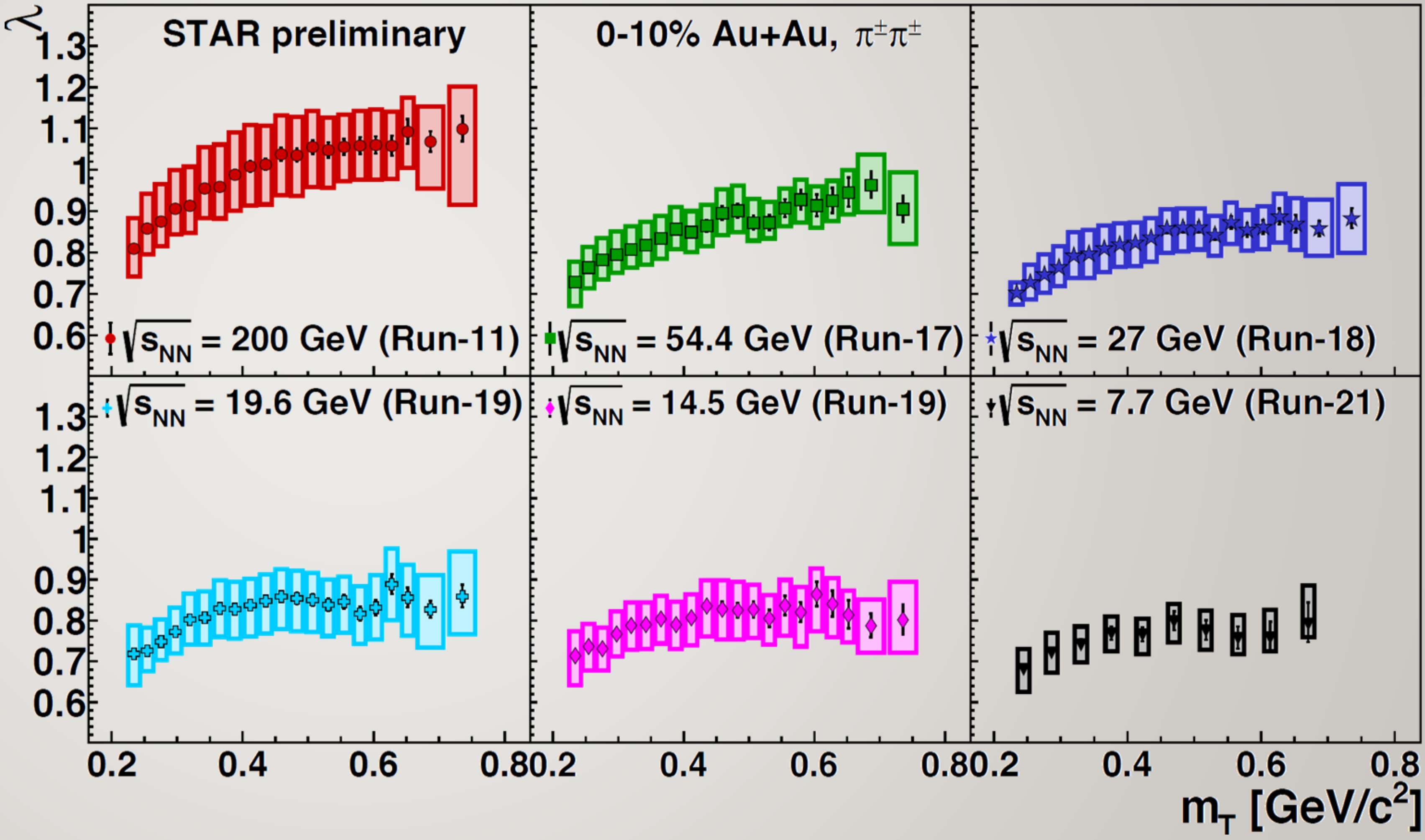
RESULTS AT COLLIDER ENERGIES: 7.7 TO 200 GEV

- Small, smooth increase in α with $\sqrt{s_{NN}}$ from 200 to 7.7 GeV
  - Connection to decreased density?
- No strong dependence on m_T
- Average α
  - ≈1.33 at 200 GeV
  - ≈1.62 at 7.7 GeV
- Significantly below 2.0 and above 1.0



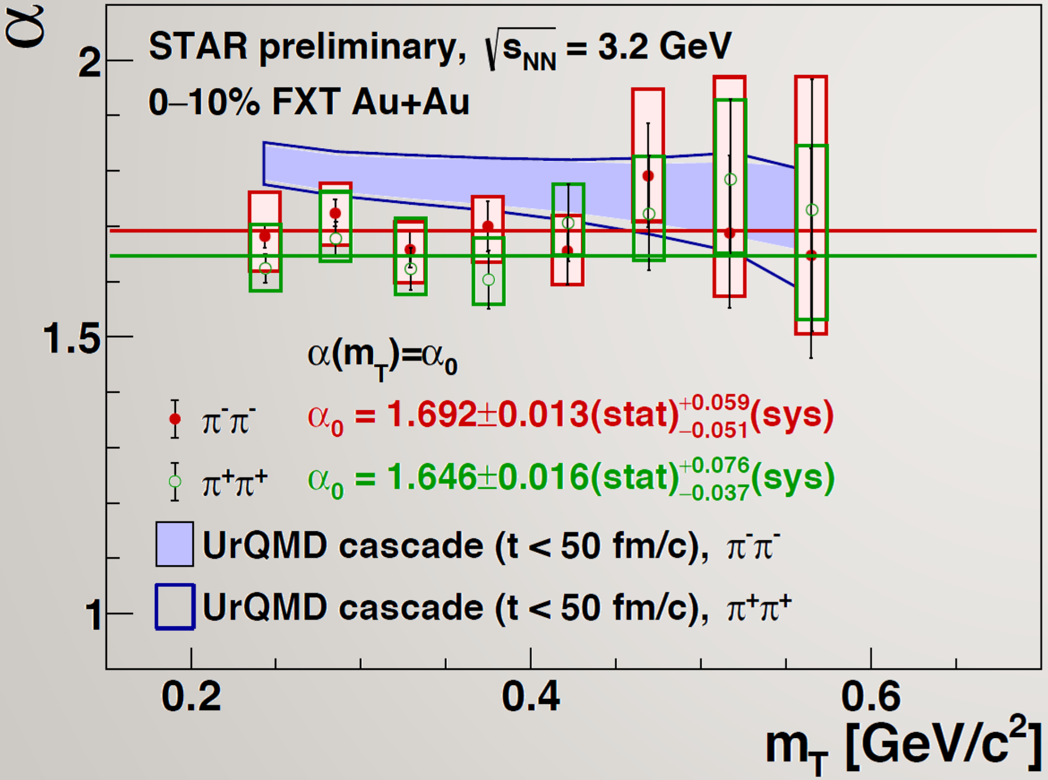
RESULTS AT COLLIDER ENERGIES: 7.7 TO 200 GEV

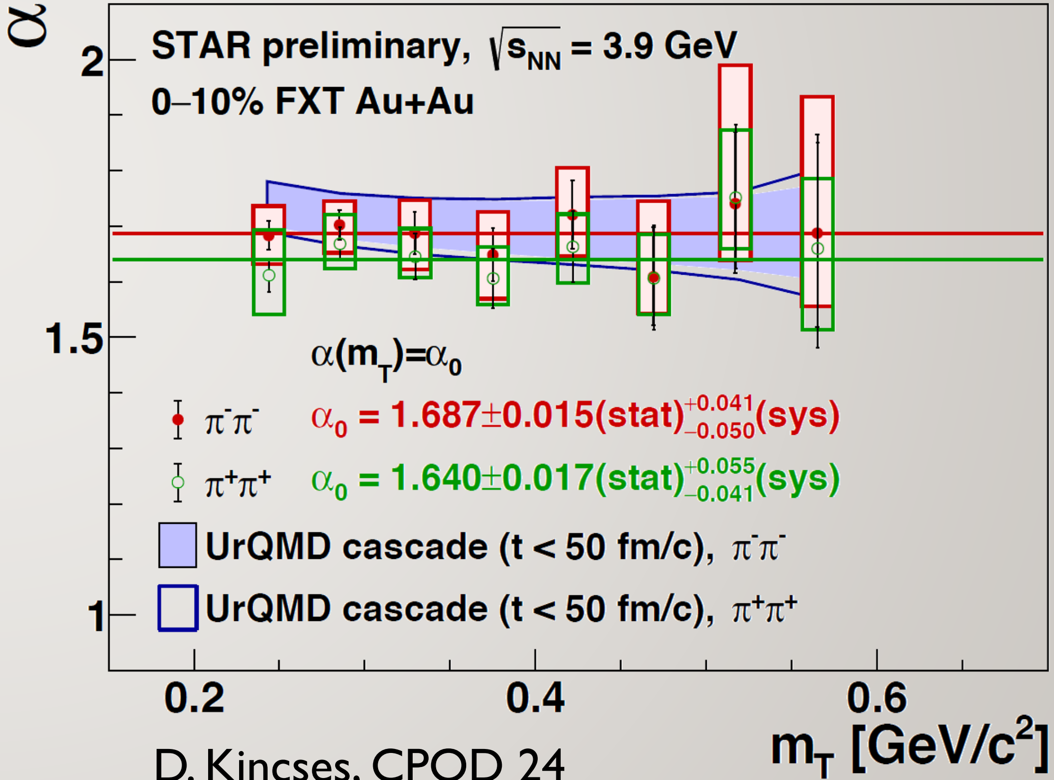
- Clear decrease in λ with $\sqrt{s_{NN}}$ from 200 to 7.7 GeV
  - Decrease in multiplicity
  - Larger role of halo
- Decrease towards small m_T values
  - Increase in halo for small m_T
  - Attributed to **modified in-medium η' mass** in literature



FIXED TARGET ENERGIES: 3.2 AND 3.9 GEV

- Non-Gaussian values ($\alpha < 2$); small systematic difference between $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs
- 3.9 and 3.2 GeV compatible, no m_T dependence observed
- UrQMD within uncertainties – no other effect but rescattering and decays, good agreement (t<50 fm/c!)

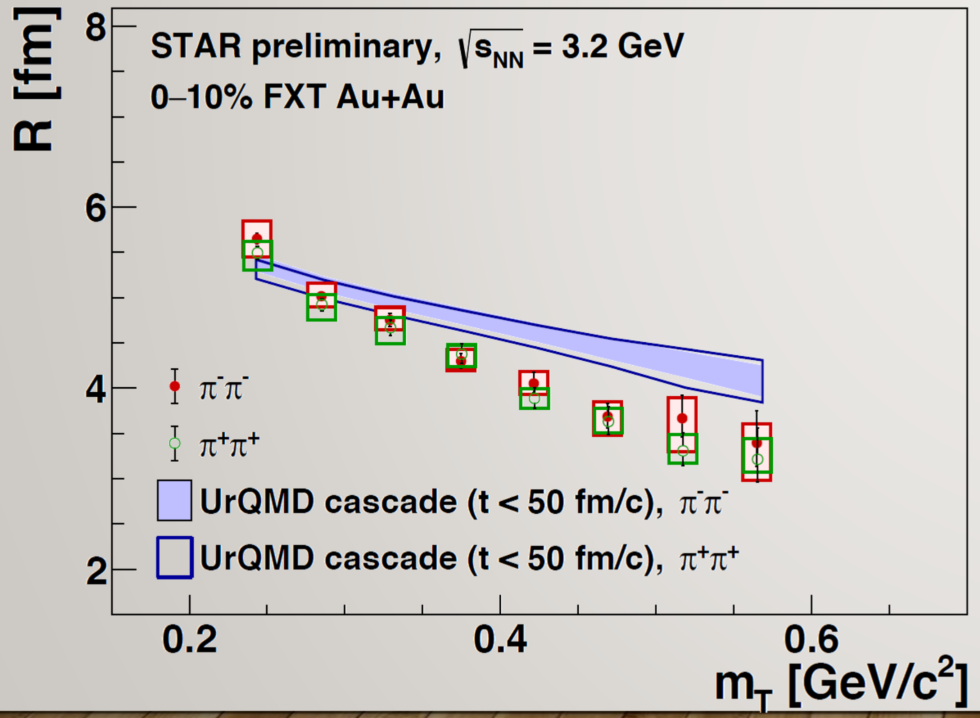


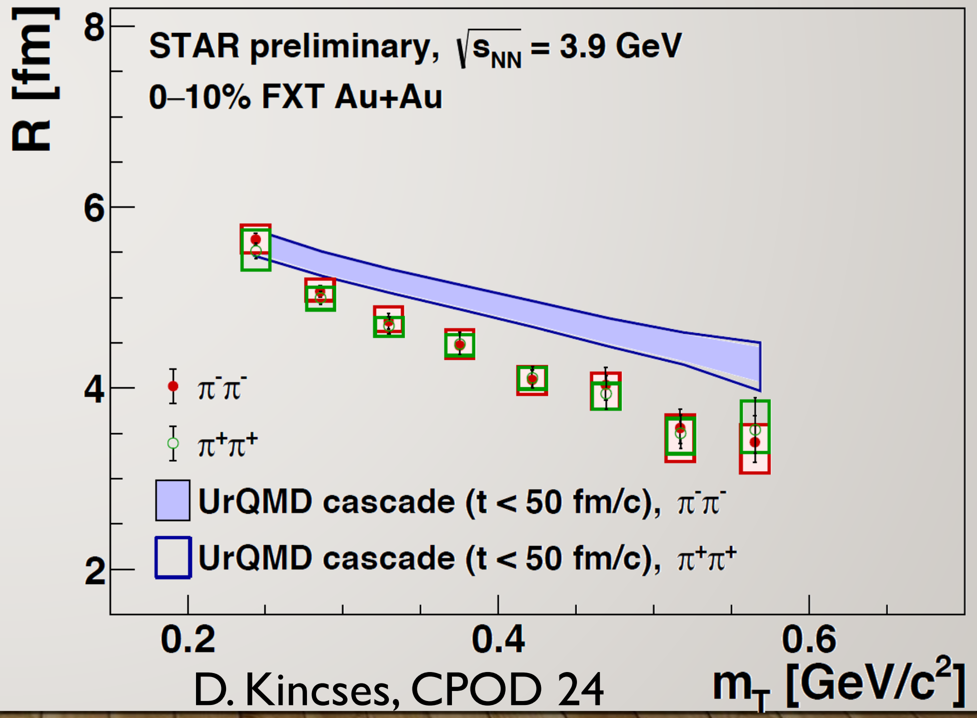


D. Kincses, CPOD 24

LÉVY SCALE R AT FXT ENERGIES

- Decreases towards higher m_T and lower energies
- Small systematic difference between $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs
- Two FXT energies compatible
- UrQMD describes the trends qualitatively well, moderate quantitative mismatch, but ran only until 50 fm/c



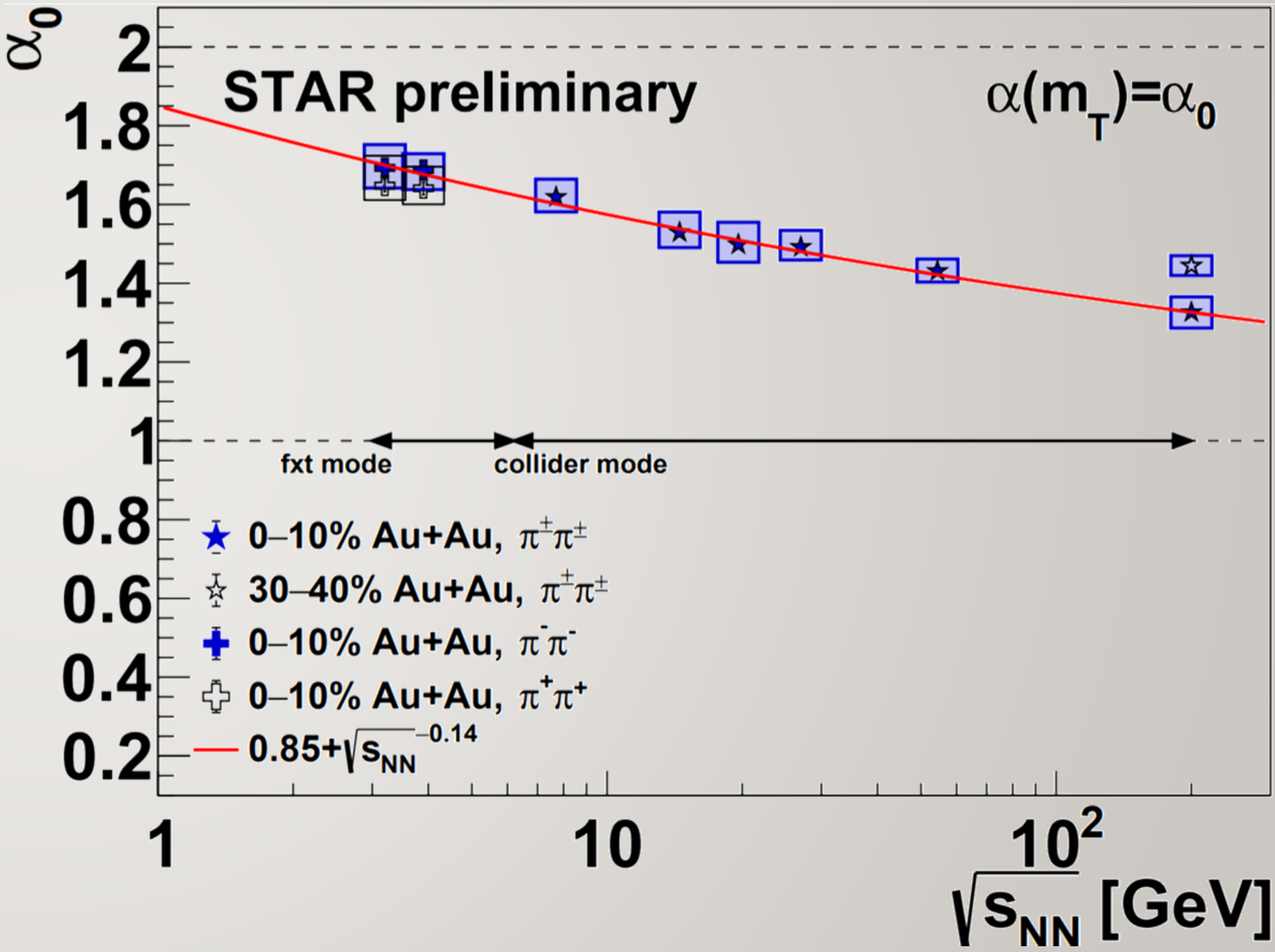


D. Kincses, CPOD 24

LÉVY EXPONENT FROM 3.2 TO 200 GEV

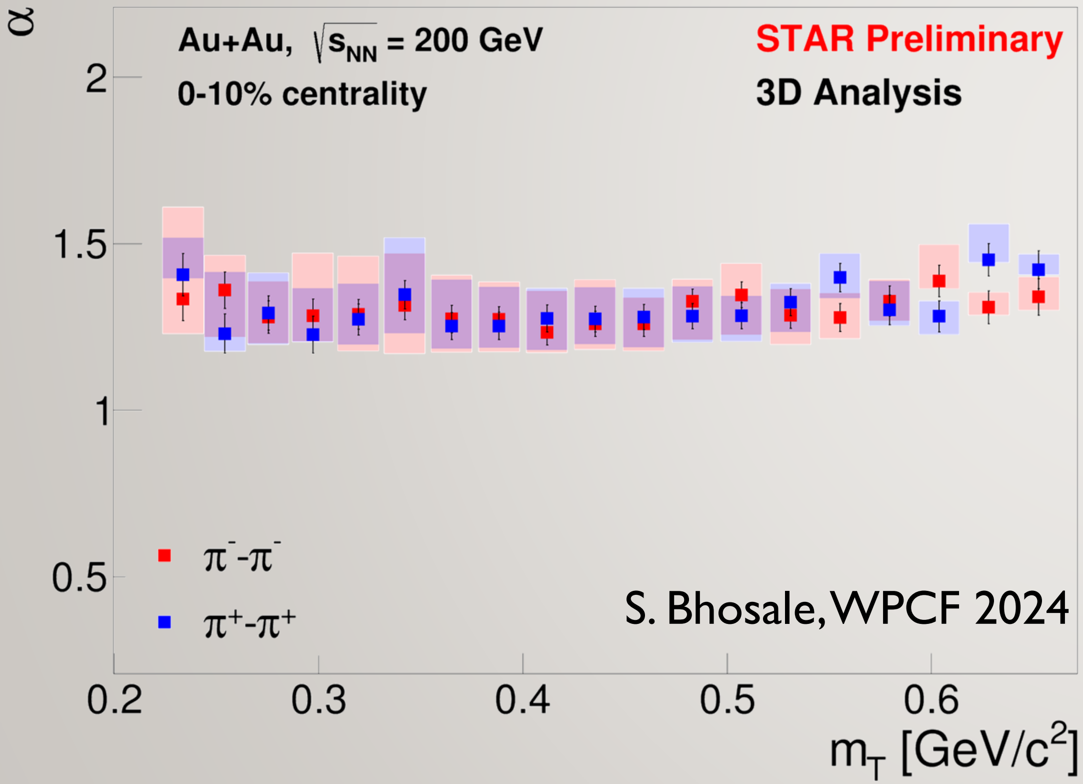
- Non-gaussian values ($\alpha \ll 2$)
- Increasing density → rescattering decreases α?
- 200 GeV centrality dependence, same trend:
  - Larger α for peripheral collisions
- Trend illustrated by power-law:
  $\alpha_0 \approx 0.85 + \sqrt{s_{NN}}^{-0.14}$
- Good description by UrQMD at FXT energies, comprehensive energy scan is ongoing
- No non-monotonic trend in α observed yet, far from conjectured critical value (0.5)

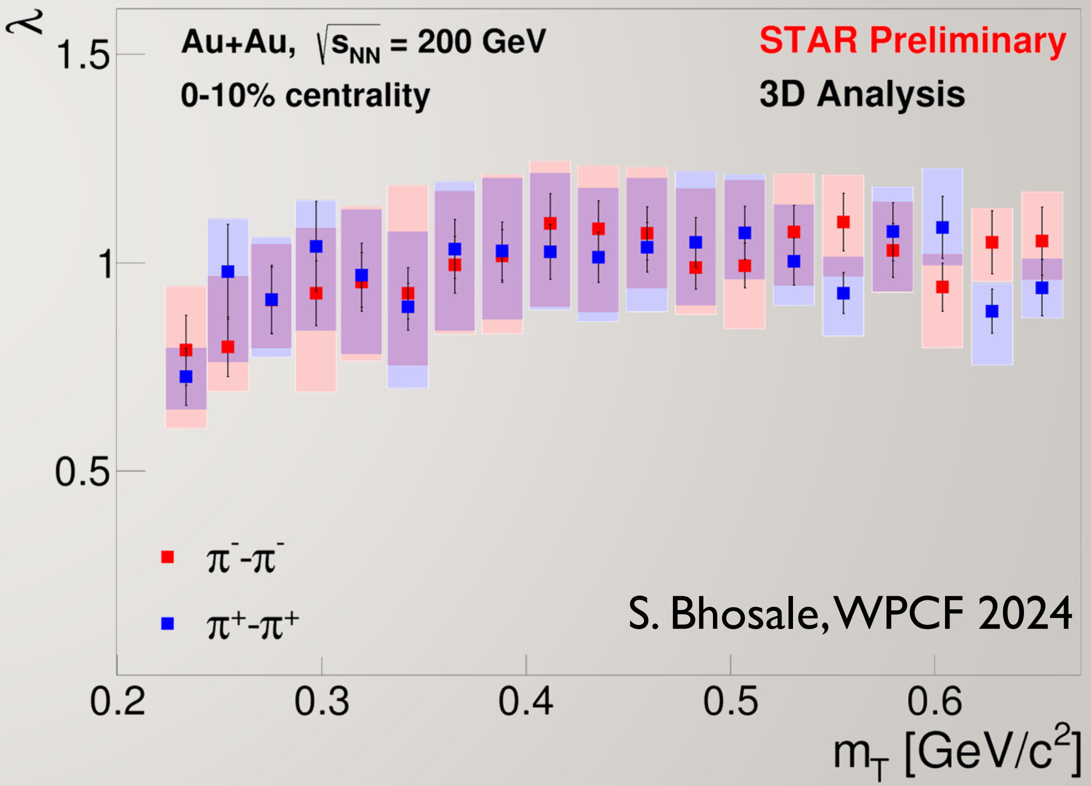
D. Kincses, CPOD 24



LÉVY FEMTOSCOPY IN 3D AT 200 GEV

- Lévy exponent α: negligible dependence on m_T, average value ~1.3
  - Far from critical value (0.5), Cauchy (1.0), and Gauss (2.0).
- Correlation strength λ: small increase from low to high m_T, can be attributed to resonance ratio changes

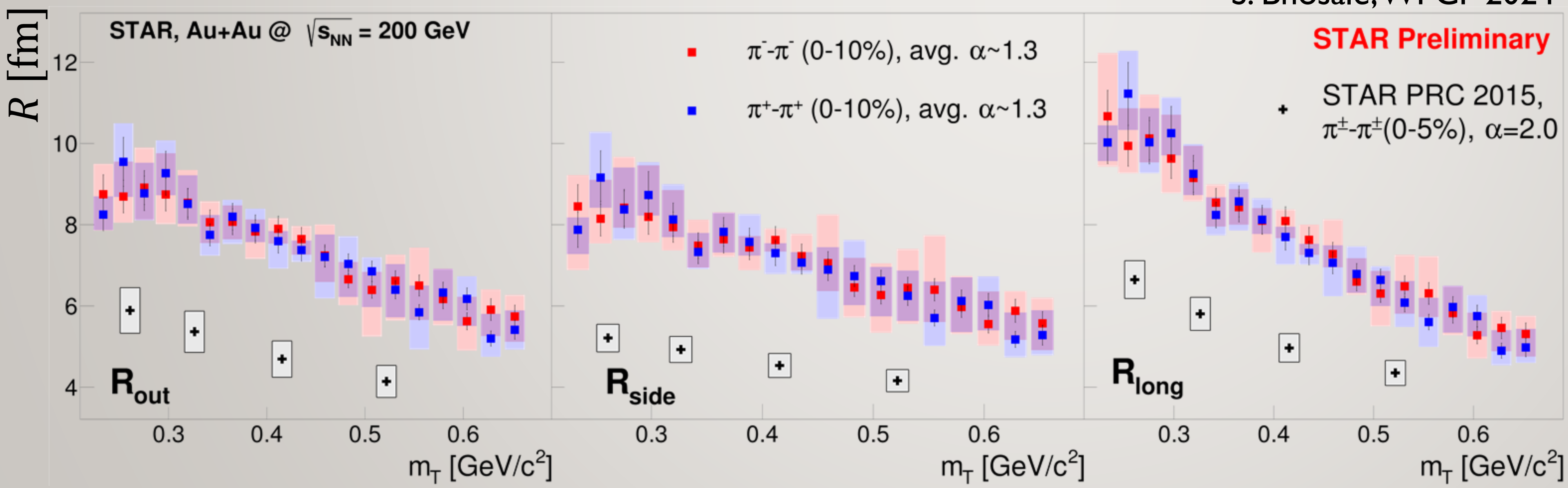




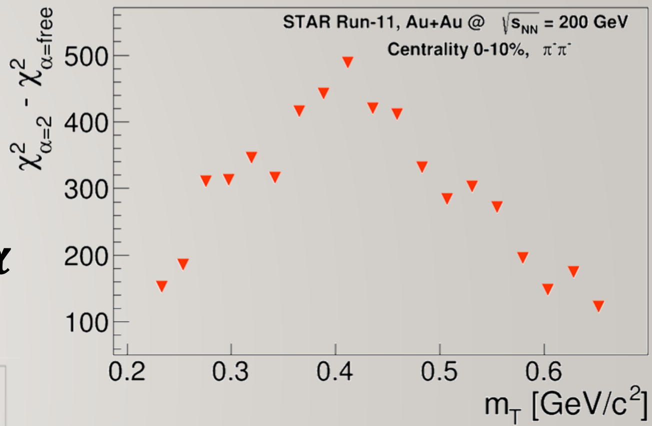
SOURCE RADII: 3D LÉVY MEASUREMENT VS GAUSSIAN

- Lévy-scale R: usual decreasing trend with m_T
- Free α fits reduce χ^2 by 200-500 units compared to Gaussian fits
- χ^2/NDF values within 1-1.04 for all fits
- Confidence levels (p-values) improve by 1-3 orders of magnitude with free α

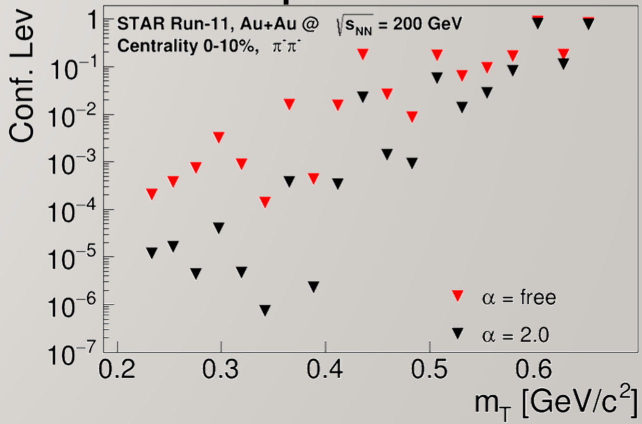
S. Bhosale, WPCF 2024



χ^2 difference



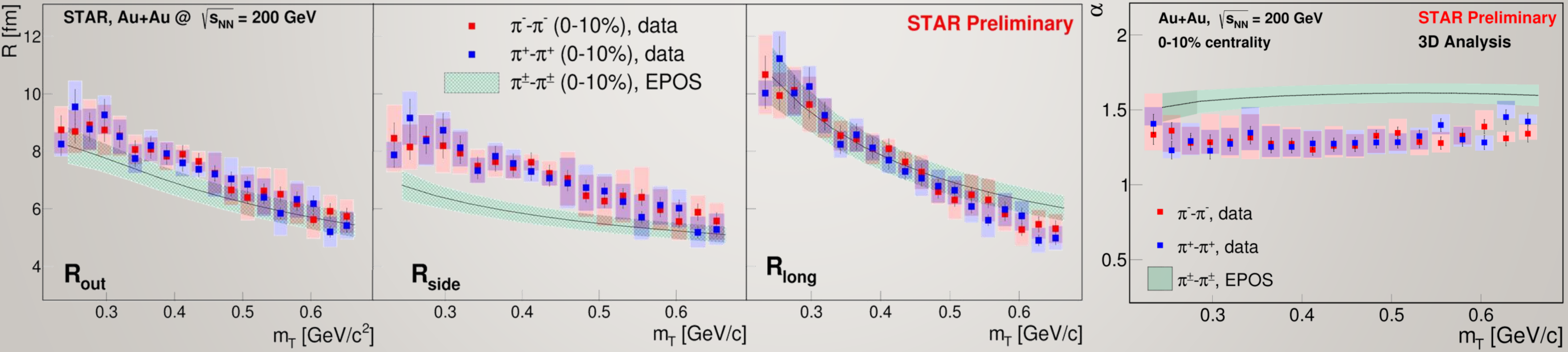
fit p-values



EPOS COMPARED TO STAR 3D PRELIM. DATA AT 200 GEV

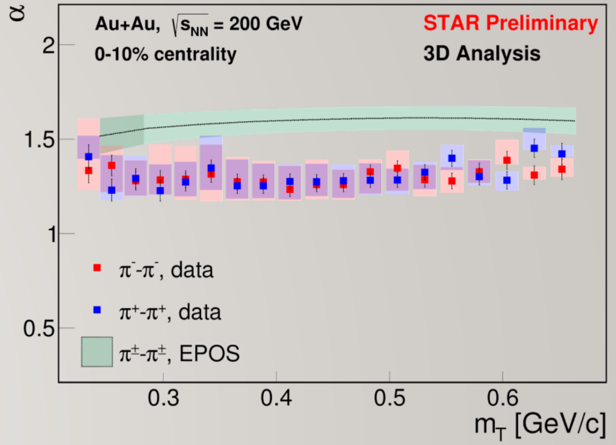
- EPOS and data (both from 3D analysis) comparison shows good agreement for radii
  - EPOS analysis described in arXiv:2409.10373
- Moderate discrepancy for R_{side} and α: maybe due to long-range Coulomb scattering (not in EPOS)
  - See effect of Coulomb potential in a 2D solid-state physics paper: E. I. Kiselev, Phys. Rev. B 103, 235116 (2021)

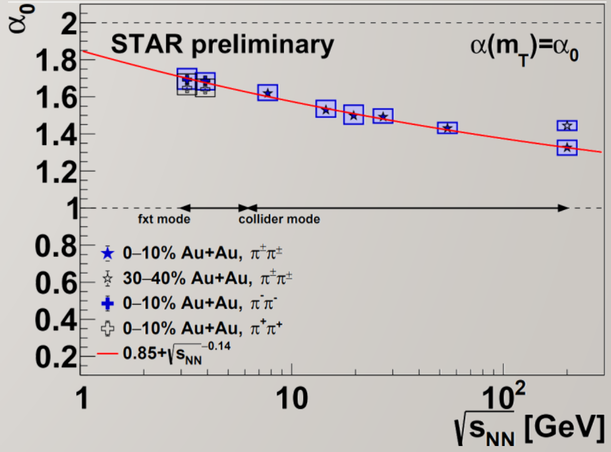
$R_{o,s,l}$ vs m_T S. Bhosale, WPCF 2024 α vs m_T

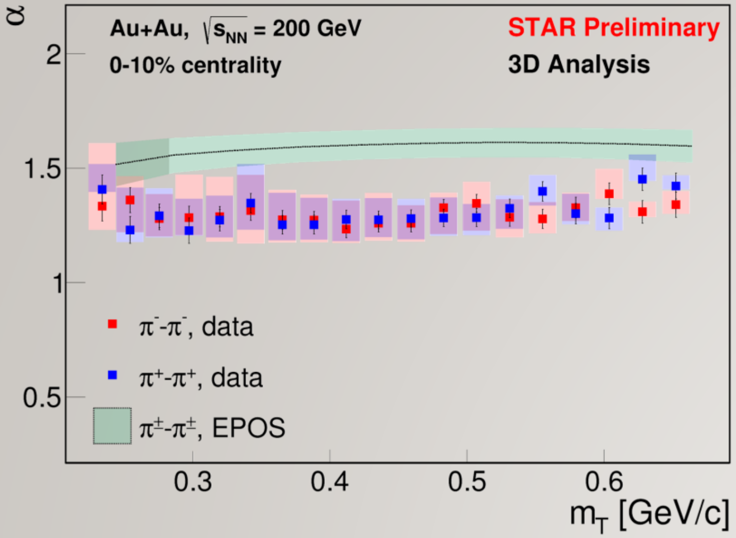


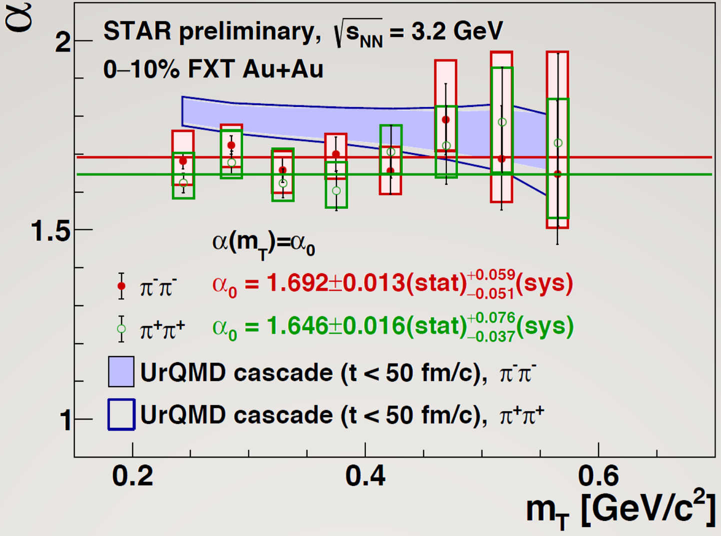
CONCLUSIONS AND OUTLOOK

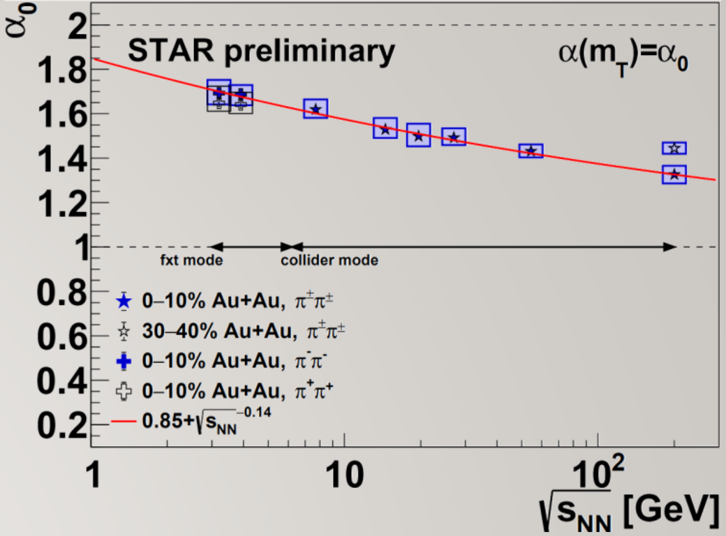
- Lévy parameters for pions measured from 3.2 to 200 GeV with STAR
  - **Lévy α**: between 1 and 2, decrease with $\sqrt{s_{NN}}$, constant with m_T
  - ***R***: decrease with m_T, similarly to Gaussian radii
    - Relation to Gaussian through HWHM/HWHI
  - λ: decrease at low m_T, overall increase with $\sqrt{s_{NN}}$
- Possible reasons for power-law tails and Lévy sources:
  - **Critical phenomena** → **no** non-monotonicity seen in α vs s_{NN}, more energies to be investigated
  - **Resonance decays** → part of the reason, predicts larger α
  - **Hadronic scattering, Lévy walk** → close to measurements
- Questions to be answered:
  - EoS (& model) dependence of α and $R^2_{out} - R^2_{side}$ vs $\sqrt{s_{NN}}$
  - What collision energy dependence do models predict?











THANK YOU FOR YOUR ATTENTION