PION FEMTOSCOPY WITH LÉVY SOURCES: RECENT DEVELOPMENTS

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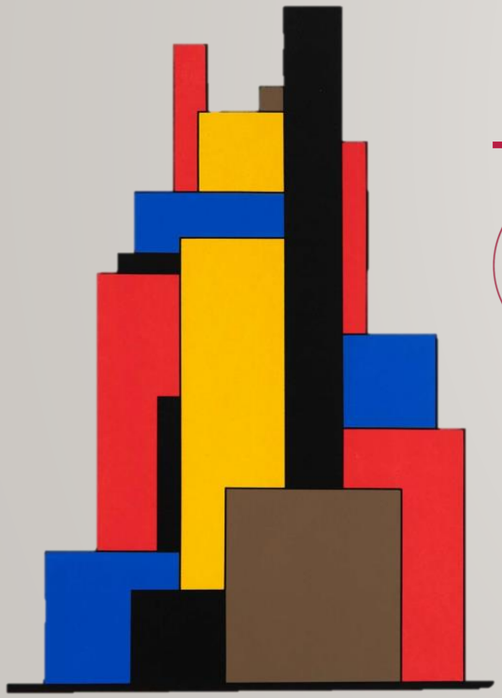
2024 ZIMÁNYI SCHOOL WINTER WORKSHOP



ZHI MAN YI

Overflowing with knowledge

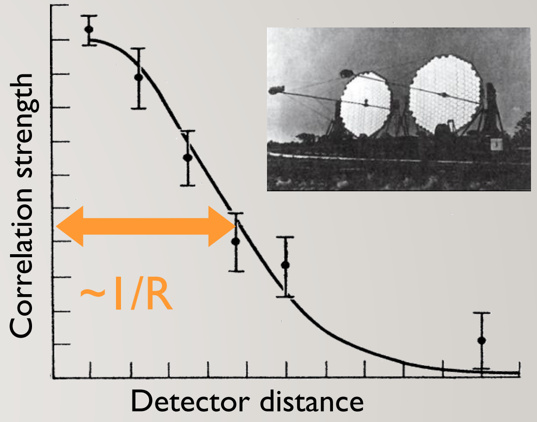
HBT OR FEMTOSCOPY IN HIGH ENERGY PHYSICS

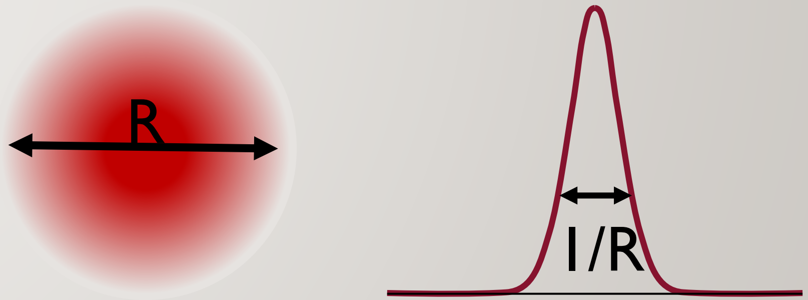
- R. Hanbury Brown, R. Q. Twiss - observing Sirius with radio telescopes
  - Intensity correlations vs detector distance ⇒ source size
  - Measure the sizes of apparently point-like sources!
- Goldhaber et al: applicable in high energy physics
- Understanding: Glauber, Fano, Baym, …
  Phys. Rev. Lett. 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

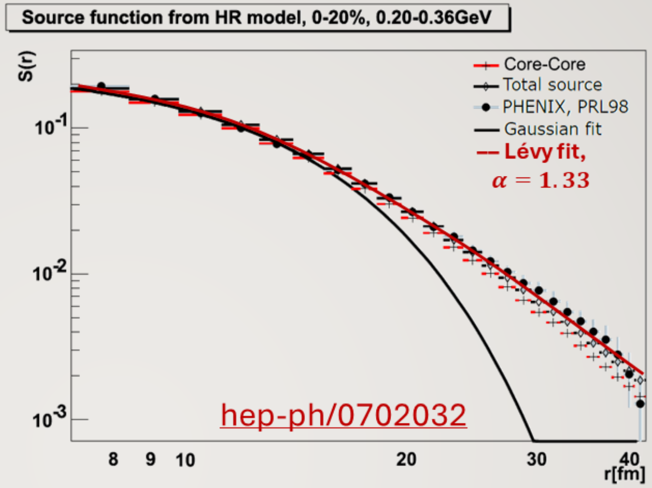
- Central limit theorem, diffusion, and thermodynamics lead to Gaussians
- Measurements suggest phenomena beyond Gaussian distribution
- Lévy-stable distribution:

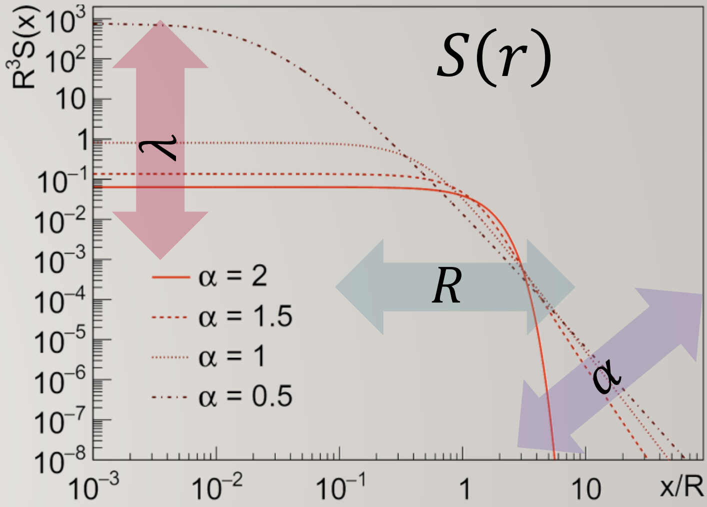
$$\mathcal{L}(\alpha, R; r) = \frac{1}{2\pi}\int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$$

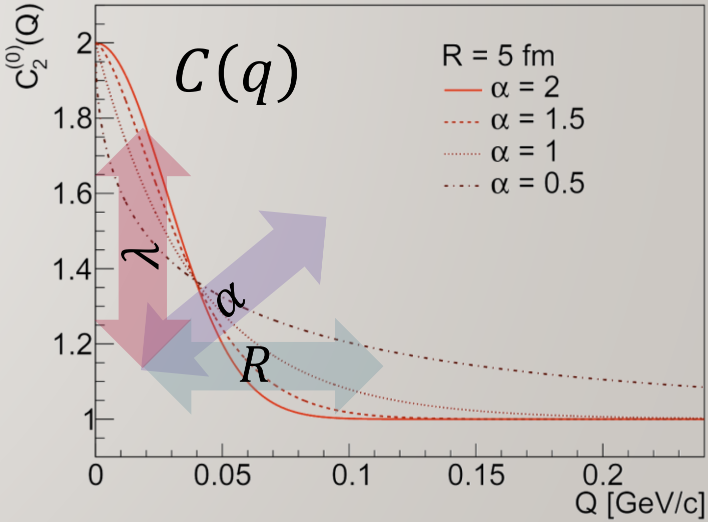
  - From generalized central limit theorem
  - Power-law tail $\sim r^{-1-\alpha}$
  - Special cases: α = 2 Gaussian, α = 1 Cauchy
- Shape of the correlation functions with Lévy source:
  - $C_2(q) = 1 + \lambda \cdot e^{-|qR|^\alpha}$; $\alpha = 2$: Gaussian; $\alpha = 1$: exponential

    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]

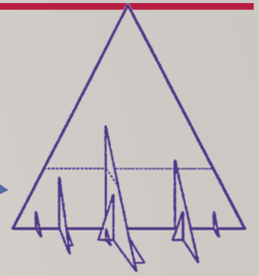


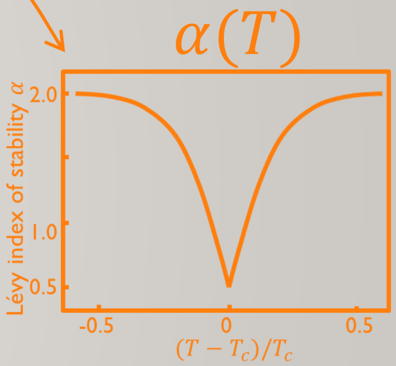


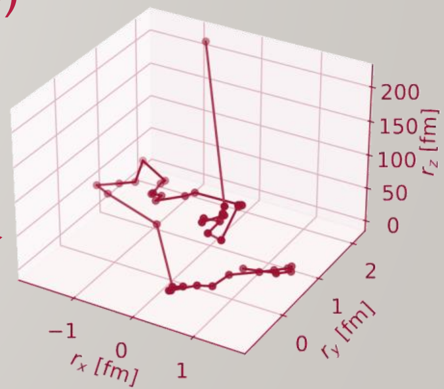


WHY DO LÉVY SHAPES APPEAR, WHY IS IT IMPORTANT?

- 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^- and other small systems
  - 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
- 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







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)

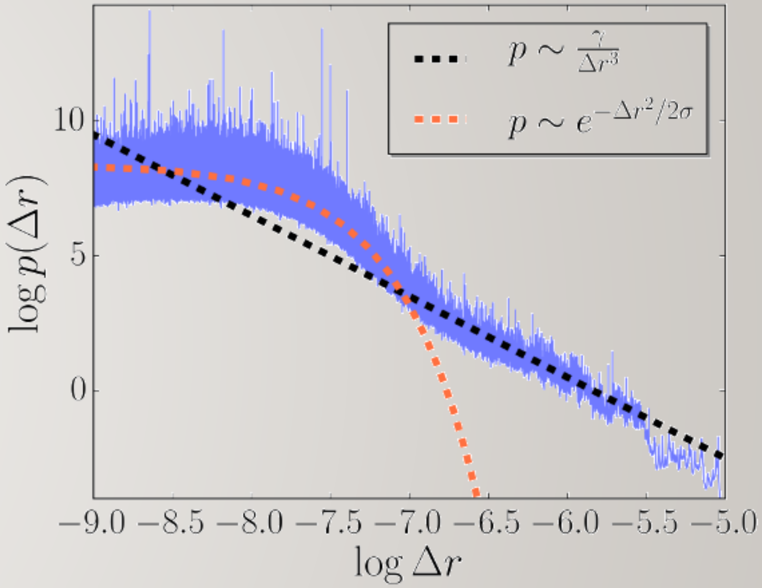
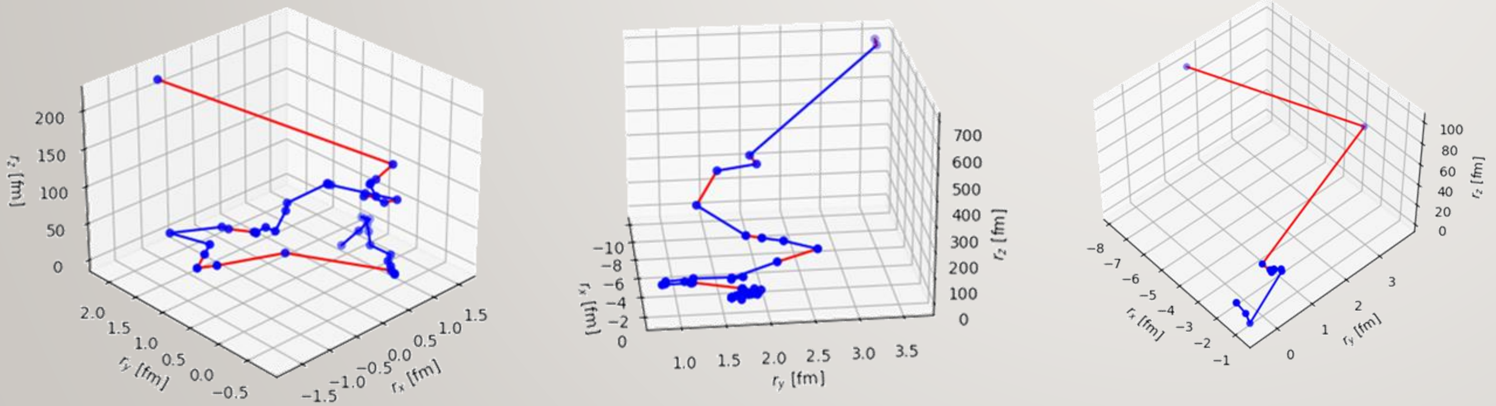
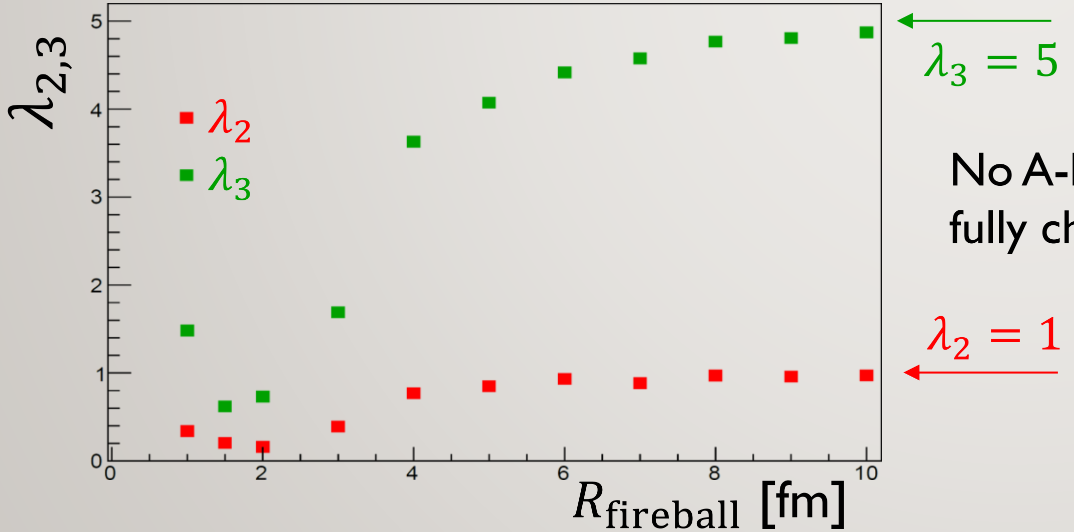


Figure 1. The Figure shows the step size distribution $p(\Delta r)$ of a random walk as performed by Coulomb interacting, diffusing particles in two dimensions. At large step sizes, the distribution clearly follows the $p \sim \Delta r^{-3}$ power-law which leads to the superdiffusive dynamics described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

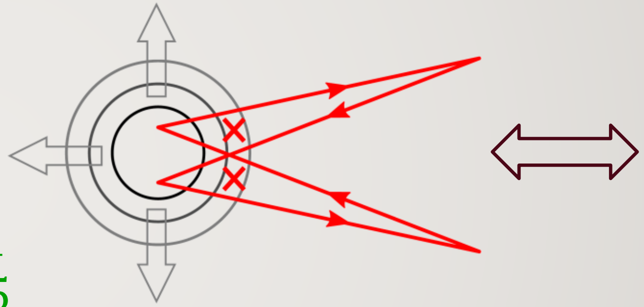


CHARGED CLOUD: ANOTHER INTERESTING EFFECT

- Coulomb potential: infinite range, affecting evolution for a long time
- Solid-state physics (as mentioned on previous slide): may cause Lévy flight and power-law tails
- Another interesting effect: distortion of flight paths after kinetic freeze-out
  - Phase shift, similarly to an Aharonov-Bohm effect (arXiv:2007.07167 and arXiv:2410.15525)
- Phase shift decreases correlation strengths

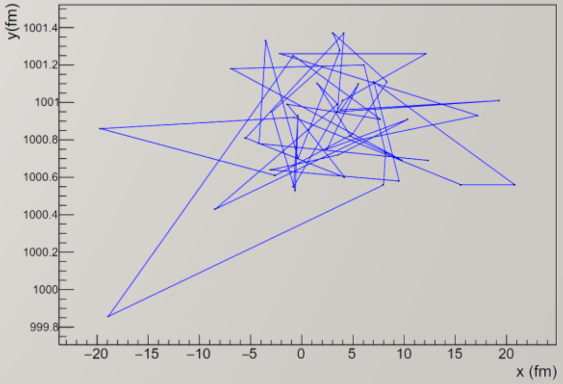


No A-B effect, pure core, fully chaotic source



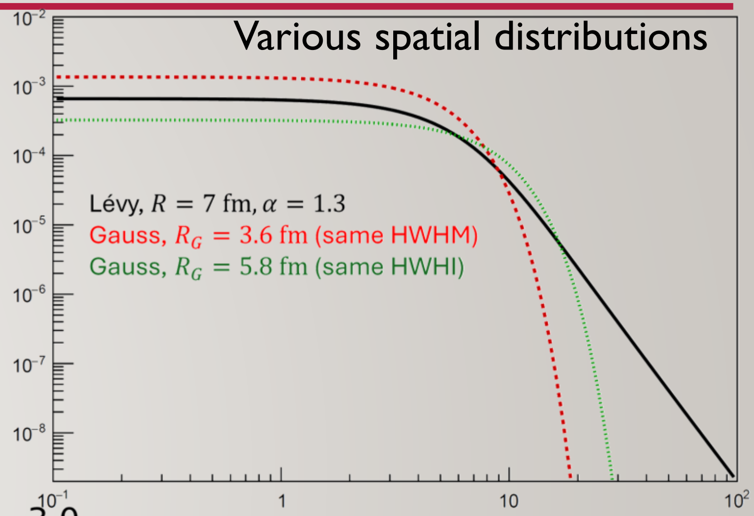
exaggerated illustration

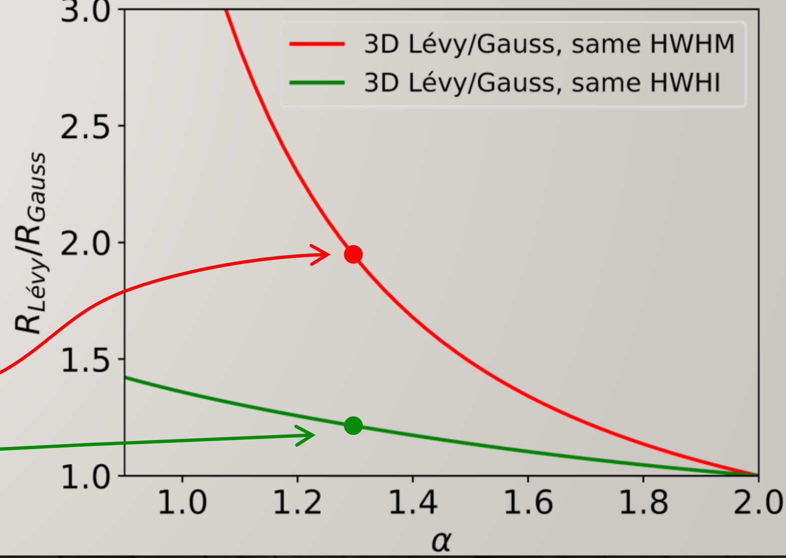
simulated transverse path



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.) $\alpha = 1.3$ and $R_L = 7$ fm "means":**
  - Same HWHM Gaussian: $R_G \approx 3.61$ fm ← $R_{Gauss} \approx R_{Lévy}/1.94$
  - Same HWHI Gaussian: $R_G \approx 5.77$ fm ← $R_{Gauss} \approx R_{Lévy}/1.21$

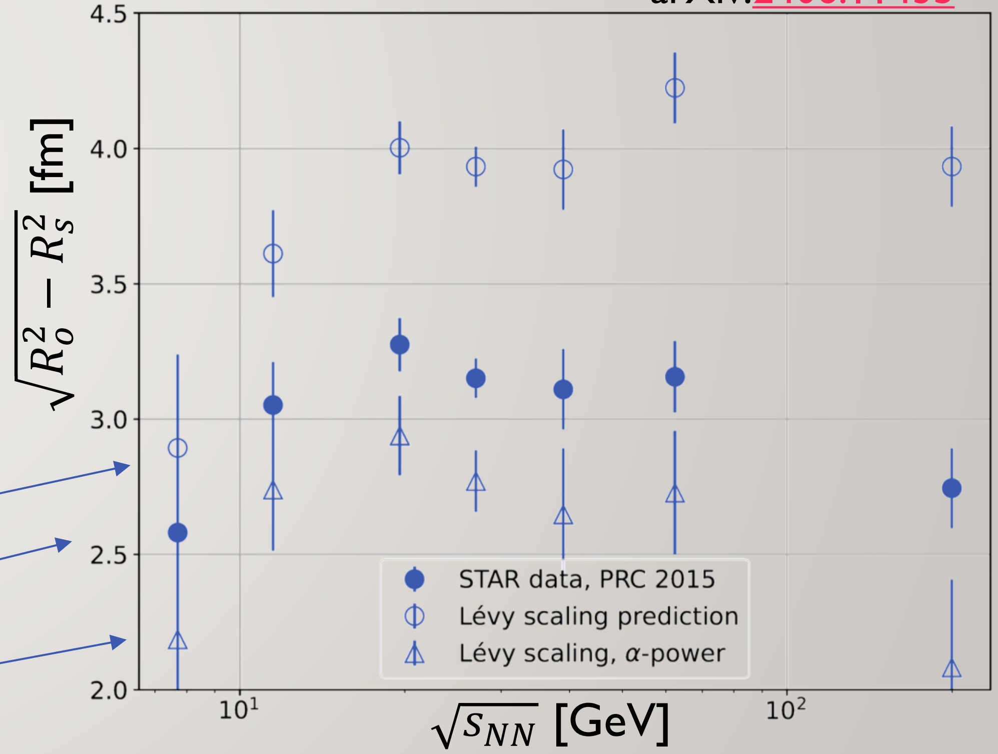




ENERGY DEPENDENCE OF LÉVY SOURCE SIZE?

- Experimental observation: $\hat{R} = \frac{R}{\lambda(1+\alpha)}$ doesn't depend on α → can estimate $R_{\text{free }\alpha} = R_{\text{Gauss}} \frac{\lambda_{\text{free }\alpha}(1+\alpha)}{\lambda_{\text{Gauss}}(1+2)}$
  - Assuming trends of α and λ as $A \cdot \sqrt{s_{NN}}^{B}$, with $A_\alpha = 1.85, B_\alpha = -0.06, A_\lambda = 0.6, B_\lambda = 0.06$
- Different trends of guesstimated $R_{\text{Lévy}}$ and R_{Gauss}
- Caused by shape change with $\sqrt{s_{NN}}$
- Connection of $\sqrt{R_o^2 - R_s^2}$ to emission duration: based on Gaussian sources,
- Maybe $(R_o^\alpha - R_s^\alpha)^{1/\alpha}$ for Lévy source,
  Csörgő, Hegyi, Zajc, EPJC36(2004)67
- Importance of measuring $R_{o,s,l}$ with free α

arXiv:2406.11435



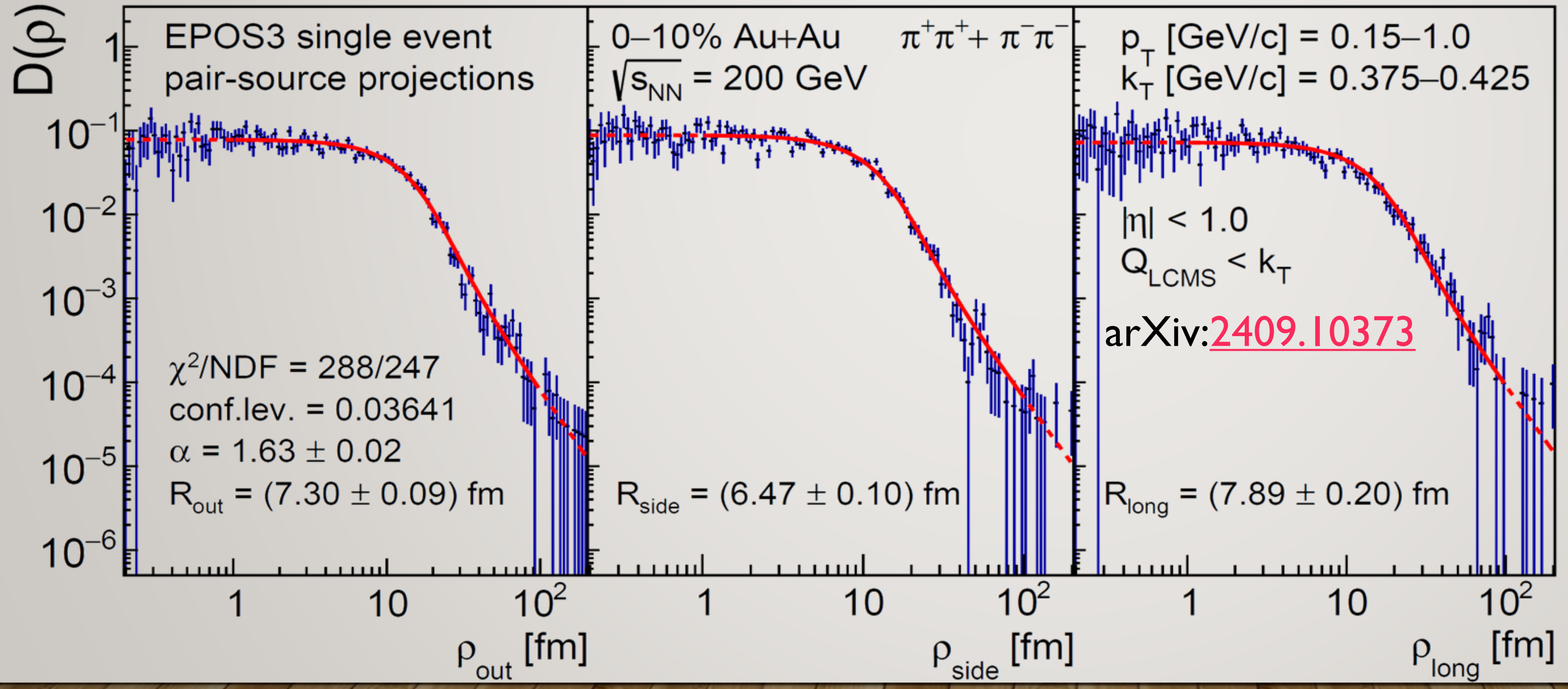
$\hat{R}$ scaling guesstimate for Lévy radii

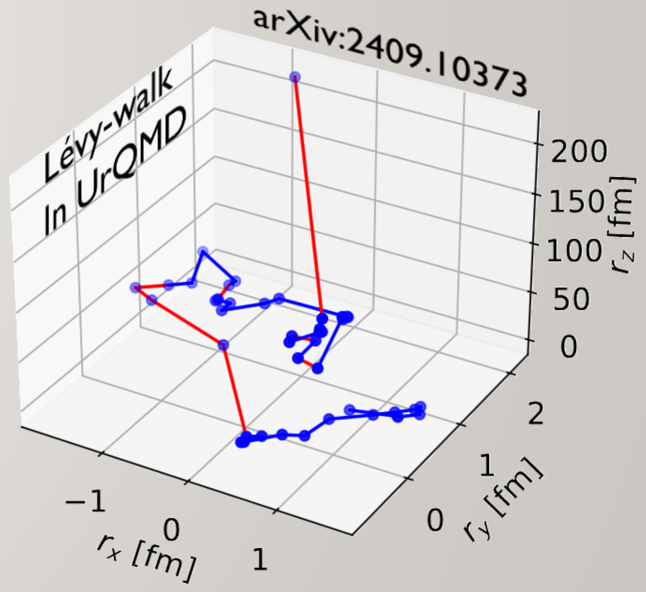
original Gaussian radii

α-powered version

LÉVY SHAPES IN SINGLE 3D EPOS EVENTS, 3D

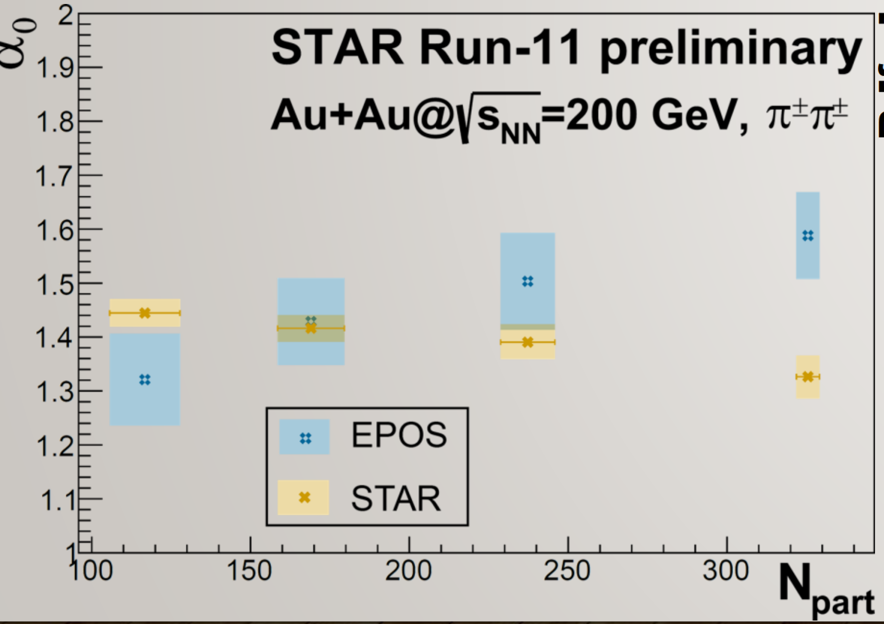
- What if the Lévy shapes appeared only because of directional averaging?
- Let's check 3D event shapes in EPOS! → Also Lévy, with similar α and radii (as those in 1D)
- Clear physical reason: Lévy walk, see poster/talk by D. Kincses on Thu

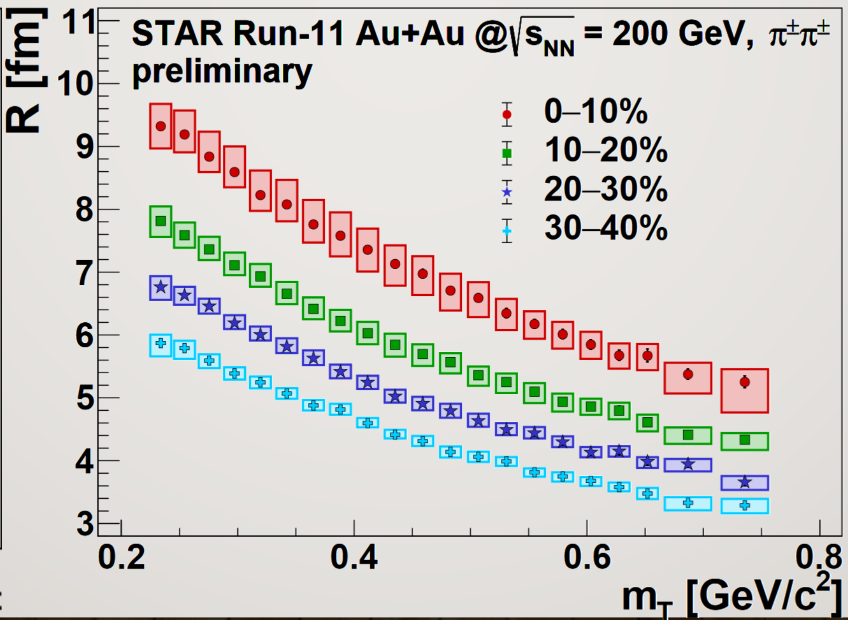


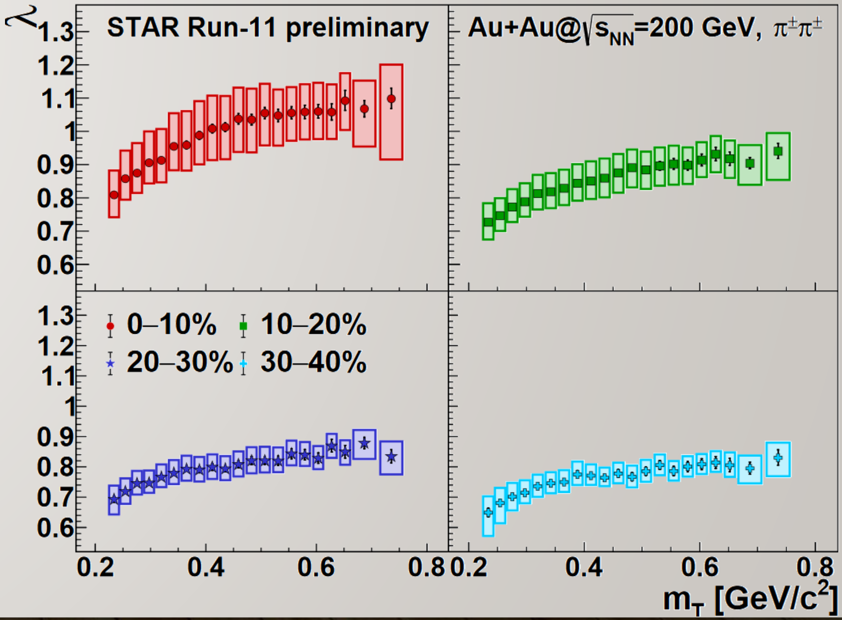


CENTRALITY DEPENDENCE AT 200 GEV

- 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: modified in-medium η' mass? PRL81(1998)2205, PRL105(2010)182301, arXiv:2407.08586 (see next talk by S. Lökös)

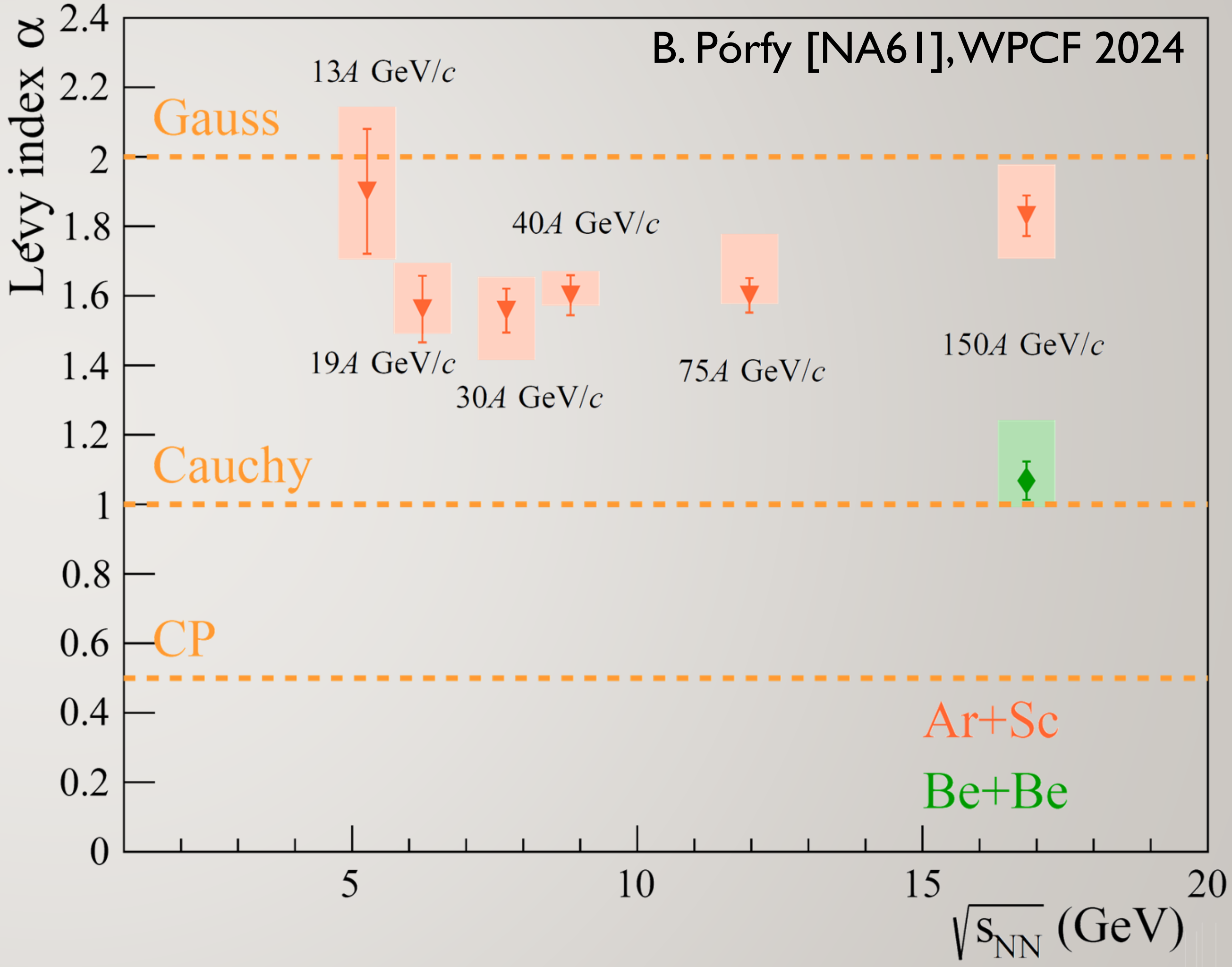






NA61/SHINE RESULTS

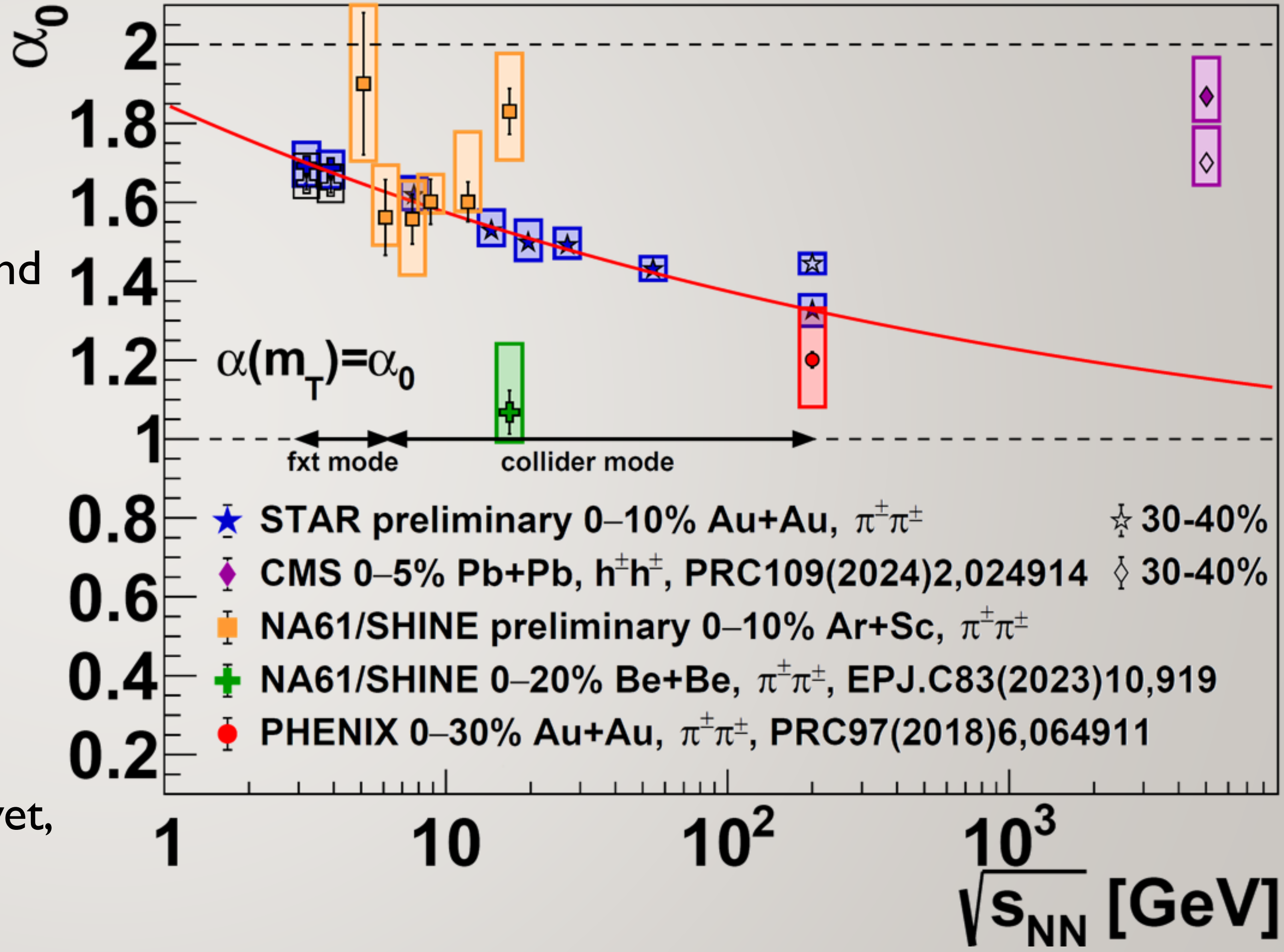
- At 150 AGeV: α(Be+Be) < α(Ar+Sc)
- Interesting trend of α
  for smaller energies in Ar+Sc
  - (not incompatible with constant)
- Next step: Xe+La, 3D analysis
- See more details by B. Pórfy on Thu
  - $\alpha(m_T)$ approximately constant
  - $R(m_T)$ shows sign of flow
  - $\lambda(m_T)$ shows no „hole" at low m_T
  - Compare to RHIC energies



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 described 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)



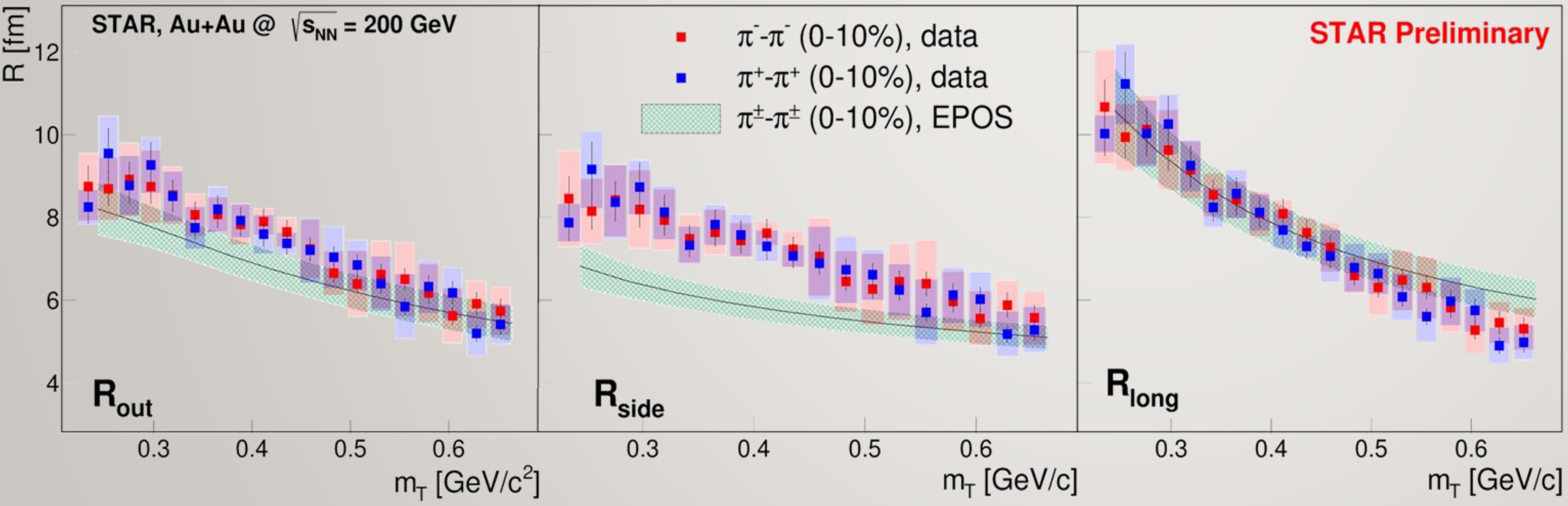
STAR 3D PRELIMINARY DATA AT 200 GEV VS EPOS

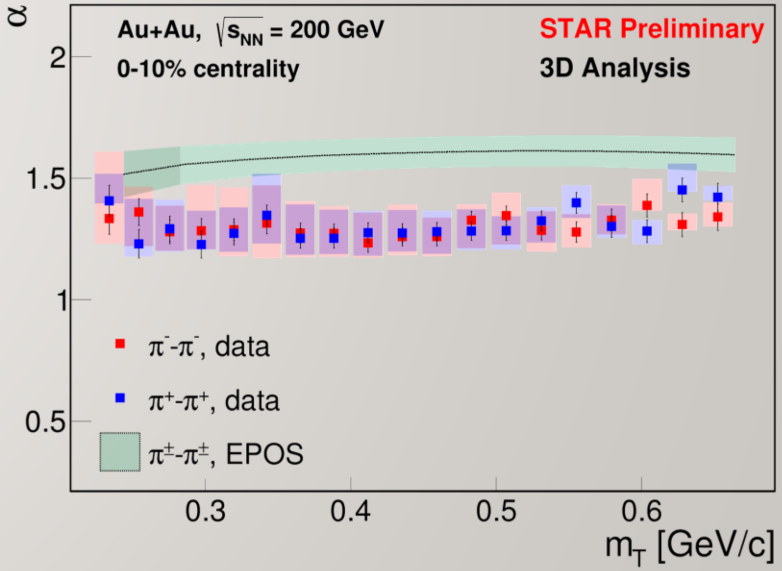
- See STAR analysis in talk by S. Bhosale
- EPOS and data (both from 3D analysis) comparison shows good agreement for radii
  - EPOS from arXiv:2409.10373
- Moderate discrepancy for R_{side} and α: maybe due to long-range Coulomb scattering (not in EPOS)

$R_{o,s,l}$ vs m_T

S. Bhosale, WPCF 2024

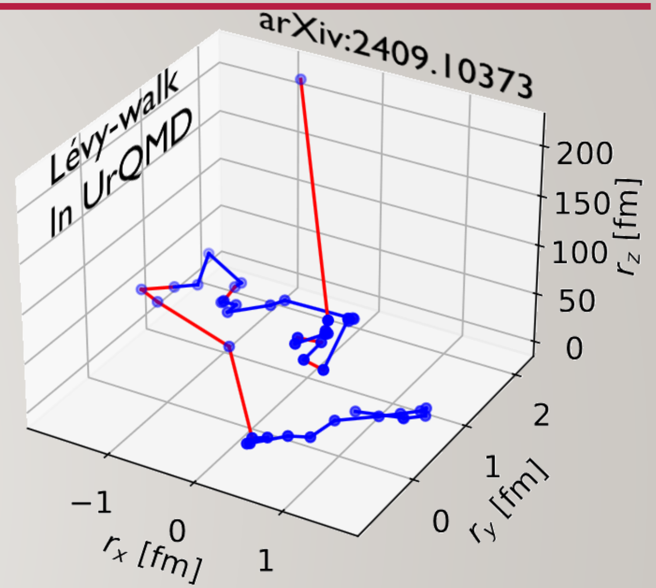
α vs m_T

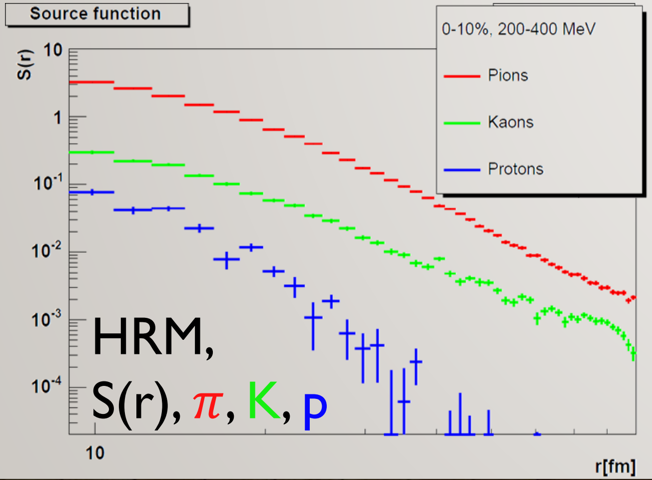


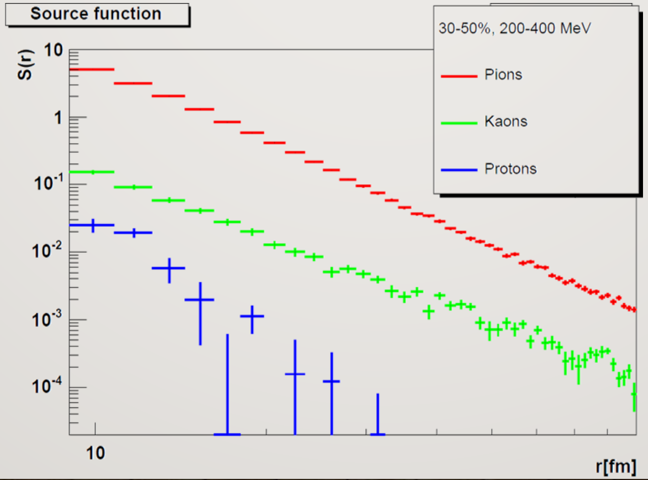


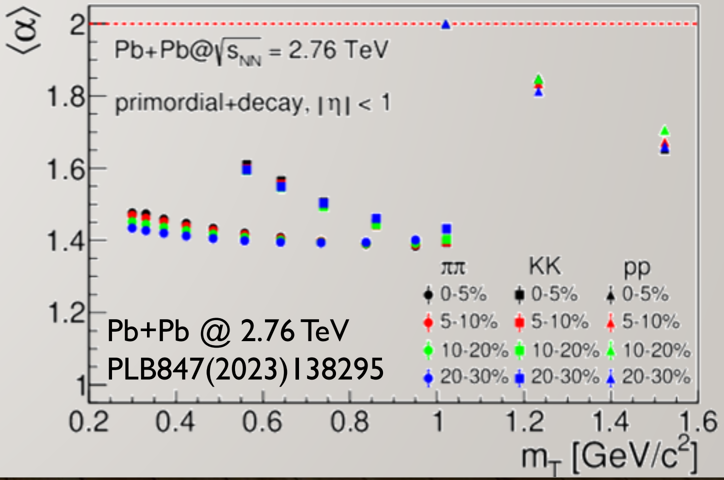
SO WHEN DO THE POWER-LAW TAILS FORM?

- Based on EPOS: apparently Gaussian in hydro phase
- Power-law tails due to Lévy-walk: scattering processes
  - 2-by-2, decay, coalescence, etc
- How to test? Particle type dependence!
  - Based on cross-sections: $\alpha(p) > \alpha(\pi) > \alpha(K)$
    Humanic, IJMPE15(2006)197, Csanád, Csörgő, Nagy, BJP37(2007)1002
  - Not confirmed by EPOS! Role of decays and inelastic collisions?



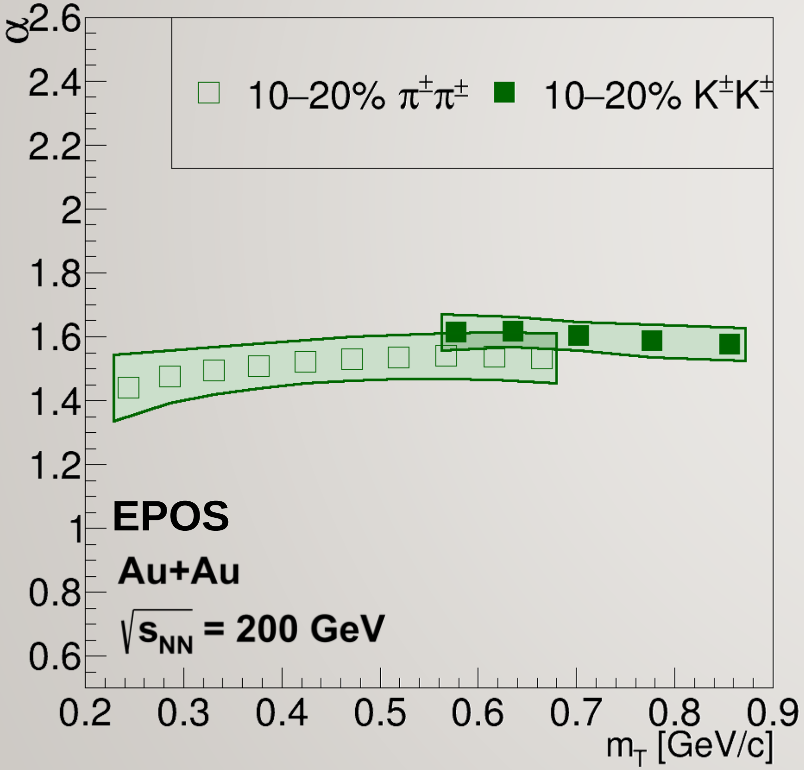


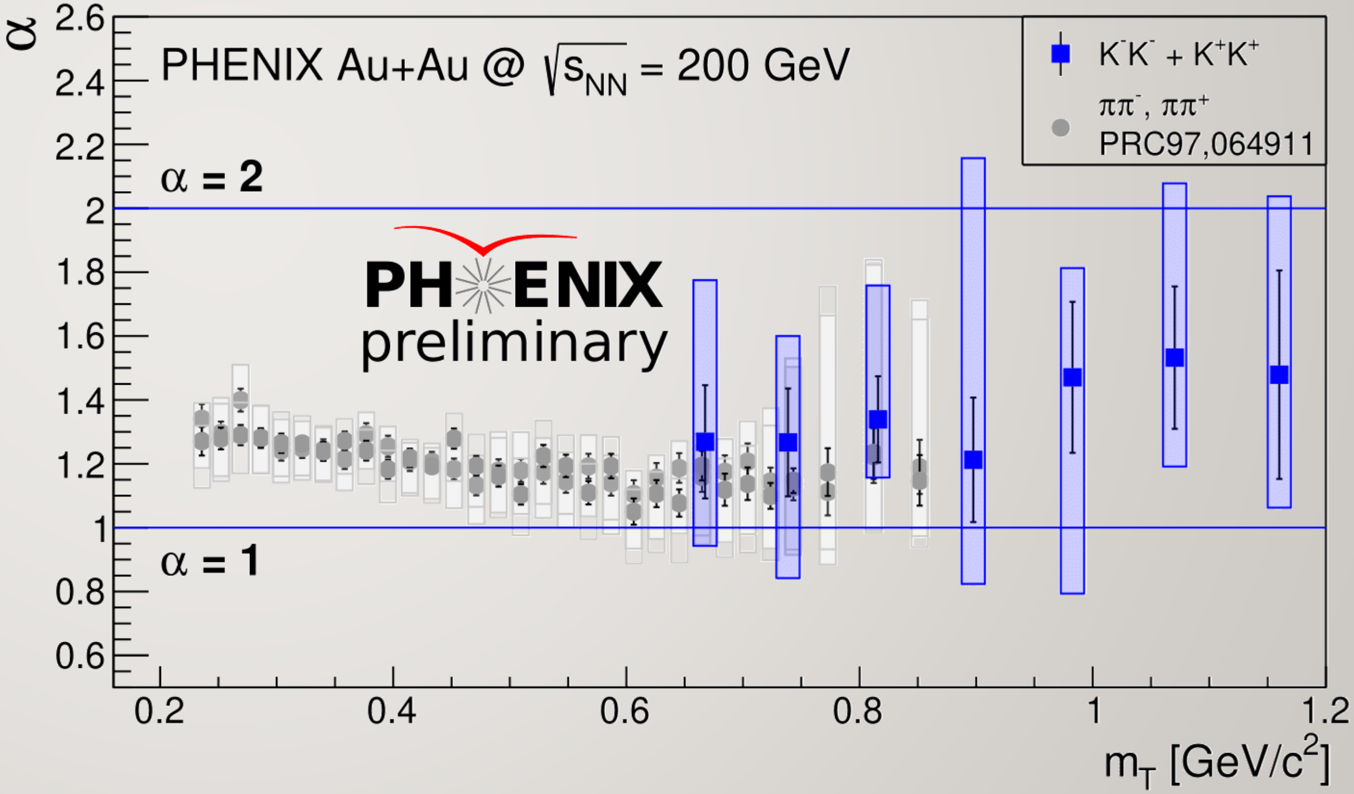




PARTICLE SPECIES COMPARISION, DATA VS EPOS, LÉVY α

- Good agreement between kaons and pions, experiment and EPOS
  - Slightly surprising: same source for kaons and pions, despite role of scattering?
  - See talk/poster by L. Kovács on Thursday





PARTICLE SPECIES COMPARISION, DATA VS EPOS, LÉVY R

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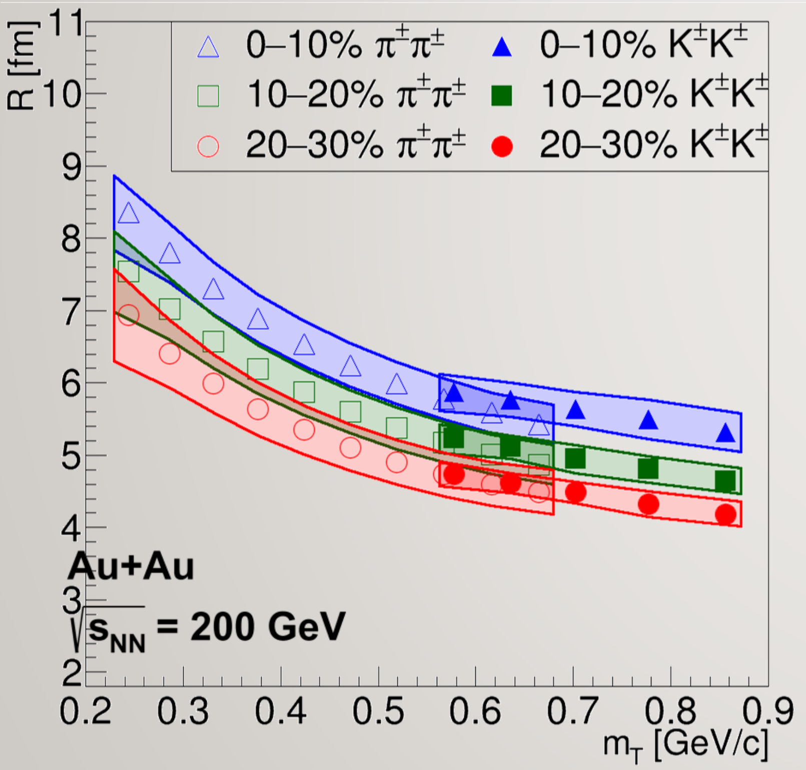
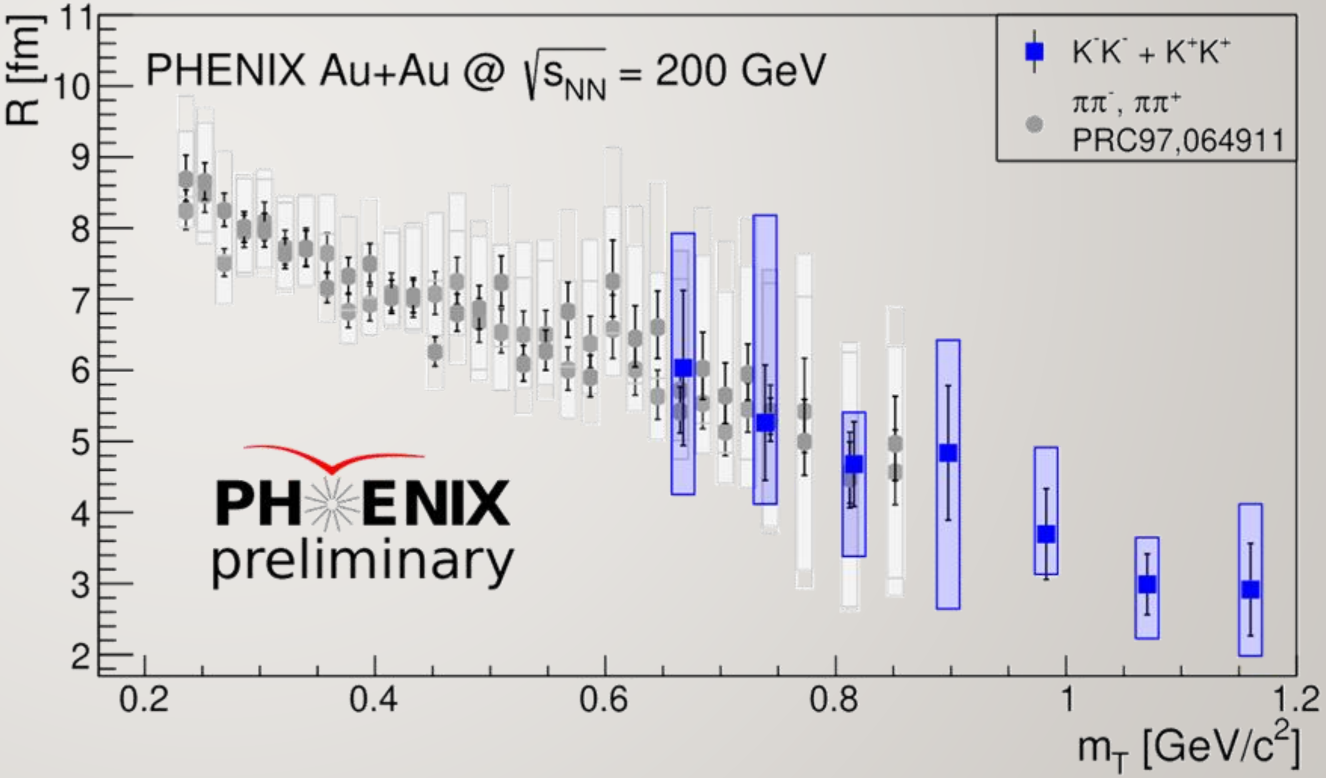
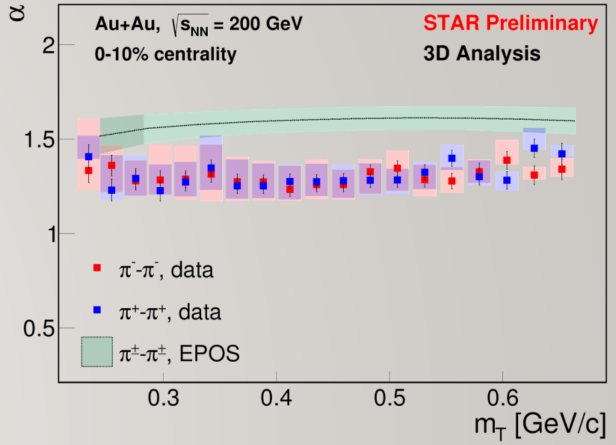


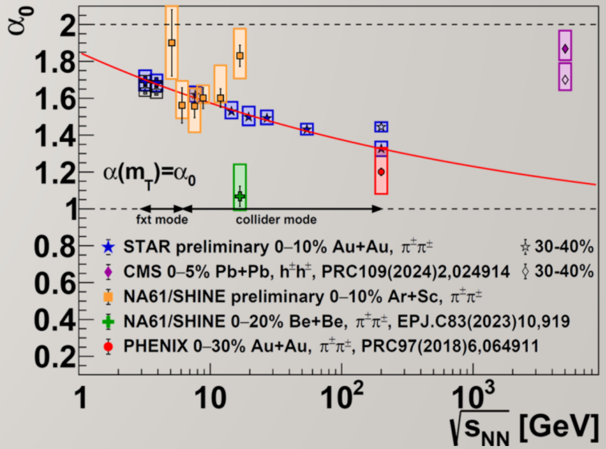


CONCLUSIONS AND OUTLOOK

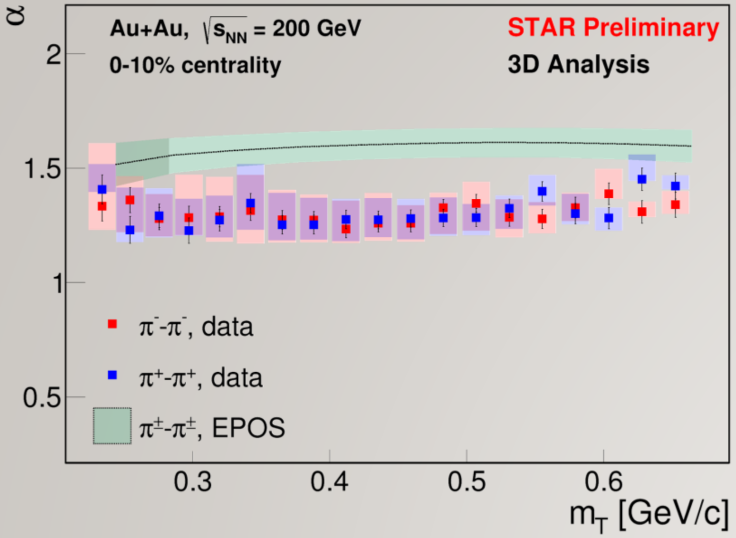
- Lévy sources for pions seen from 3.2 to 200 GeV with STAR, also in 3D
  - **Lévy α**: between 1 and 2, increases with $\sqrt{s_{NN}}$
  - **Lévy R**: hydro scaling, relation to Gaussian through HWHM/HWHI
  - **Lévy λ**: decrease at low transverse mass

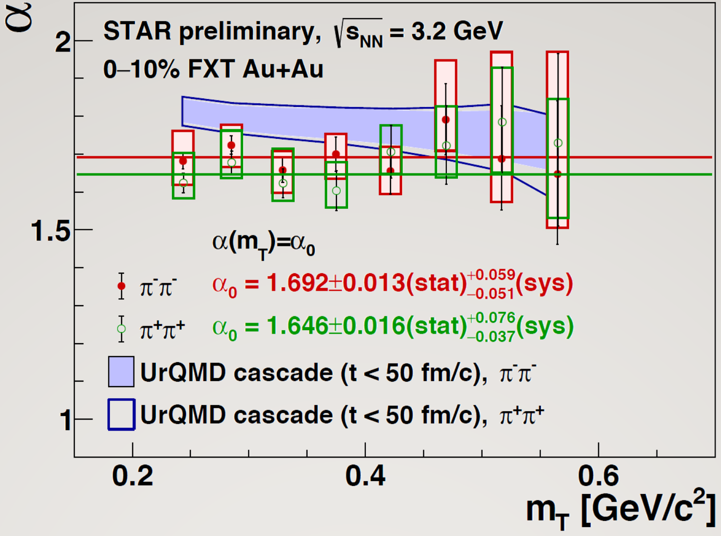


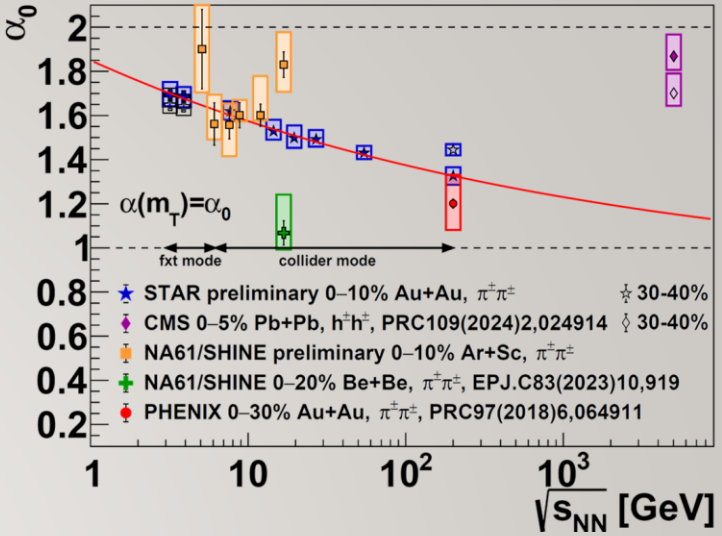
- Possible reasons:
  - ~~Jet fragmentation~~ → not dominant in AA collisions
  - **Critical phenomena** → no non-monotonicity seen, more energies to be investigated
  - ~~Directional averaging~~ → good fits and same Lévy exponent in 1D and 3D
  - ~~Event averaging~~ → event-by-event simulations show Lévy
  - **Resonance decays** → part of the reason, not enough alone
  - **Hadronic rescattering, Lévy walk** → good description of measurements



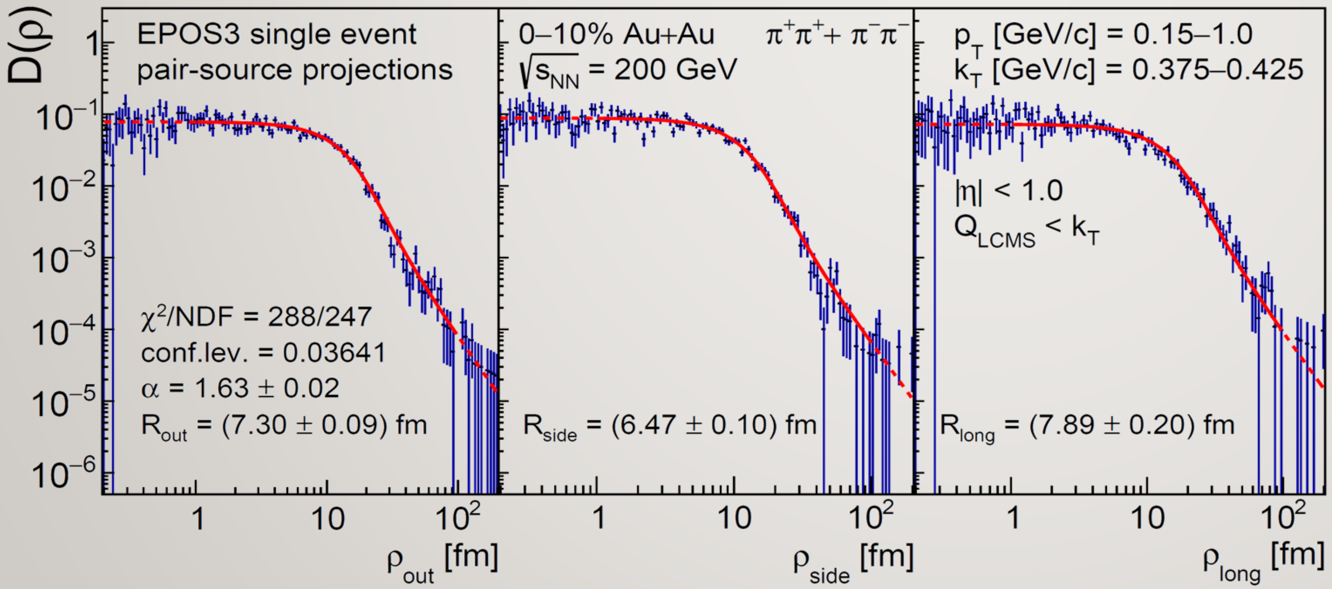
- Questions to be answered:
  - Effect of EoS on α and $R^2_{out} - R^2_{side}$ versus $\sqrt{s_{NN}}$?
  - What collision energy dependence do models predict?

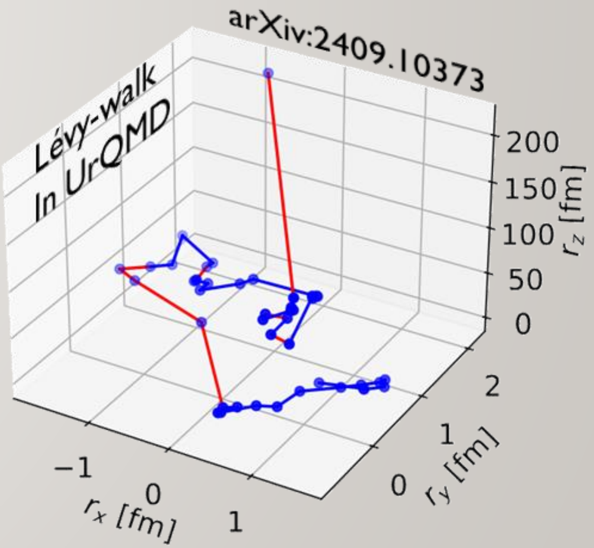






THANK YOU FOR YOUR ATTENTION





BACKUP

INTERACTIONS

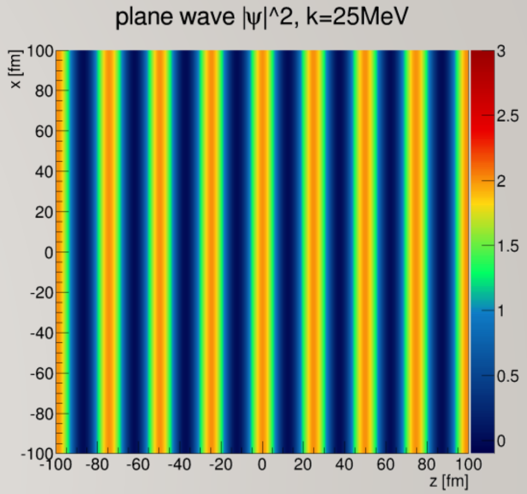
- Plane-wave result, based on $\left|\Psi_{2,\mathrm{q}}^{(0)}(r)\right|^2 = 1 + e^{iqr}$, for pair source $D(r)$

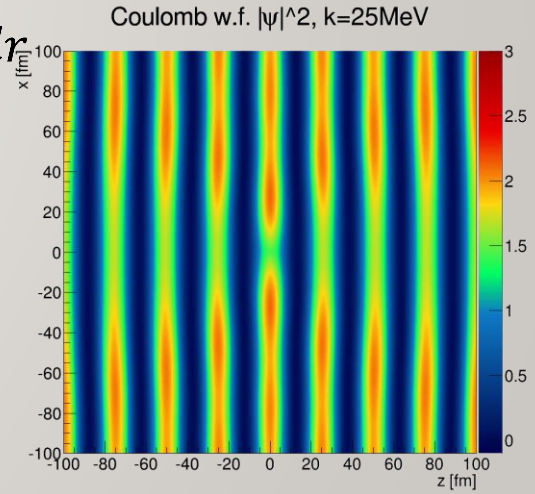
$$C_2(q,K) \cong \int D(r,K) \left|\Psi_{2,q}^{(0)}(r)\right|^2 dr = 1 + \int D(r,K) e^{iqr} dr$$

- If there are interactions, solve Schrödinger eq: $\Psi_{2,q}^{(0)}(r) \to \Psi_{2,q}^{(\mathrm{int})}(r_1, r_2)$
- For Coulomb, solution is known: $\left|\Psi_{2,\mathrm{q}}^{(C)}(r)\right|^2 = \frac{\pi\eta}{e^{2\pi\eta}-1} \cdot$ (hypergeometric expression)
- Direct fit with this, or the usual iterative Coulomb-correction:

$C_{\mathrm{Bose-Einstein}}(q)K(q)$, where $K(q) = \int D(r,K) \left|\Psi_{2,\mathrm{q}}^{(C)}(r)\right|^2 dr / \int D(r,K) \left|\Psi_{2,\mathrm{q}}^{(0)}(r)\right|^2 dr$

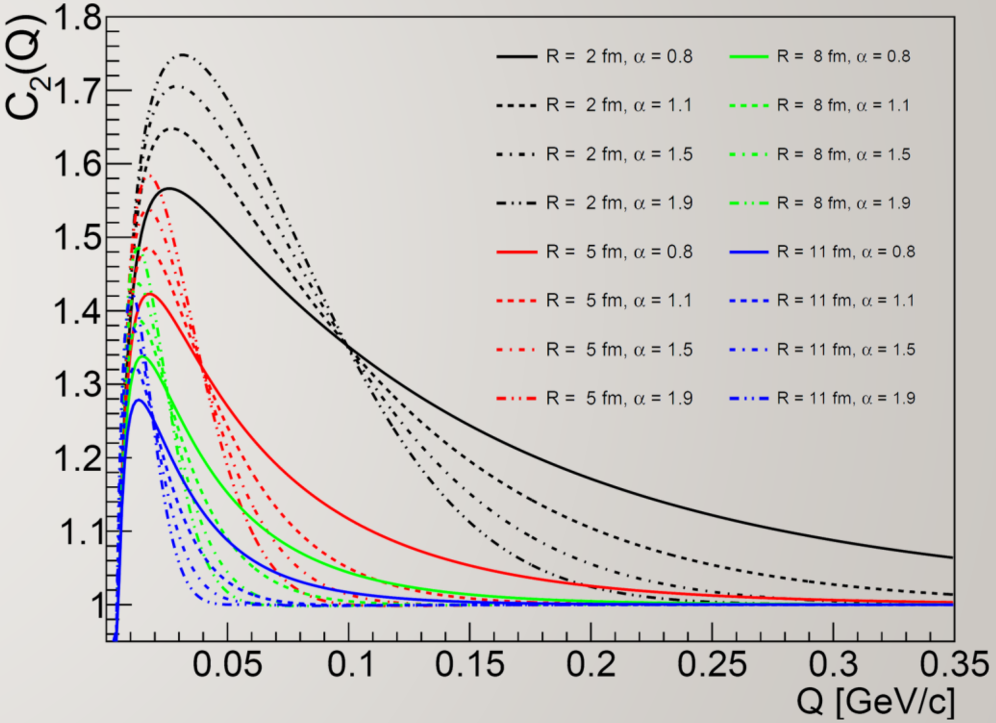
- Complication: need for integrating power-law tails
  - Precalculated in a tabular form, iterative fitting, e.g., PHENIX, PRC97(2018)064911
  - Interpolating functional form, see Csanád, Lökös, Nagy, Phys.Part.Nucl. 51(2020)238
  - Role of the strong interaction, see Kincses, Nagy, Csanád, PRC102(2020)064912
  - Recent method: EPJC83(2023)1015, code at github.com/csanadm/CoulCorrLevyIntegral
- Many new results, also for the strong interaction: see talk by M. Nagy on Tuesday





HOW TO CALCULATE THE COULOMB EFFECT

- Calculating correlation functions with the Coulomb effect included: time consuming in the past
- Method used in early analyses: Coulomb correction calculated for fixed radius and shape
  - For example, fixing $R = 5$ fm and $\alpha = 2$
- More consistent method: correlation function with Coulomb FSI precalculated in a tabular form
  - Iterative fitting, see e.g., PHENIX, PRC97 (2018) 6, 064911
- Convenient, but somewhat restricted method: interpolating functional form, in a limited R, α range
  - See Csanád, Lökös, Nagy, Phys.Part.Nucl. 51 (2020) 238, used in arXiv:2306.11574 [CMS], arXiv:2302.04593 [NA61]



- Recent method: see talk by Márton Nagy
  - Nagy, Purzsa, Csanád, Kincses Eur. Phys. J. C 83, 1015 (2023), code at github.com/csanadm/CoulCorrLevyIntegral
  - Recent developments: 3D calculation, protons, see talk by M. Nagy on Wednesday

LÉVY INDEX AS A CRITICAL EXPONENT?

- 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) 67

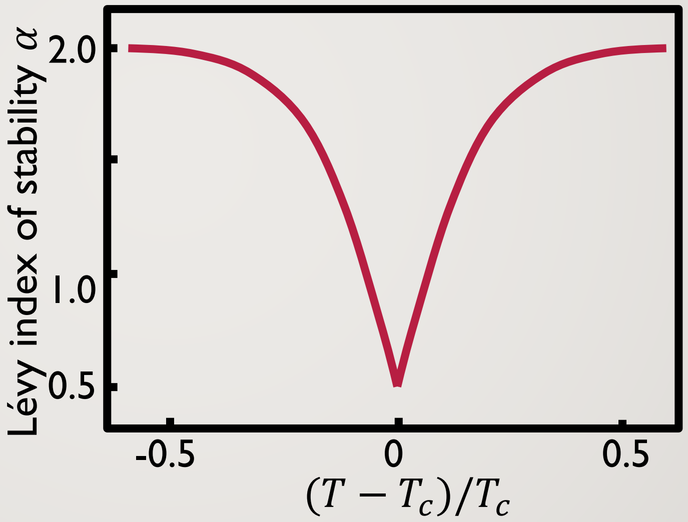
- QCD universality class ↔ 3D Ising

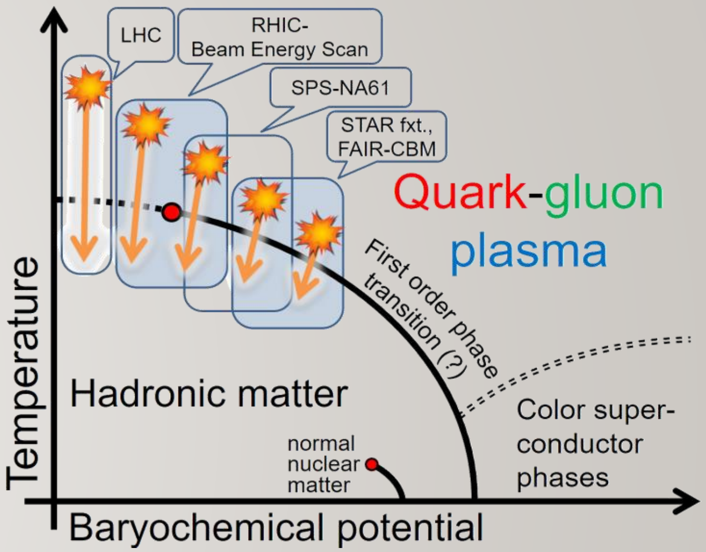
  Halasz et al., Phys.Rev.D58 (1998) 096007
  Stephanov et al., Phys.Rev.Lett.81 (1998) 4816

- At the critical point:
  - Random field 3D Ising: η = 0.50±0.05
    Rieger, Phys.Rev.B52 (1995) 6659
  - 3D Ising: η = 0.03631(3)
    El-Showk et al., J.Stat.Phys.157 (4-5): 869

- Motivation for precise Lévy HBT!

- Change in α_{Levy} proximity of CEP?

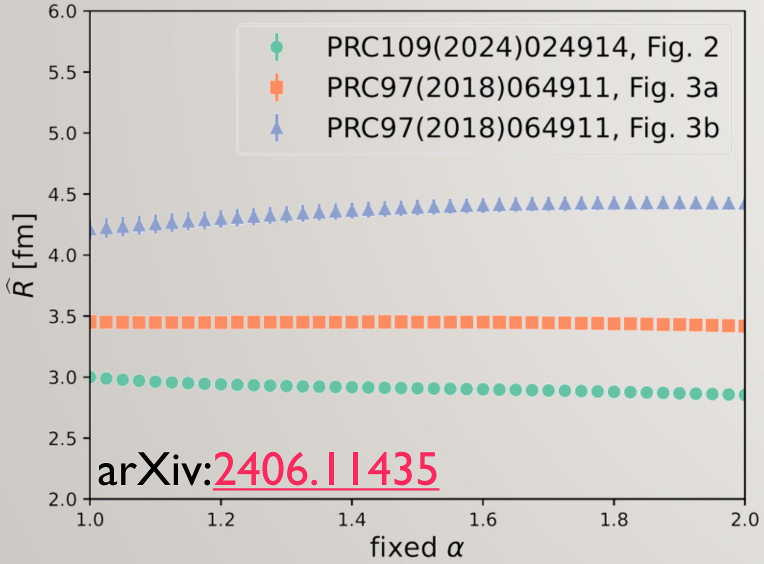


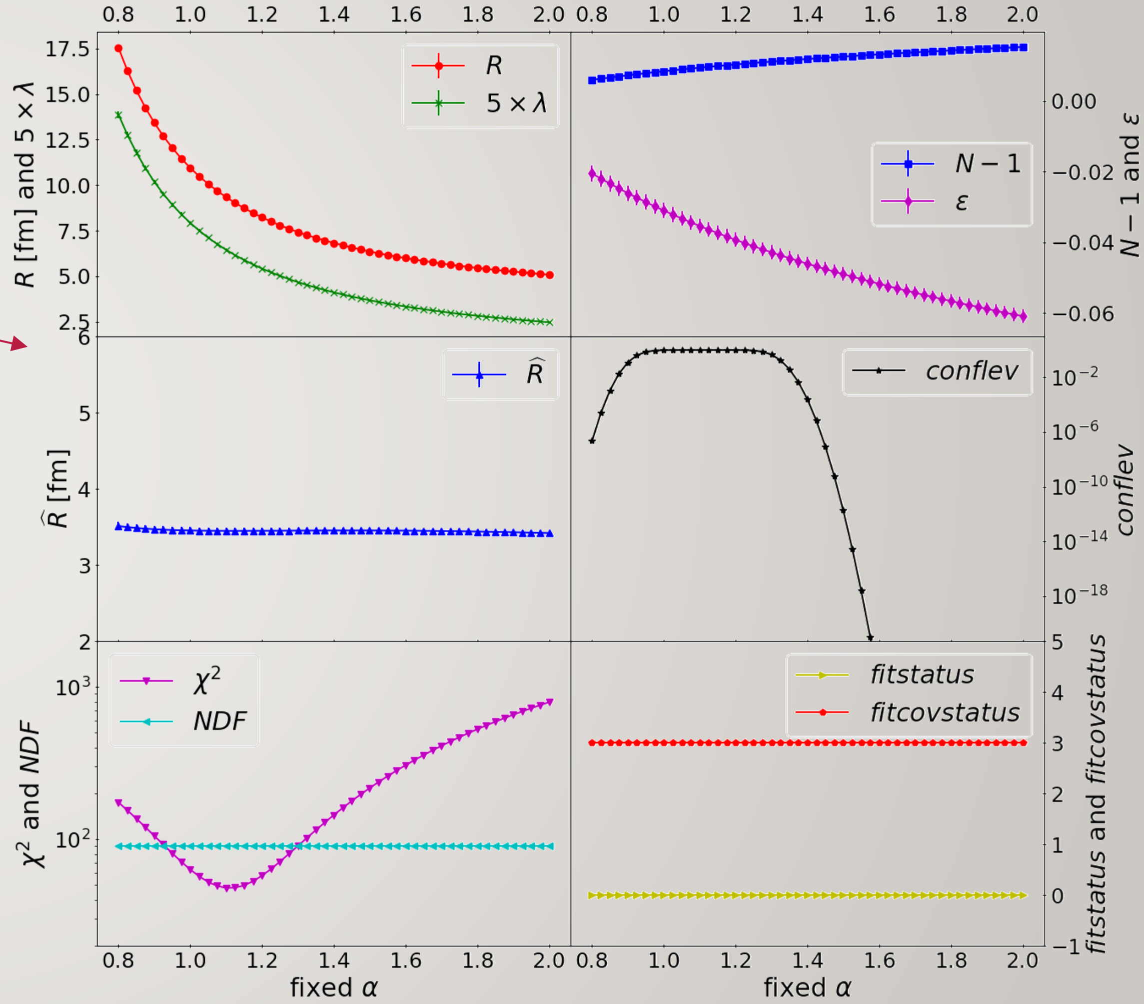


- Finite-size/time & non-equilibrium effects → what does power-law tail mean?
  - Finite-size effects not important? See e.g. Fytas et al, PRE93, 063308 (2016), Ballesteros et al., PLB387 (1996) 125

RESCALING HBT RADII FROM GAUSS TO LÉVY

- Source shape and size entangled in Gaussian radii
- Fits possible with many α values
  - Some statistically acceptable, some not
  - Fits to PHENIX HBT paper PRC 2018, Fig 3a
- $\hat{R} = R/[\lambda(1+\alpha)]$ scaling observed generally

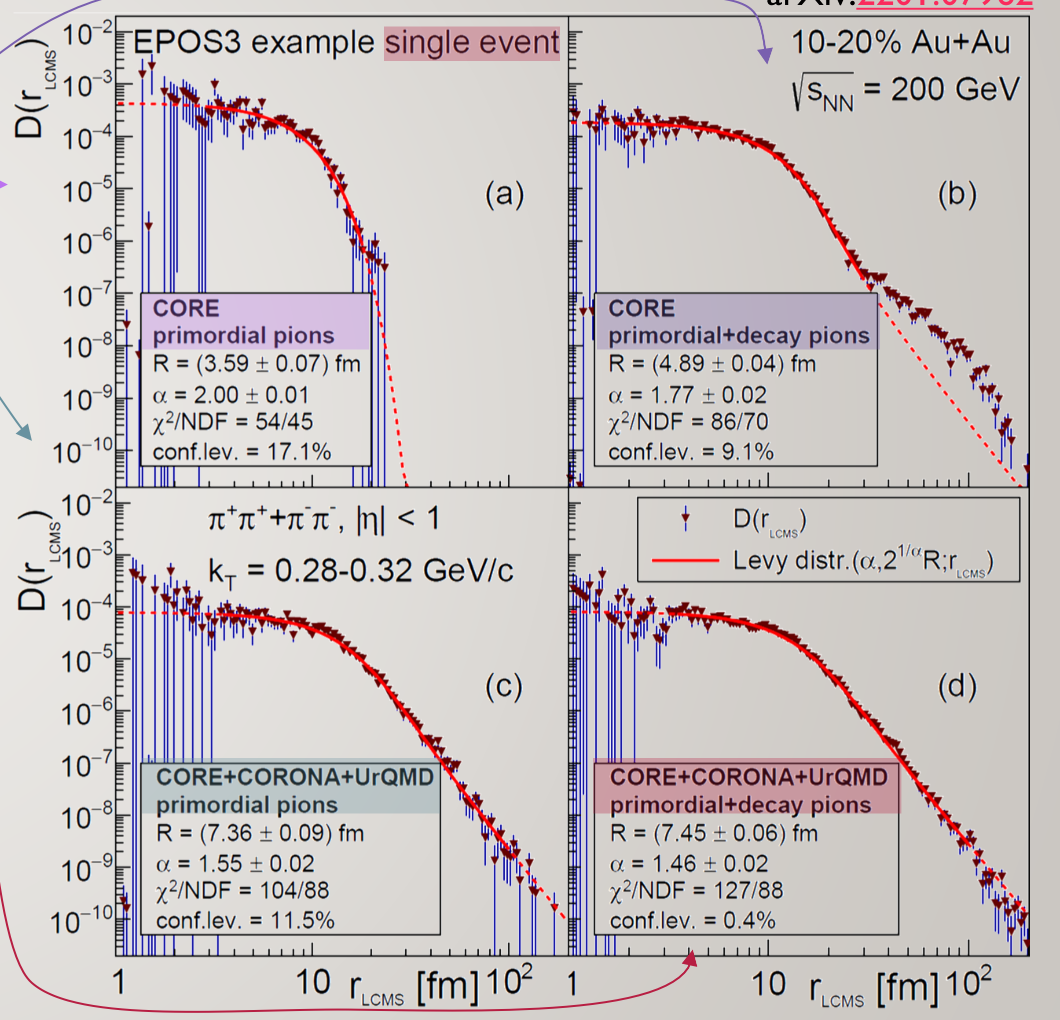




LÉVY SHAPES IN SINGLE EPOS EVENTS, 1D

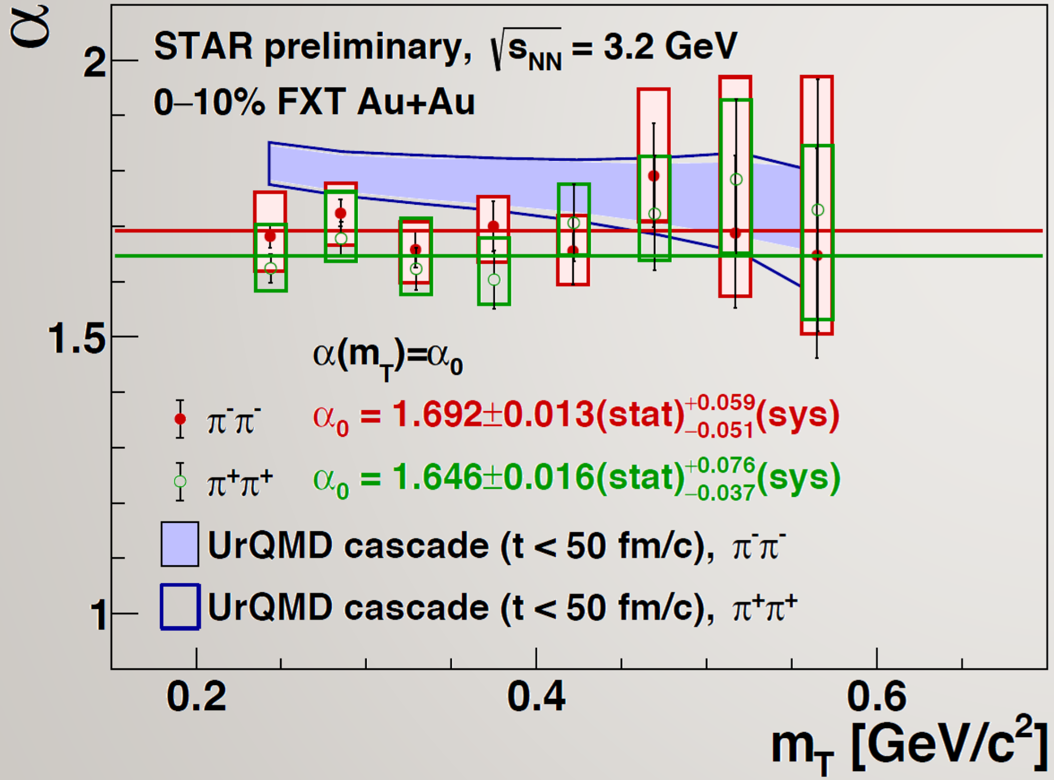
- EPOS model: parton-based Gribov-Regge theory (PBGRT)
  - Werner et al., PRC82 (2010) 044904, PRC89 (2014) 064903, …
- Source observed in four stages:
  - a) CORE, primordial pions: close to Gaussian
  - b) CORE, with decay products: power-law structures
  - c) CORE+CORONA+UrQMD, primordial pions: Lévy 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
- Can one relate the observed HBT radii to the hydro phase homogeneity lengths?
- More investigations needed…
- See talks by D. Kincses, E. Árpási, L. Kovács, M. Molnár on Thu

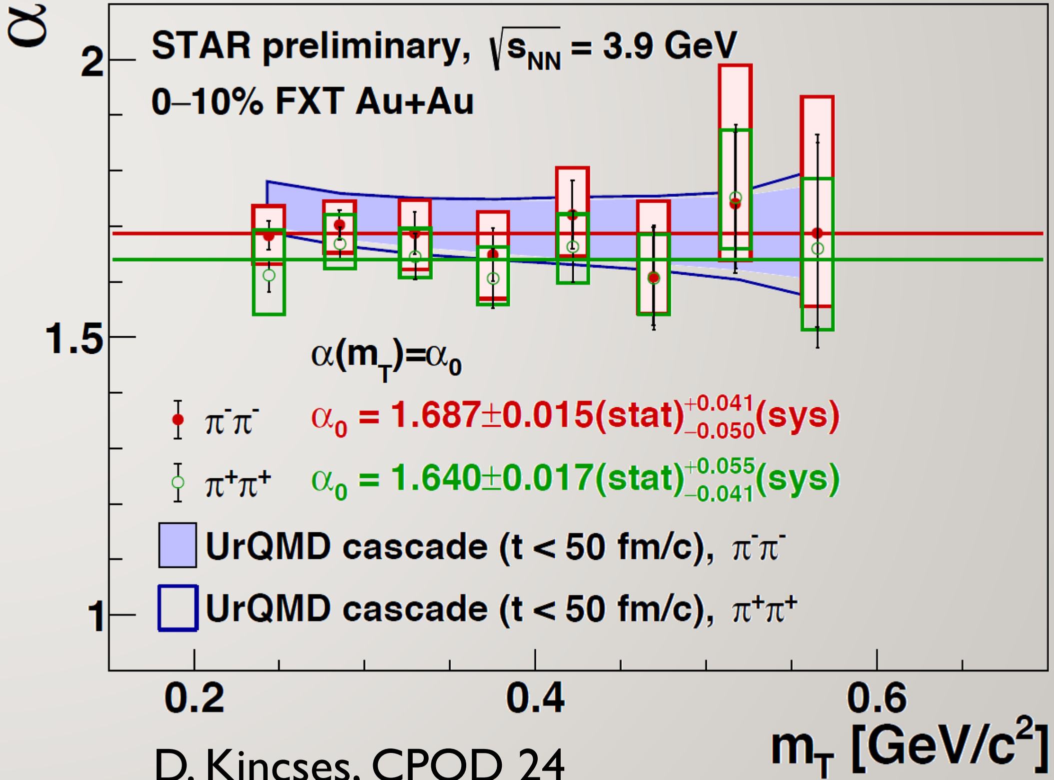
arXiv:2201.07962



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!)



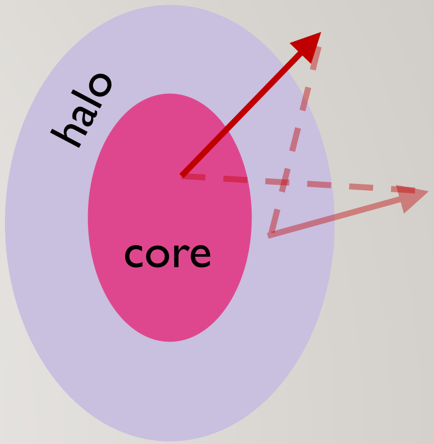


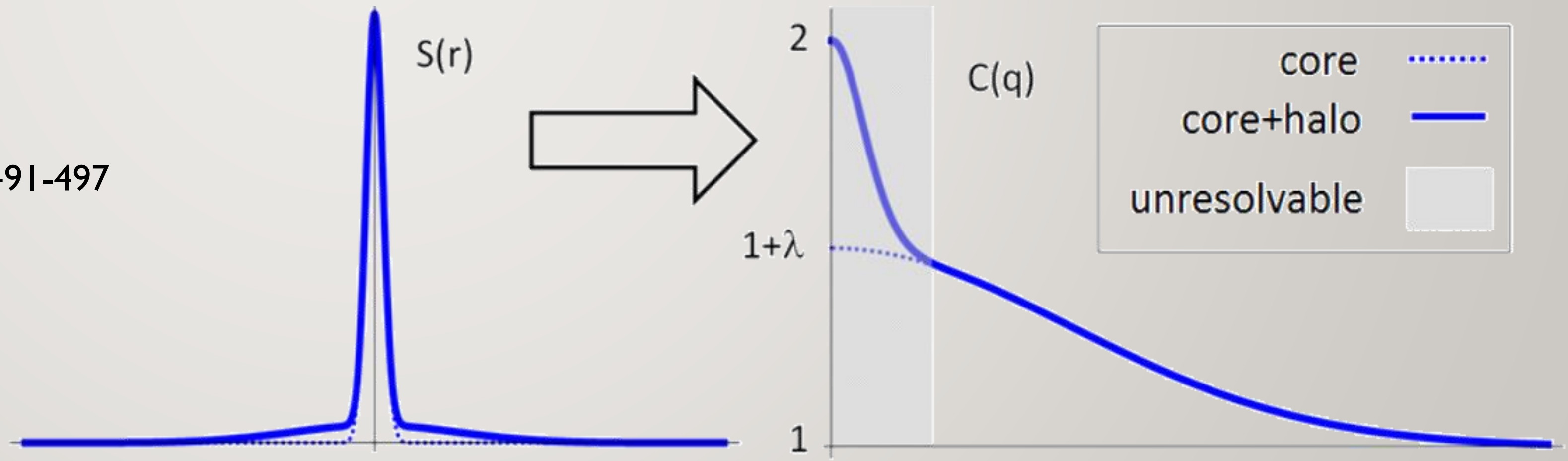
D. Kincses, CPOD 24

CORRELATION STRENGTH λ: CORE/HALO

- Two-component core+halo source
  - Core: hydrodynamically expanding, thermal medium
  - Halo: long lived resonances ($\gtrsim$ 10 fm/c, ω,η,η',K_0^S,...)
  - Unresolvable experimentally
  - Define $f_C = N_{\text{core}}/N_{\text{total}}$
- True $q \to 0$ limit: $C(0) = 2$
- Apparently $C(q \to 0) \to 1 + \lambda$
- $\lambda(m_T) = f_C^2(m_T)$

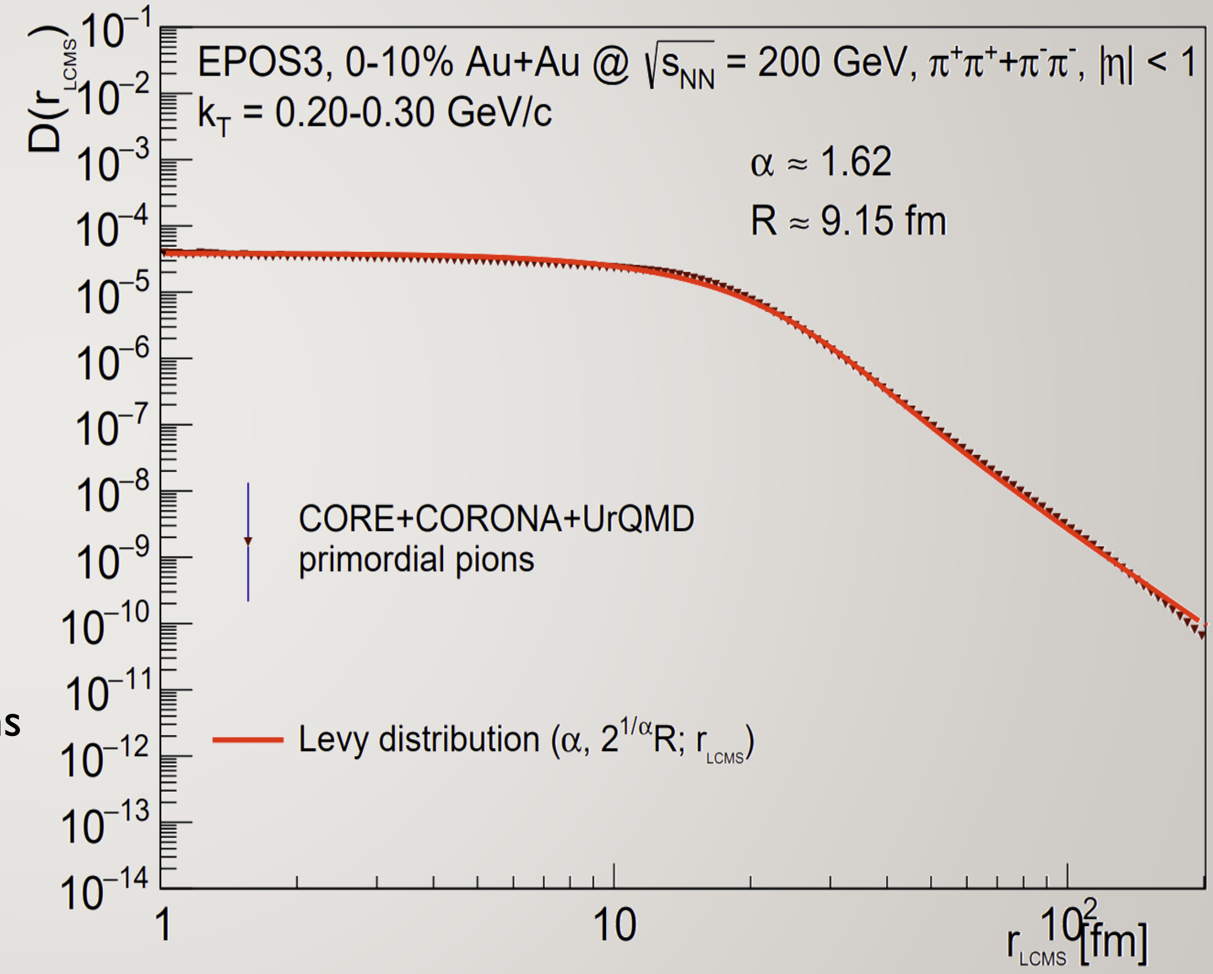
Bolz et al, Phys.Rev. D47 (1993) 3860-3870;
Csörgő, Lörstad, Zimányi, Z.Phys. C71 (1996) 491-497





ROLE OF EVENT AVERAGING?

- Event-averaged source also analyzed
- Not perfectly Lévy shape, very large χ^2
- Nevertheless: similar parameters achieved
  - Event averaged:
    $\alpha \approx 1.62, R \approx 9.15$ fm
  - Event-by-event:
    $\alpha \approx 1.66, R \approx 8.96$ fm
- More reasonable approach for kaons
  - No event-by-event analysis possible for kaons



SOURCE OR PAIR DISTRIBUTION?

- Under some circumstances (thermal emission, no interactions, …):

$$C_2(q,K) = \int S\left(r_1, K+\frac{q}{2}\right) S\left(r_2, K-\frac{q}{2}\right) |\Psi_2(r_1,r_2)|^2 dr_1 dr_2$$

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

- Let us introduce the spatial pair distribution:

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

- Then the Bose-Einstein correlation function becomes:

$$C_2(q,K) \cong \int D(r,K)|\Psi_2(r)|^2 dr = 1 + \int D(r,K)e^{iqr}dr$$

- **Bose-Einstein correlations measure spatial pair distributions!**
- Coulomb and strong Final State Interactions? Under control for Lévy sources

  Csanad, Lökös, Nagy, Phys. Part. Nuclei 51 (2020) 238 [arXiv:1910.02231]

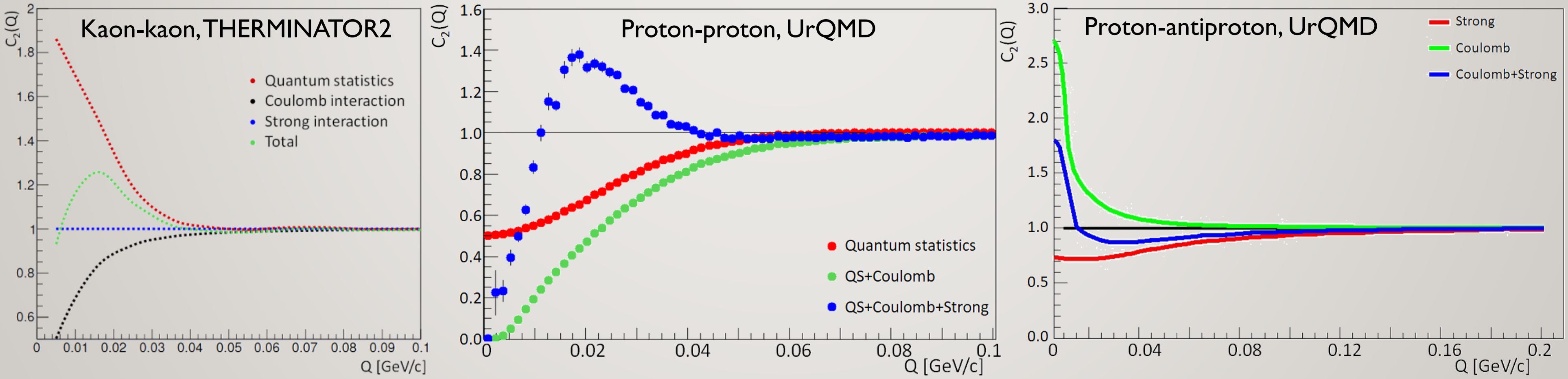
  Kincses, Nagy, Csanad Phys. Rev. C102, 064912 (2020) [arXiv:1912.01381]

ROLE OF THE STRONG INTERACTION

- In case of other interactions or not identical bosons, the formula still works:

$$C_2(q,K) \cong \int D(r,K)|\Psi_2(r)|^2 dr$$

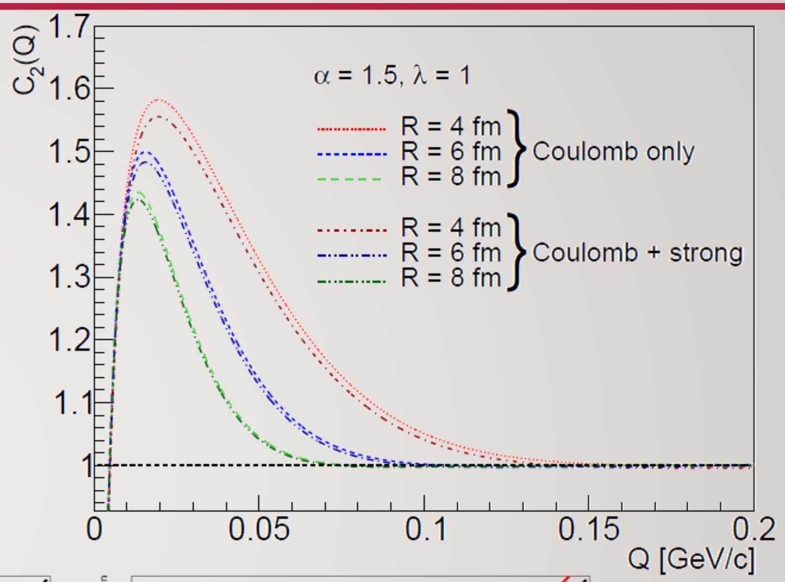
- Pair wave function determines $D \leftrightarrow C_2$ connection
- Mesons, baryons: strong interaction; fermions: anticorrelation
- Non-identical pairs: interaction modifies wave function

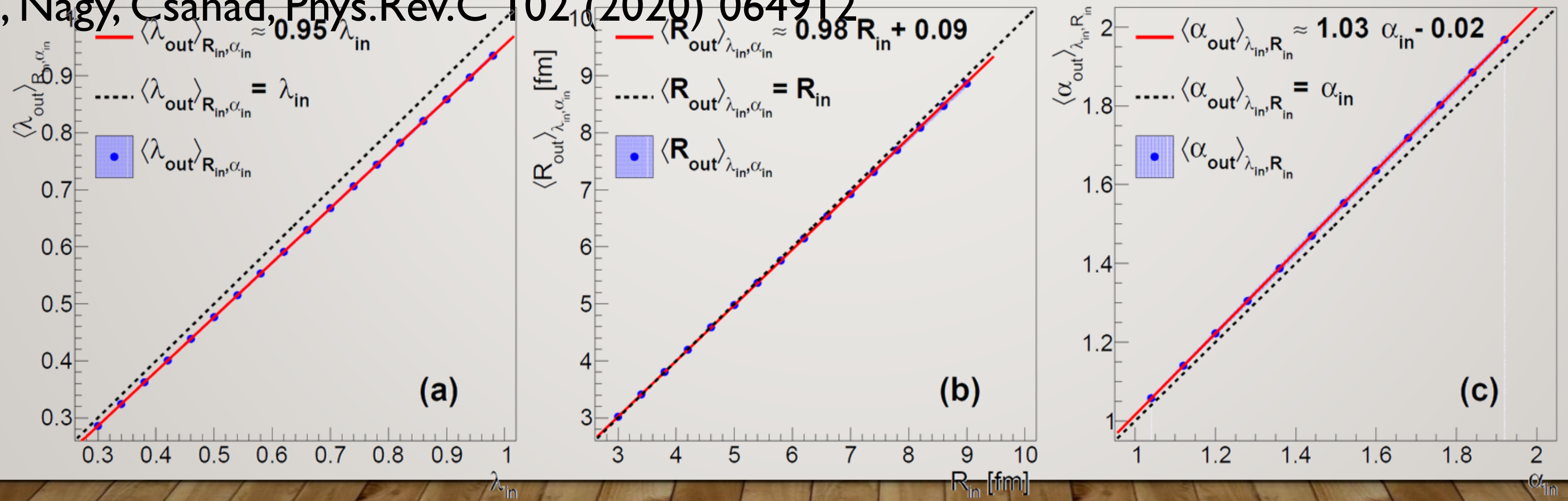


From e.g. H. Zbroszczyk's talk at Zimányi School 2019

STRONG INTERACTION FOR PION PAIRS

- Additional potential appearing
- Possible handling: strong phase shift,
  Modify s-wave component in wave func.
  R. Lednicky, Phys. Part. Nucl.40, 307 (2009)
- Small difference in case of pions
- Few percent modification in λ, α
  Kincses, Nagy, Csanád, Phys.Rev.C 102 (2020) 064912





TWO-PARTICLE SPATIAL CORRELATIONS

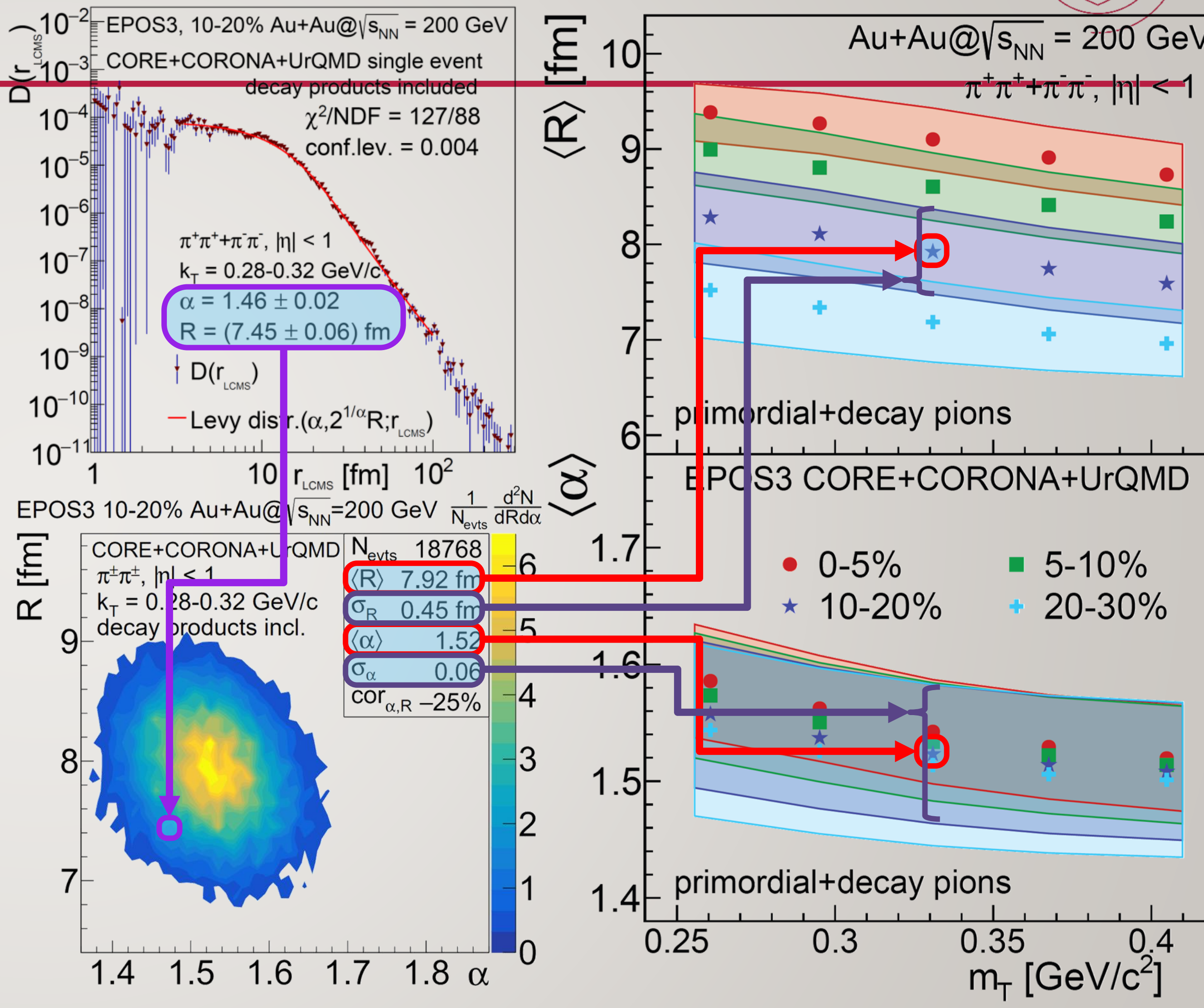
- Object to be investigated: two-particle source

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

- Experimental results measure power-law tails, Lévy shapes
  - Measure momentum-space correlations, reconstruct $D(r)$ or fit its parameters
- Why do these Lévy shapes appear?
  - What physics does contribute to it? Rescattering, decays?
  - What role does event averaging have in it?
    Cimerman, Plumberg, Tomasik, Phys.Part.Nucl. 51 (2020) 282, PoS ICHEP2020 538
  - What do specific α values mean?
- Event generator models (like EPOS) – direct access to pair-source!
  - Phenomenological investigations of $D(r)$ possible
  - Effects can be turned off or on, investigated separately

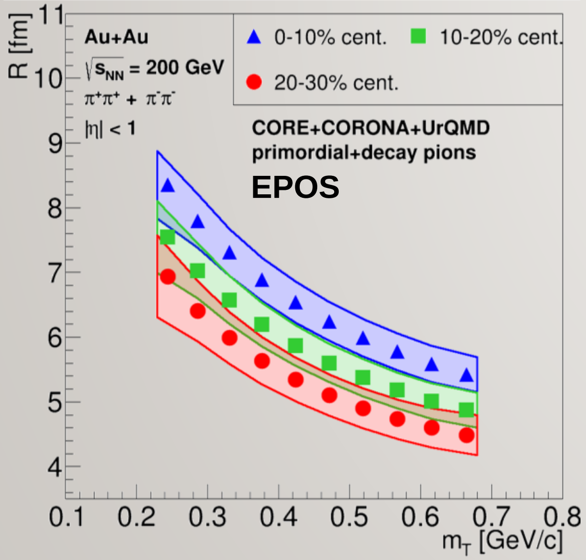
EPOS SUMMARY

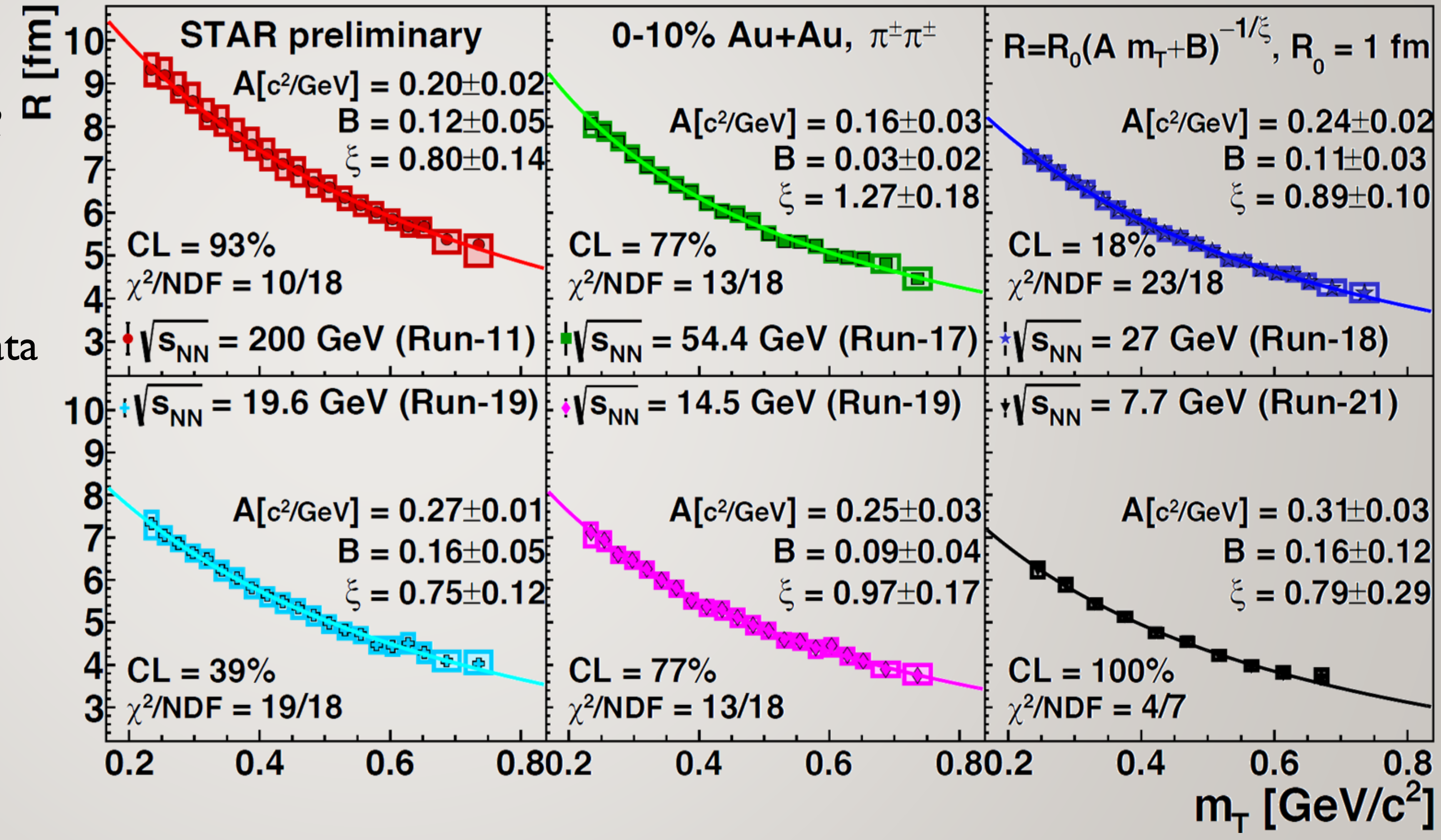
- D(r) calculated in EPOS evt-by-evt
- Lévy fits done evt-by-evt
- Non-Gaussianity in single events
- Extracting mean, & std.dev. of R, α
- m_T & centrality dependence



RESULTS AT COLLIDER ENERGIES: 7.7 TO 200 GEV

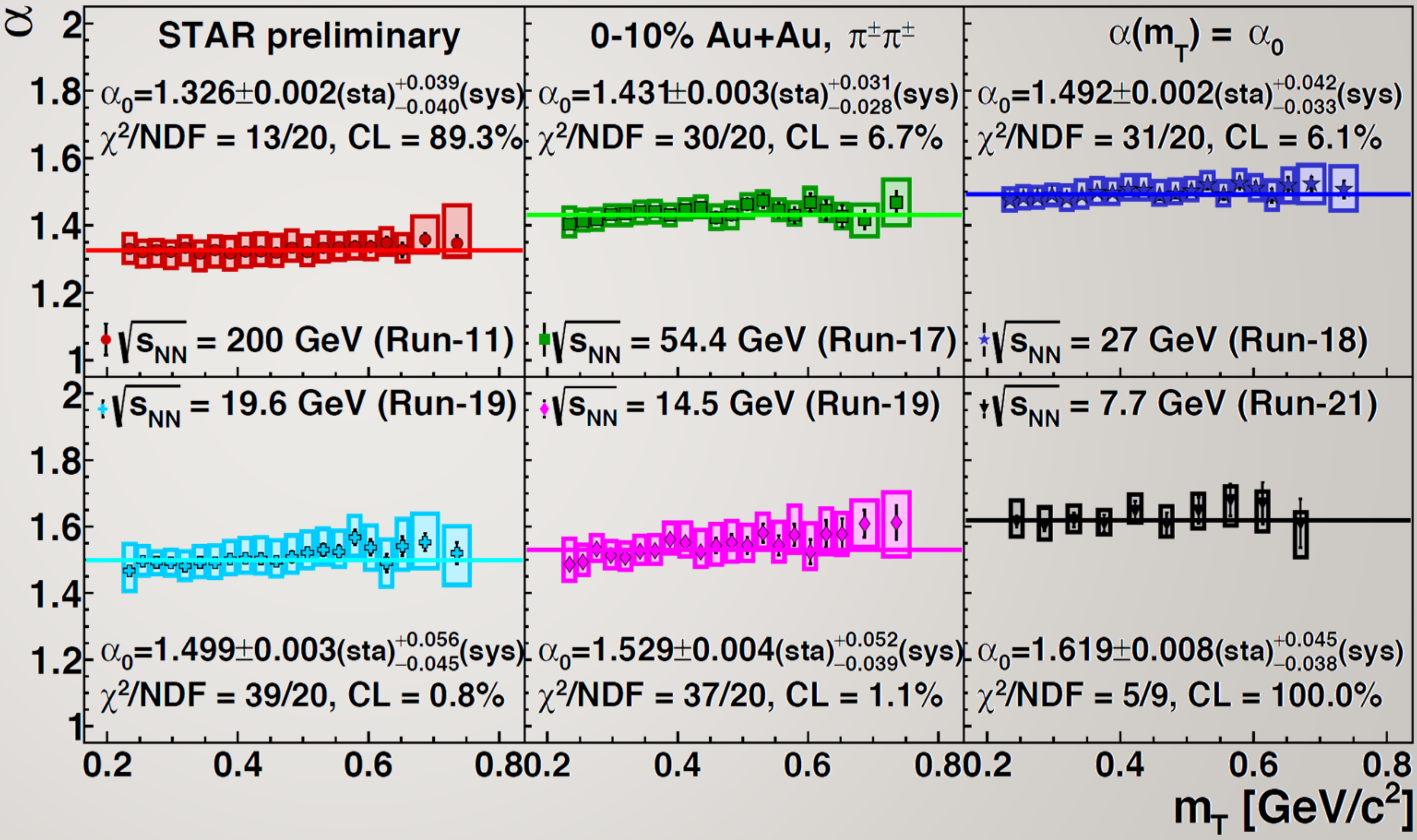
- Slow decrease with $\sqrt{s_{NN}}$ from 200 to 7.7 GeV
  - Same trend as Gaussian R
- Decrease in R with m_T
  - Connection to flow
- 200 GeV: EPOS close to data





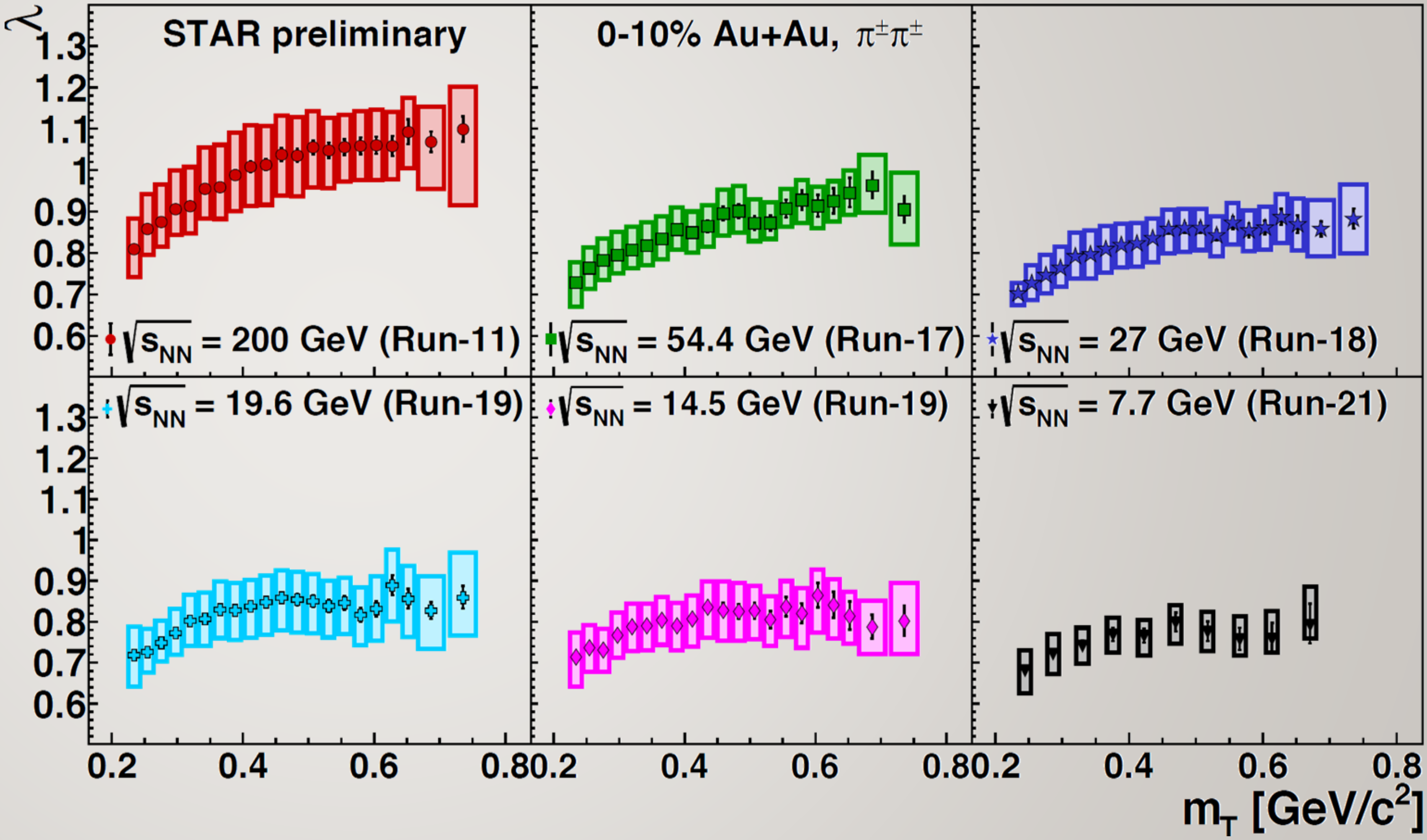
RESULTS AT COLLIDER ENERGIES: 7.7 TO 200 GEV

- 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
  - $\approx$1.33 at 200 GeV
  - $\approx$1.62 at 7.7 GeV
- Significantly below 2.0 and above 1.0



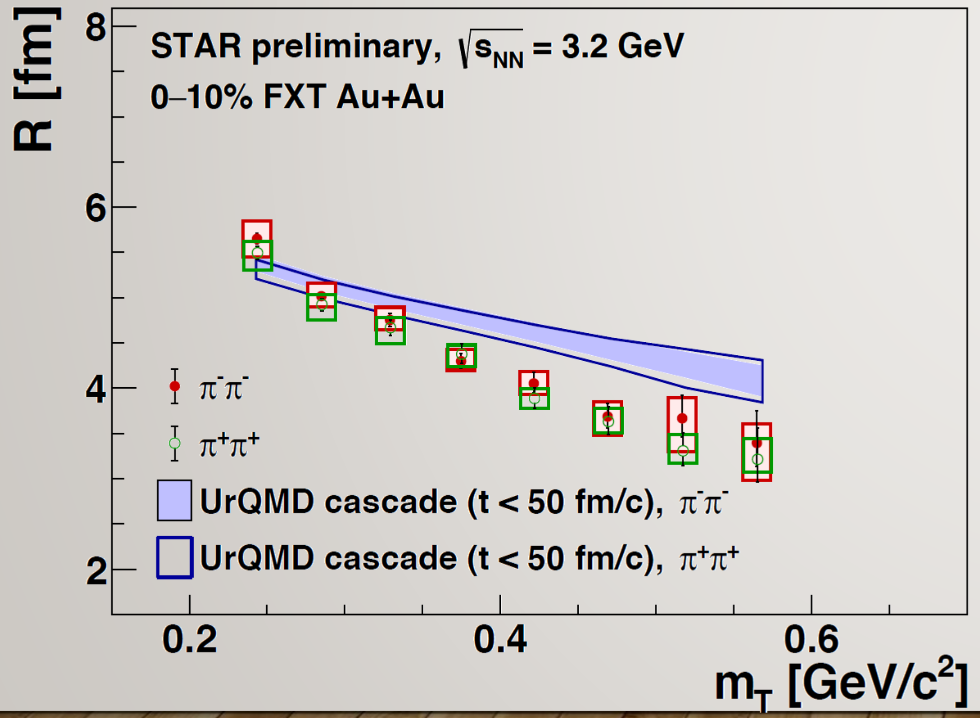
RESULTS AT COLLIDER ENERGIES: 7.7 TO 200 GEV

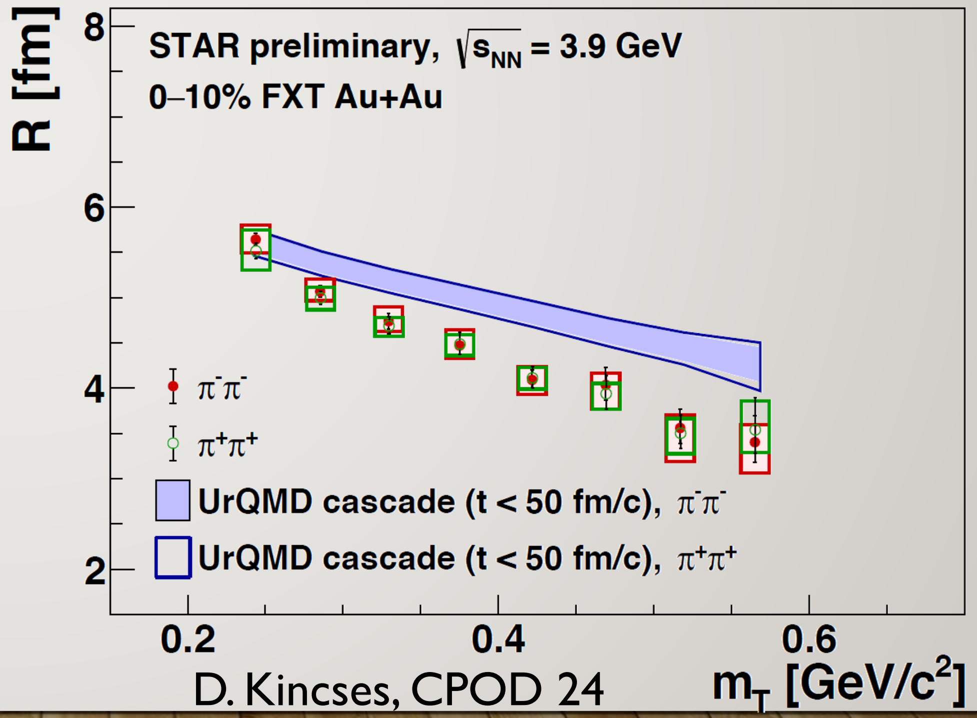
- Clear decrease in λ with $\sqrt{s_{NN}}$ from 200 to 7.7 GeV
  - Decrease in multiplicity
  - Larger role of halo
- Decrease towards small m_T values
  - Increase in halo for small m_T
  - Attributed to modified in-medium η' mass in literature



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





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