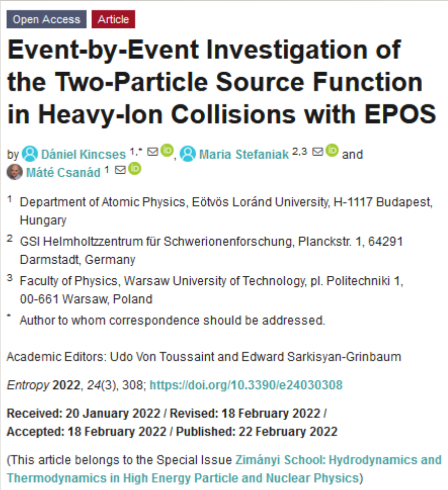
Open Access Article

Event-by-Event Investigation of the Two-Particle Source Function in Heavy-Ion Collisions with EPOS

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Entropy **2022**, *24*(3), 308
[arXiv: 2201.07962]

EVENT-BY-EVENT LEVY FEMTOSCOPY WITH EPOS

MÁTÉ CSANÁD (EOTVOS U, BUDAPEST), D KINCSES, M STEFANIAK

THE 37TH WINTER WORKSHOP ON NUCLEAR DYNAMICS, 2022

CONTENTS OF THIS TALK

- Basics of femtoscopy and Lévy sources
- EPOS event-by-event analysis
- Summary and outlook

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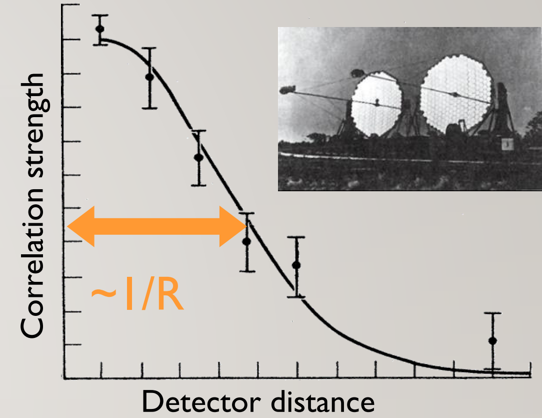
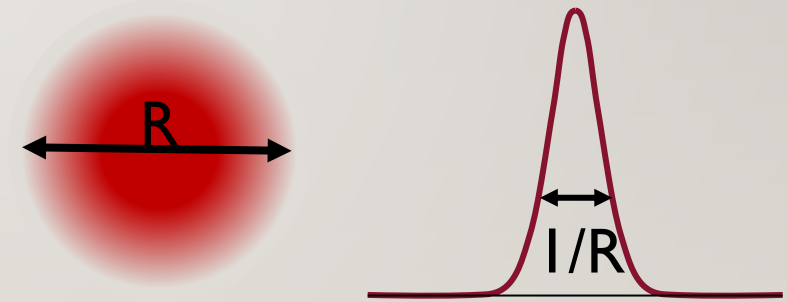
FEMTOSCOPY IN HIGH ENERGY PHYSICS

- 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)
    or the distance distribution $D(r)$
    $C(q) \cong 1 + \int D(r) e^{iqr} dr$
  - Neglected: pair reco., final state int., N-particle correlations, coherence, …



source function S(r) correlation funct. C(q)

- Measure C(q): map out source space-time geometry on femtometer scale!

5/25 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:

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

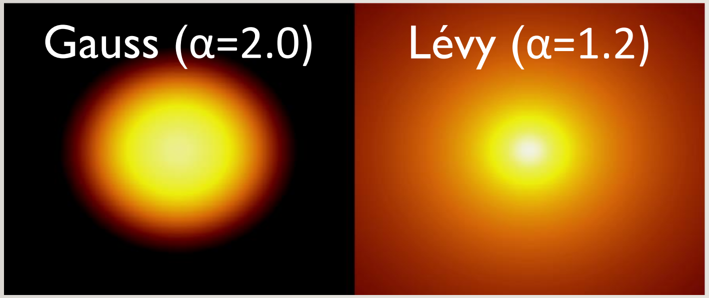
- **Bose-Einstein correlations measure spatial pair distributions!**
- Coulomb and strong Final State Interactions? Under control for Lévy sources

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

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

LÉVY DISTRIBUTIONS IN HEAVY ION PHYSICS

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

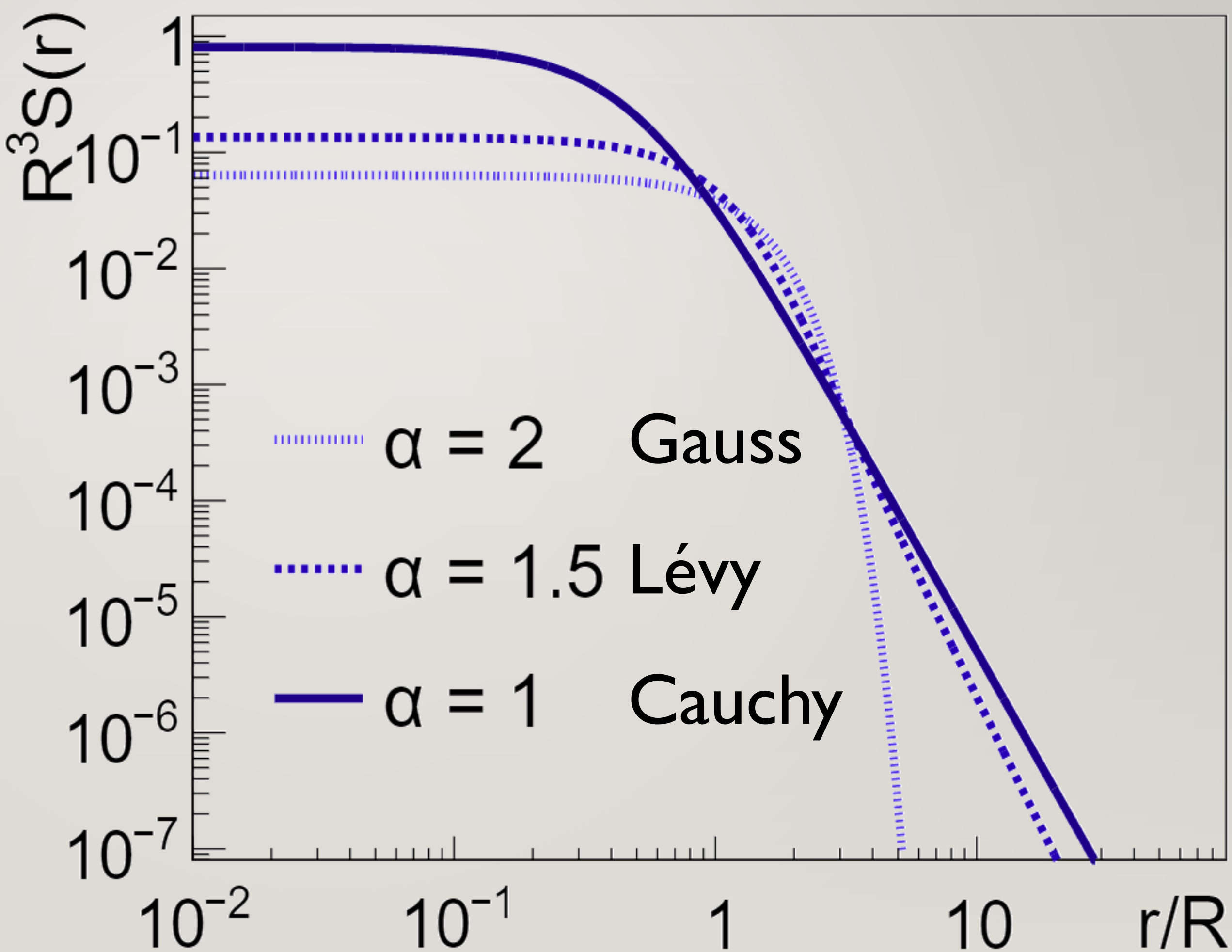


- Shape of the correlation functions with Levy source:
  - $C_2(q) = 1 + \lambda \cdot e^{-|qR|^\alpha}$; $\alpha = 2$: Gaussian; $\alpha = 1$: exponential
    Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67-78
- Reasons for Levy source:
  - Critical phenomena; QCD jets; Anomalous diffusion; what else?

  Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828 (2006) no.1, 525-532;
  Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon. B36 (2005) 329-337
  Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002; Metzler, Klafter, Physics Reports 339 (2000) 1-77

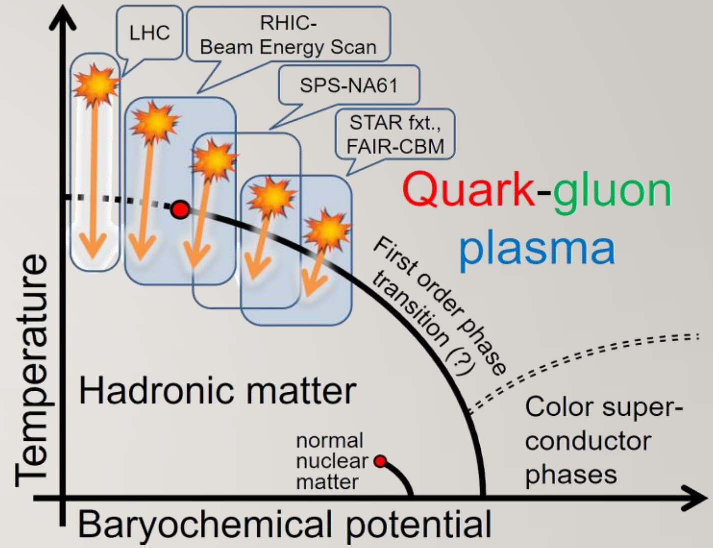
7/25 LÉVY VERSUS GAUSS VERSUS EXPONENTIAL

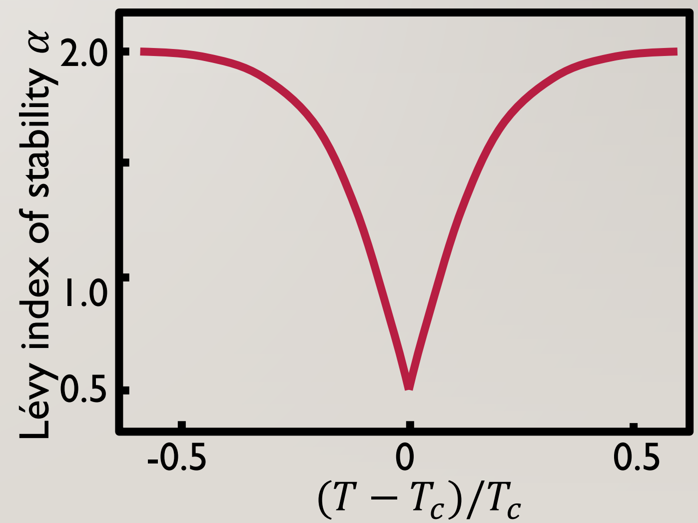
- No tail if $\alpha = 2$, power law if $\alpha < 2$; tail strength depends on α
- If $S(r)$ Lévy, $D(r)$ also Lévy with same α and $R \rightarrow 2^{1/\alpha}R$
- In principle, RMS = ∞ if $\alpha < 2$
- In practice, RMS depends on cutoff
- What do Gaussian HBT radii mean?



8/25 LÉVY INDEX AS A CRITICAL EXPONENT?

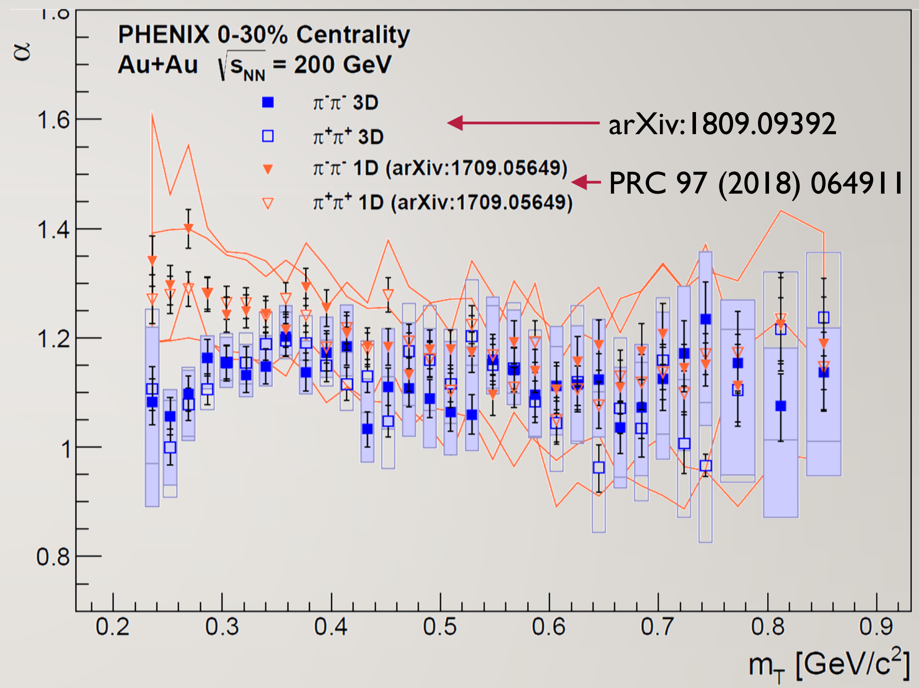
- Critical spatial correlation: $\sim r^{-(d-2+\eta)}$; Lévy source: $\sim r^{-(1+\alpha)}$; $\alpha \Leftrightarrow \eta$?
  Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67,
- QCD universality class ↔ 3D Ising
  Halasz et al., Phys.Rev.D58 (1998) 096007
  Stephanov et al., Phys.Rev.Lett.81 (1998) 4816
- 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 mean?

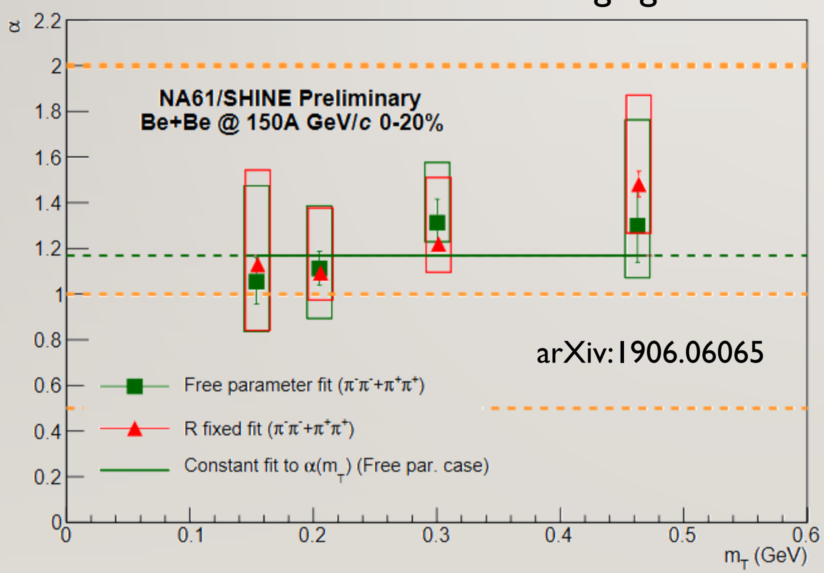


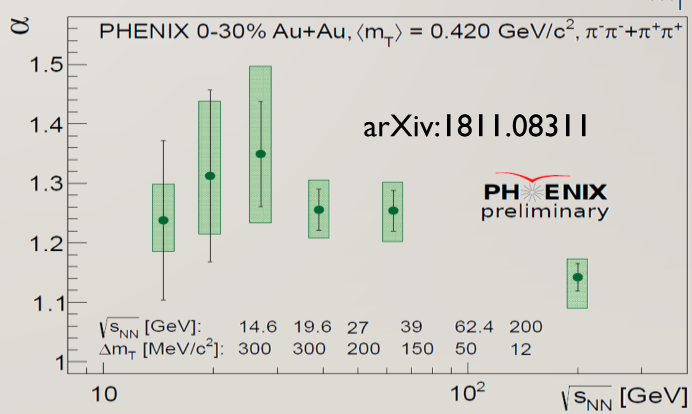


LÉVY HBT MEASUREMENTS

- Many experimental results
  - PHENIX Au+Au: $\alpha \approx 1 - 1.5$
  - STAR Au+Au: ongoing
  - NA61 Be+Be: $\alpha \approx 1 - 1.5$
  - CMS Pb+Pb: $\alpha = 1$ fixed
- Where does this Lévy shape come from? What does it mean?
  - Role of event class averaging?







CONTENTS OF THIS TALK

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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

THE EPOS MODEL

- **E**nergy conserving quantum-mechanical multiple scattering approach, based on **P**artons ladders, **O**ff-shell remnants, and **S**plitting of parton ladders
  - K. Werner et al., PRC82 (2010) 044904, PRC89 (2014) 064903, …
- Based on Monte-Carlo simulation
- Theoretical framework: parton-based Gribov-Regge theory (PBGRT)
- Three main parts of the model:
  - Core-Corona division (based on dE/dx of string segments)
  - Hydrodynamical evolution (vHLLE 3D+1 viscous hydro)
  - Hadronic cascades (UrQMD afterburner)
- Effects/components to be turned on or off (on top of Core):
  - Corona
  - Rescattering
  - Decays

DETAILS OF THE ANALYSIS

- $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions generated by EPOS359
- Observable: $\boldsymbol{D(r_{LCMS}) = \int d\Omega dt D(t, r_x, r_y, r_z)}$

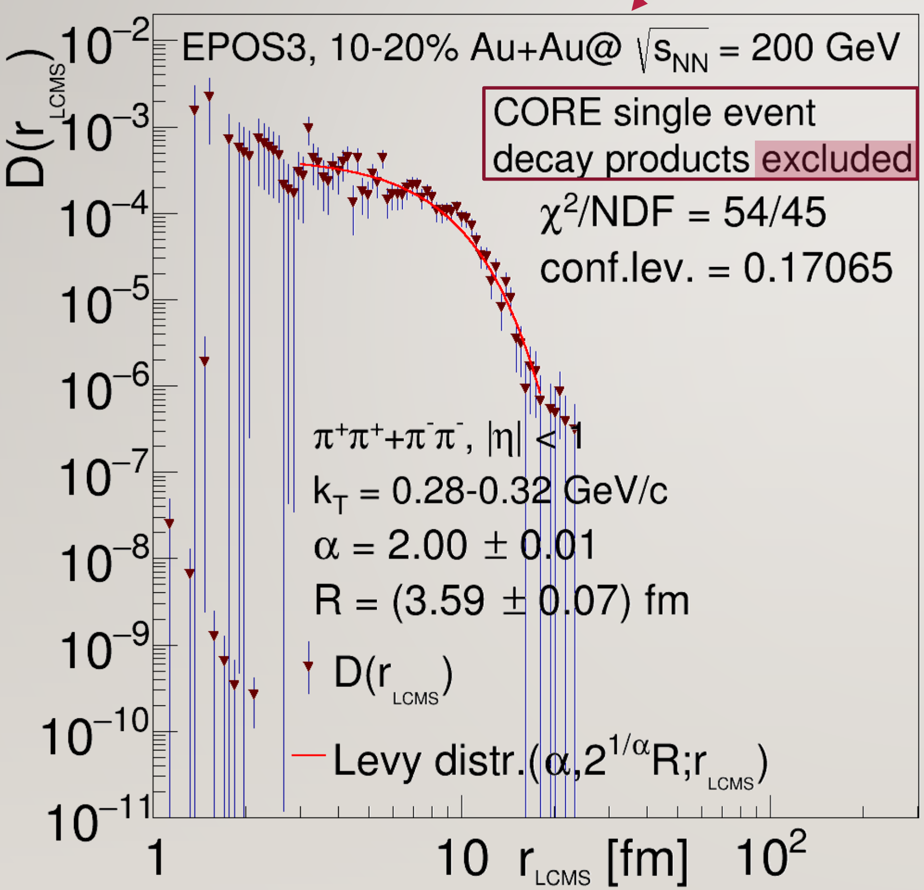
  angle-averaged radial source distribution of like-sign pion pairs

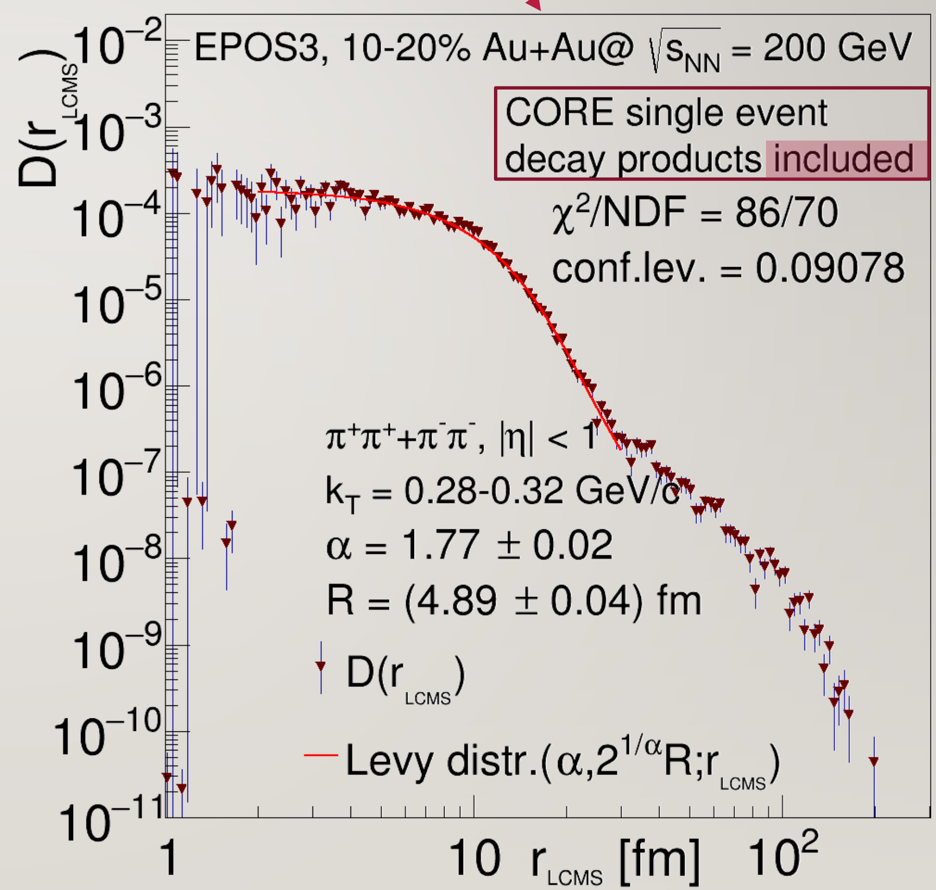
$$r_{LCMS} = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z_{LCMS})^2}; \Delta z_{LCMS} = \Delta z - \frac{\beta(\Delta t)}{\sqrt{1-\beta^2}}; \beta = \frac{p_{z,1} + p_{z,2}}{E_1 + E_2}$$

- Investigated cases:
  - CORE, primordial pions only
  - CORE, decay products included
  - CORE+CORONA+UrQMD, primordial pions only
  - CORE+CORONA+UrQMD, decay products included

EXAMPLE SINGLE EVENT, CORE ONLY

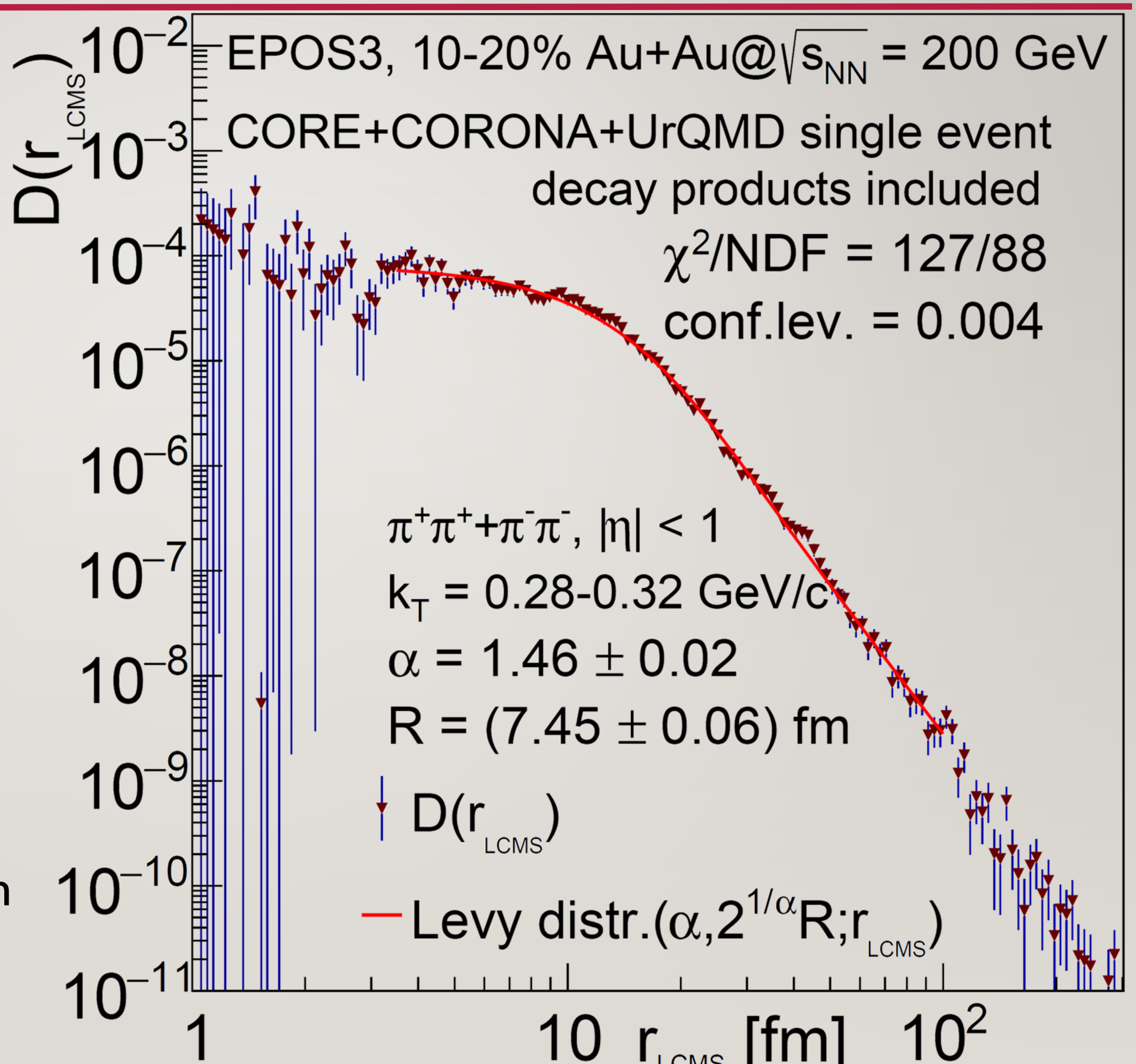
- Gaussian shape without decays, additional structure with decays





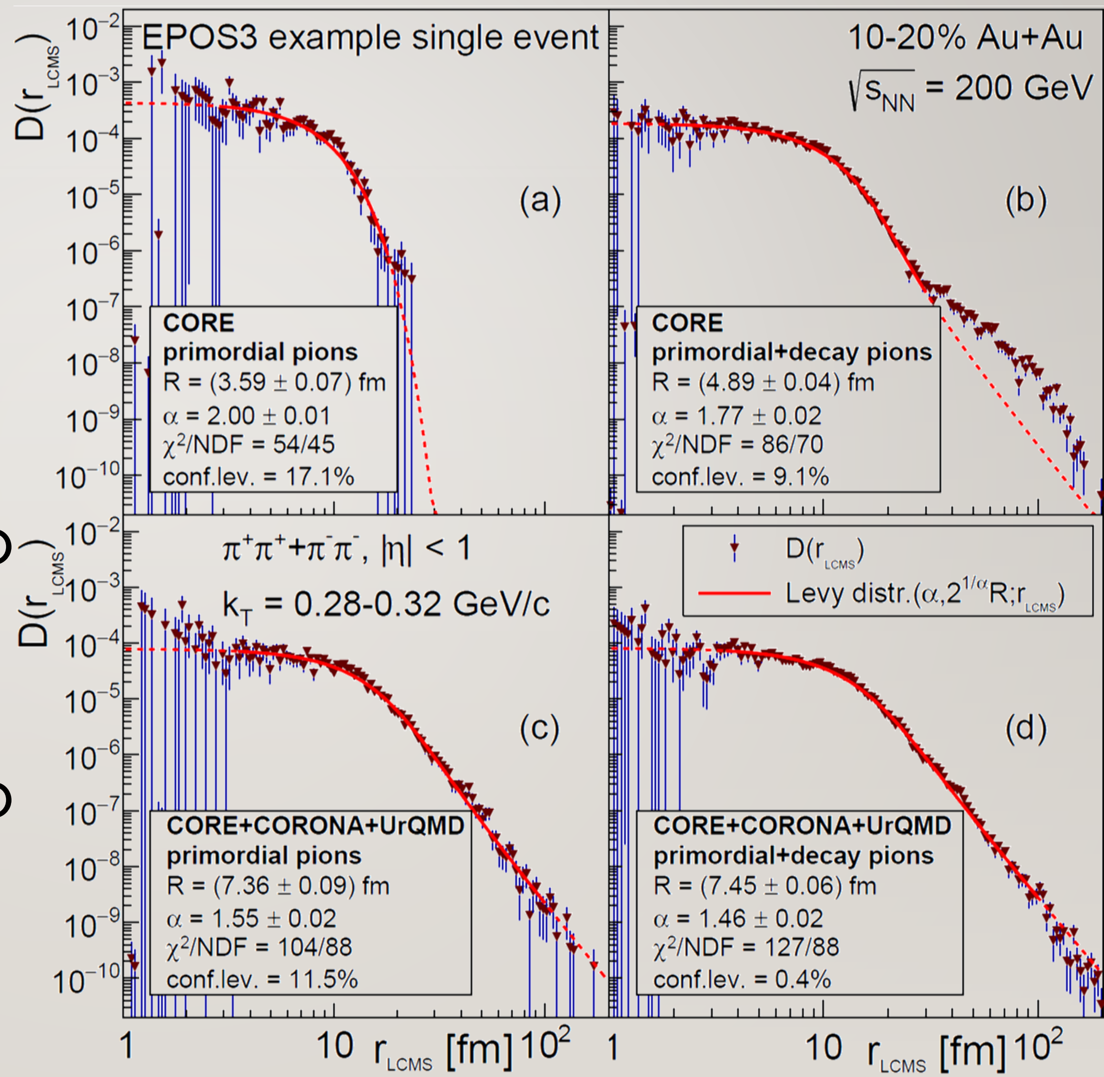
EXAMPLE EVENT, CORE+CORONA+URQMD

- Investigating $D(r)$ event-by-event
- Lévy-fits provide good description (2-100 fm range)
- Repeat such fits for thousands of events
- Extract α, R distribution



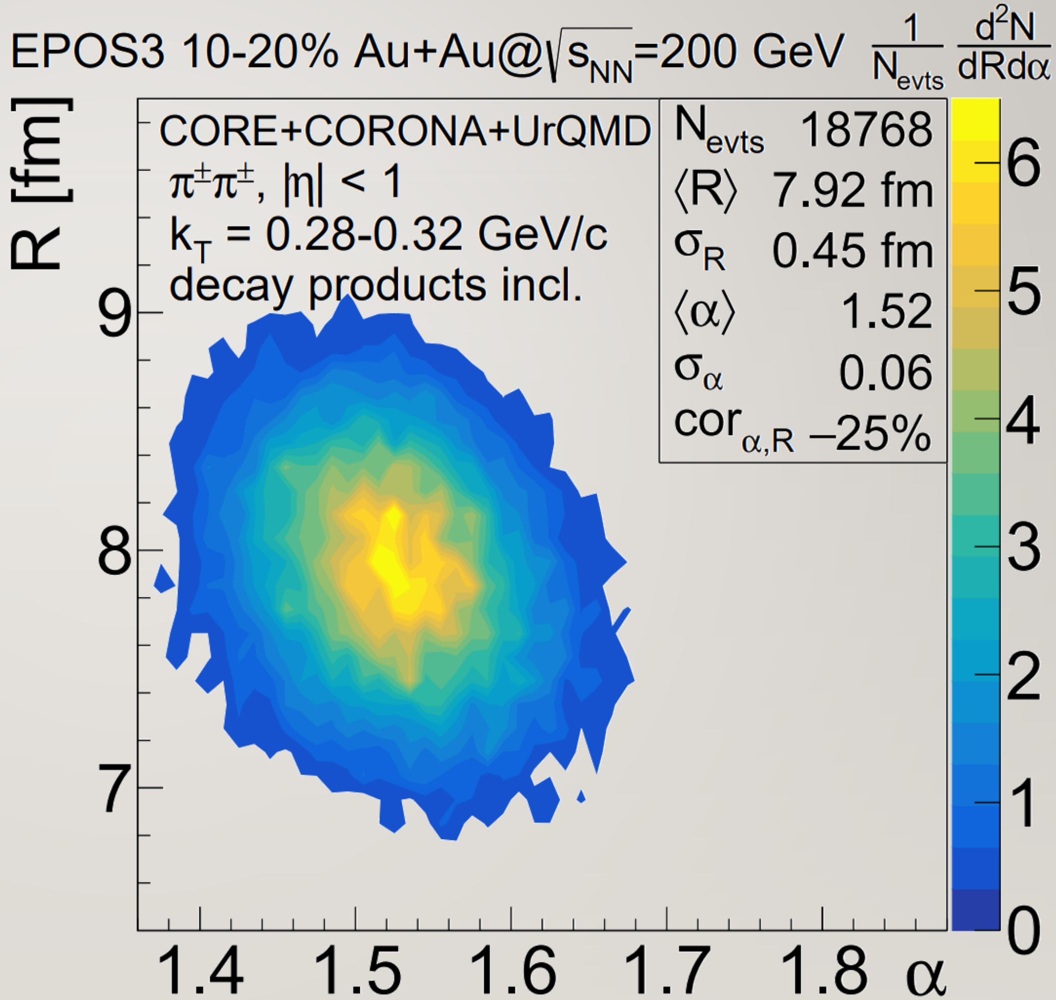
VARIOUS EVENT TYPES COMPARED

- CORE, primordial pions
  - Gaussian source
- CORE + decays
  - power-law structures
- CORE+CORONA+UrQMD
  - Lévy-shape
- CORE+CORONA+UrQMD +decays
  - Lévy-shape



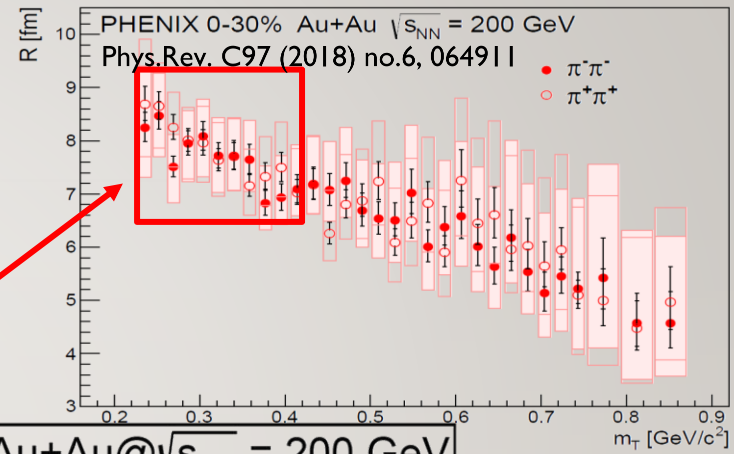
DISTRIBUTION OF α, R PARAMETERS

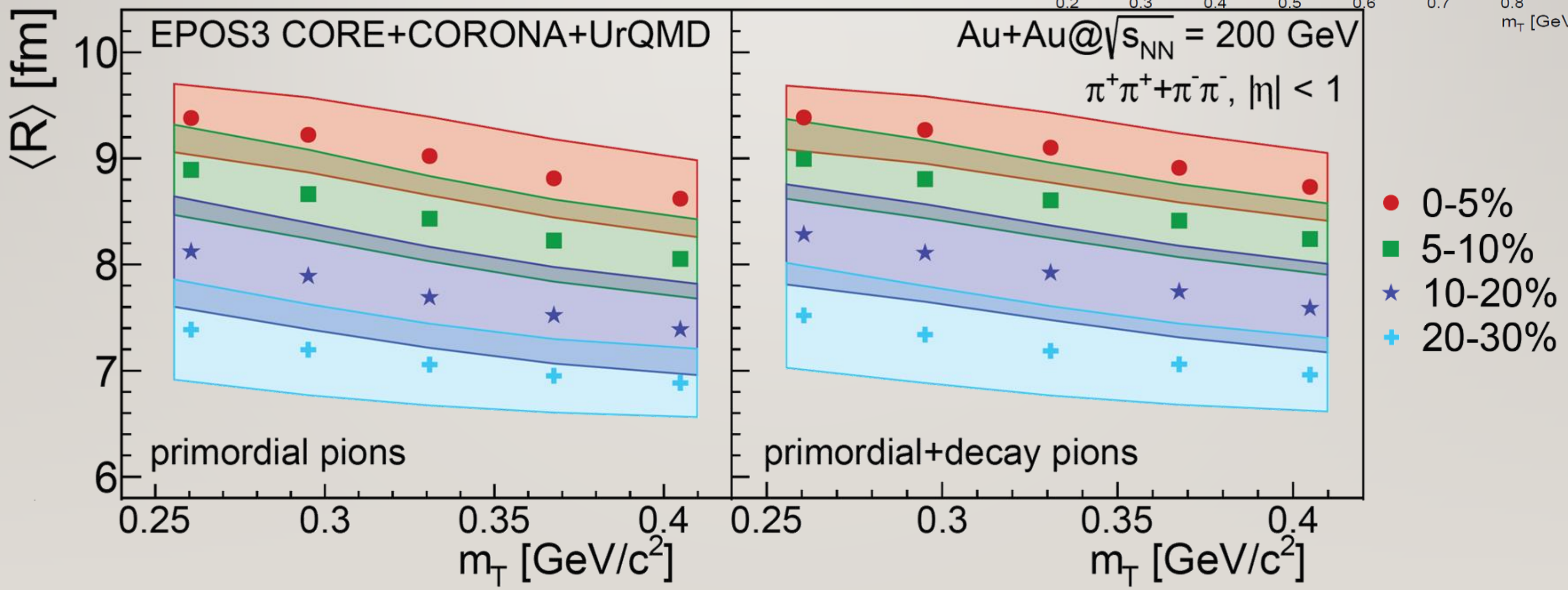
- Normal distribution of α, R for given centrality & kT
- Extract mean and std.dev,
- Investigate centrality & kT dependence
- kT dependence investigated around the peak of the pair-kT distr. to have adequate stat.



AVERAGE LÉVY SCALE R VS TRANSVERSE MASS

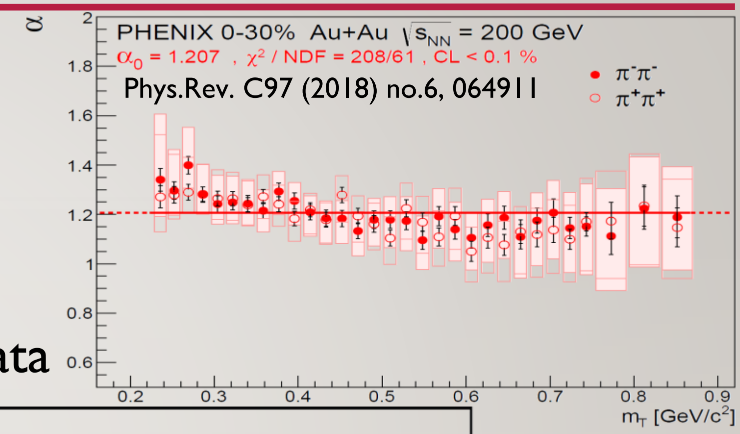
- $\langle R \rangle$ as a function of m_T and centrality
  - Clear dependence on both
  - Distribution width displayed as uncertainty band
- Trends, magnitudes like data
- With decays: slightly higher $\langle R \rangle$ values

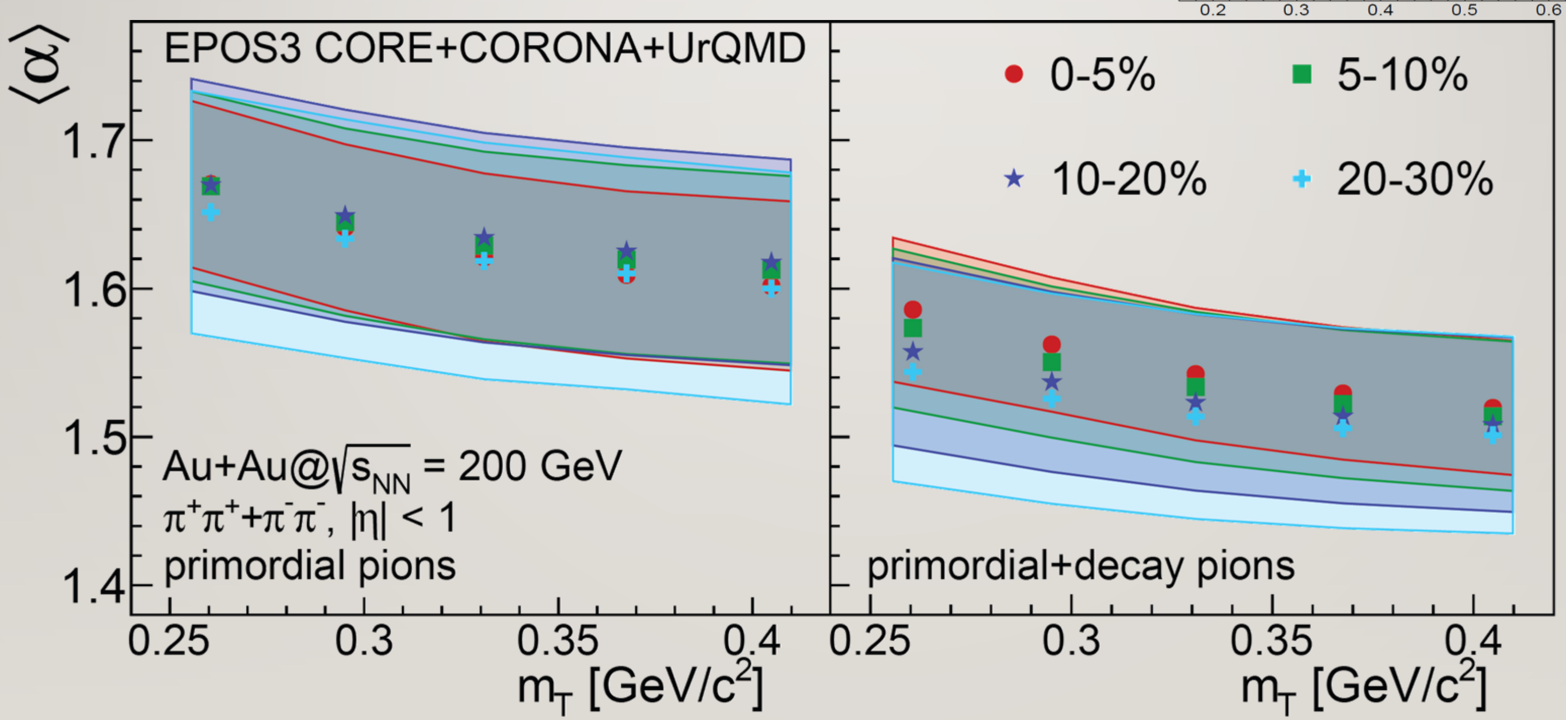




19/25 AVERAGE LÉVY EXPONENT VS TRANSVERSE MASS

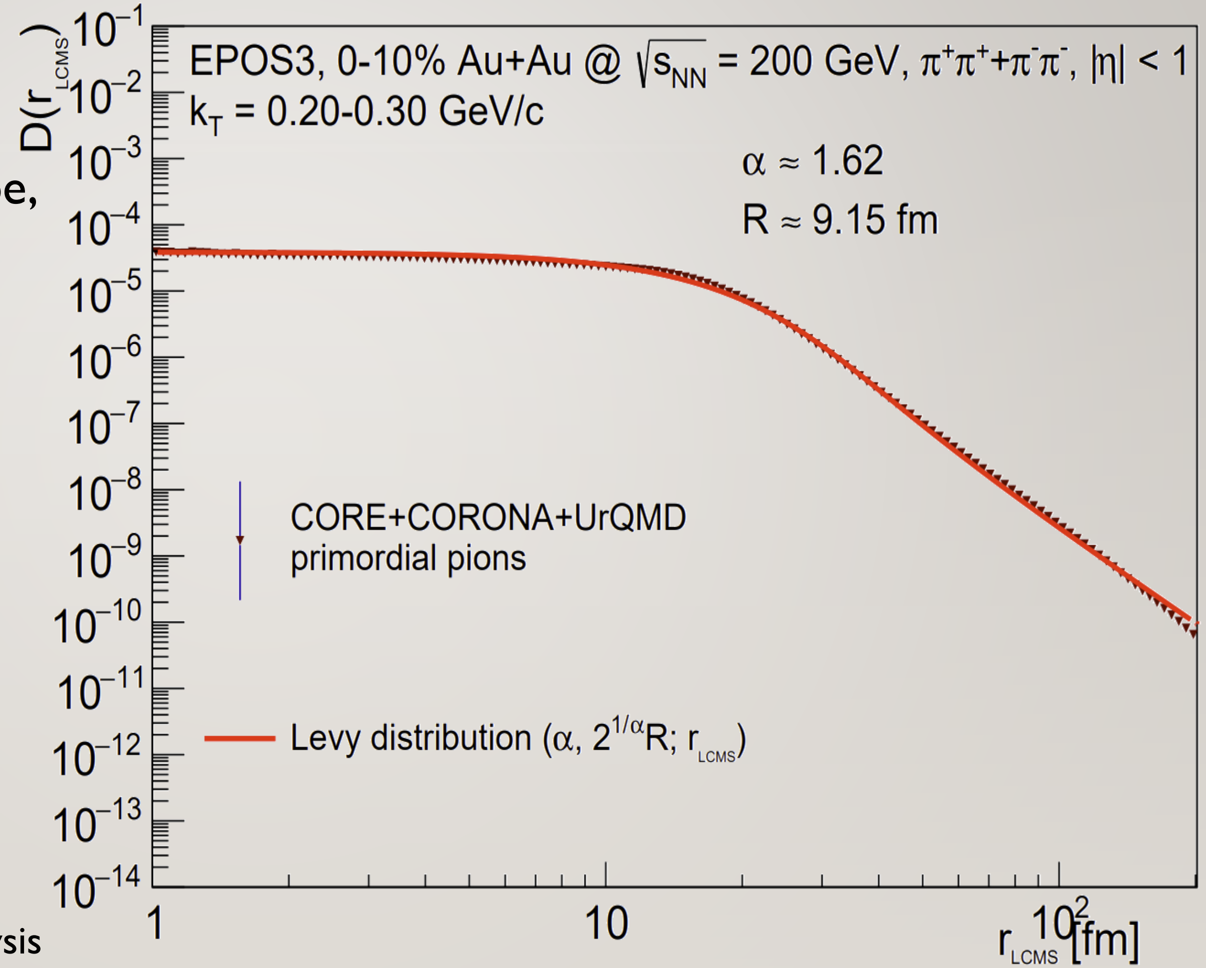
- $\langle \alpha \rangle$ as a function of m_T and centrality
  - Small m_T and centrality dependence
- With decays: clearly smaller values
- Both with and without decays: larger than data





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

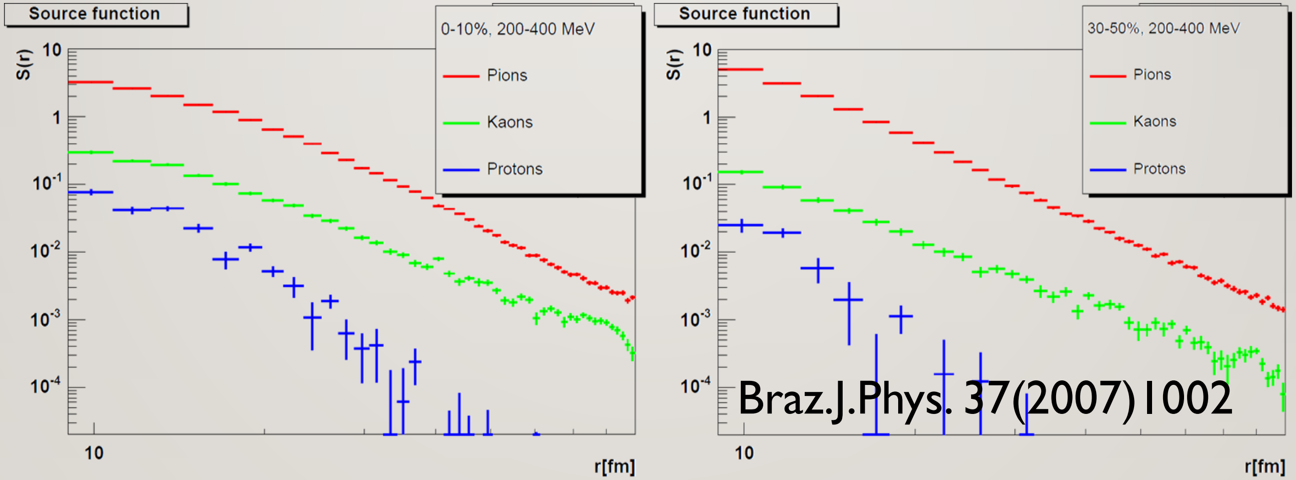


THE IMPORTANCE OF A KAON ANALYSIS

- Kaons: smaller cross-section, larger mean free path
- Heavier power-law tail?
- Prediction for π,K,p based on Humanic's Resonance Model (HRM): anomalous diffusion due to rescattering

  Humanic, Int.J.Mod.Phys. E15 (2006) 197 [nucl-th/0510049]

  Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002 [hep-ph/0702032]



- R_{HBT}(Kaon) mT-scaling or its violation for Lévy scale R?

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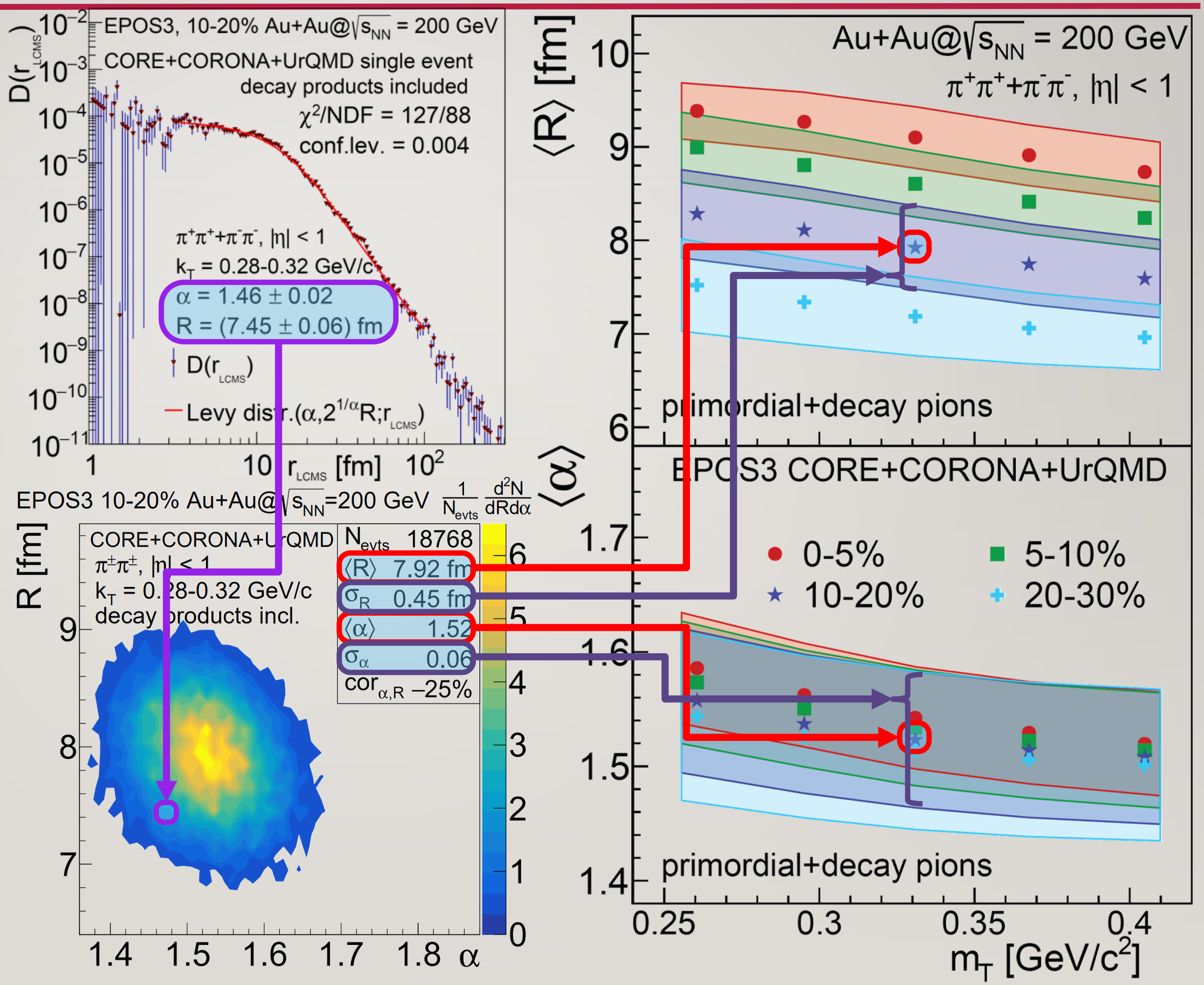
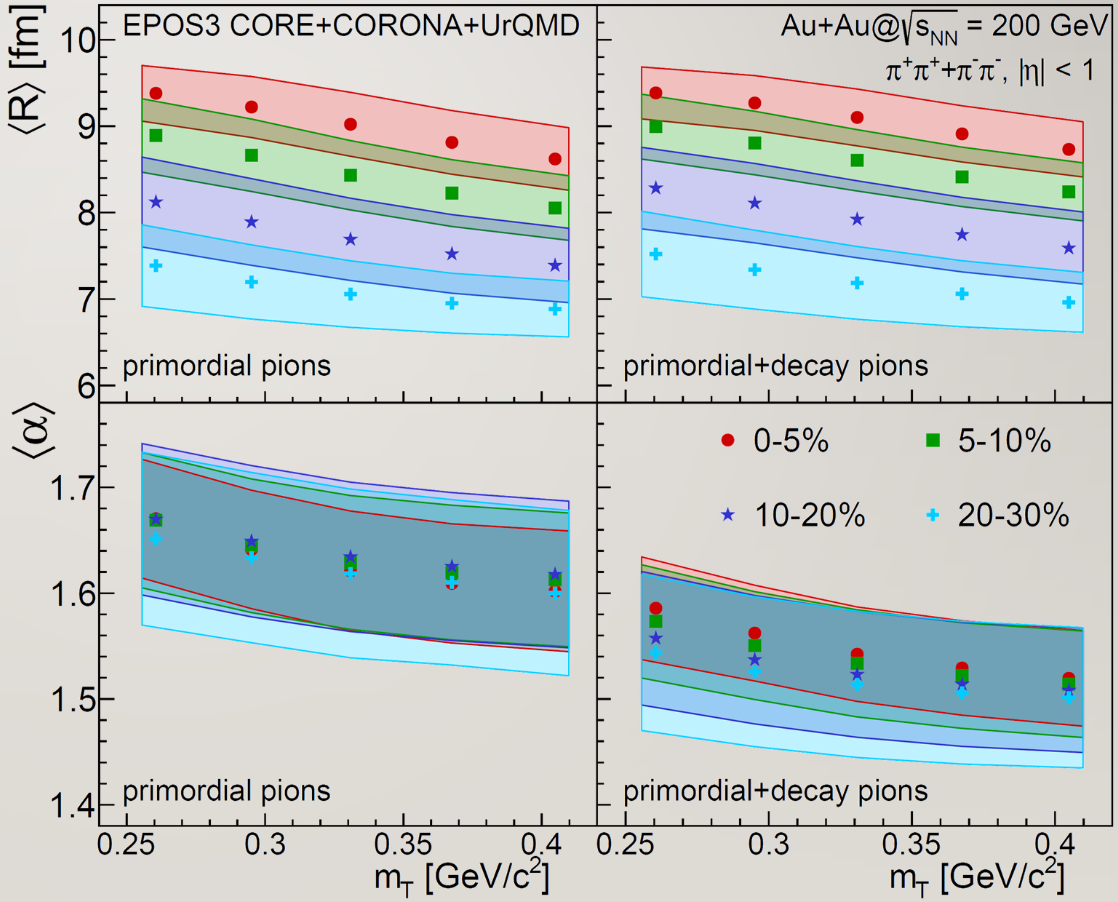
SUMMARY

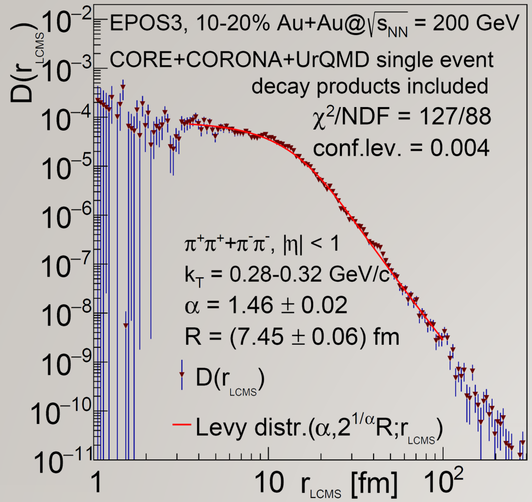
- D(r) calculated in EPOS evt-by-evt
- Lévy fits done evt-by-evt
- Non-Gaussianity in single events
- Extracting mean, & std.dev. of R, α
- m_T & centrality dependence

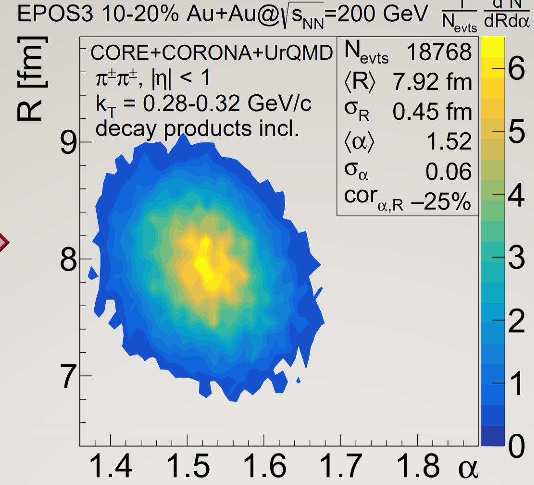


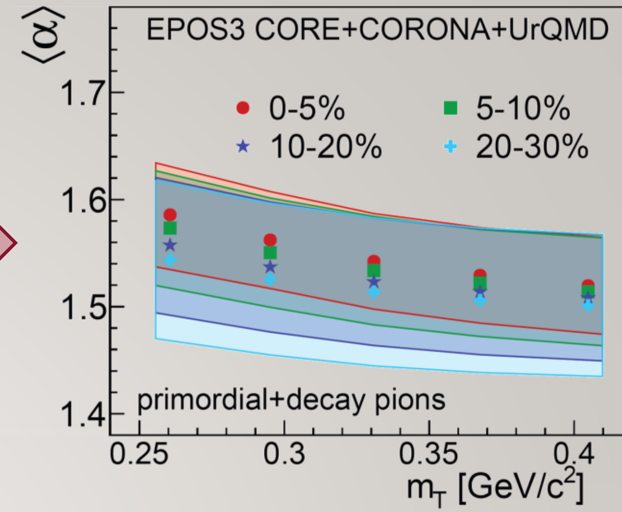
24/25 CONCLUSIONS AND OUTLOOK

- Lévy fits done to event-by-event EPOS spatial distributions, good description
- Power-law tail strongly affected by rescattering and decays
- Lévy R in EPOS: similar to data
- Lévy α in EPOS: larger than data
- Details in:
  - Entropy 24 (2022) 308 [arXiv:2201.07962]
- Next steps:
  - Multiple dimensions
  - Different particle species
  - Correlation function





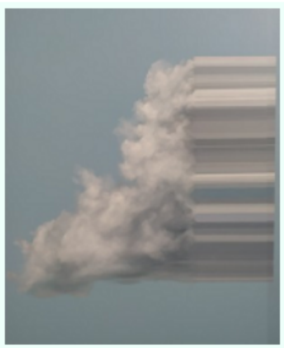




THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects:

ZIMÁNYI SCHOOL 2022


Andrea Katalin Gulyás: Error 2

22nd ZIMÁNYI SCHOOL

WINTER WORKSHOP

ON HEAVY ION PHYSICS

December 5-9, 2022

Budapest, Hungary


József Zimányi (1931 - 2006)

http://zimanyischool.kfki.hu/22

26 BACKUP

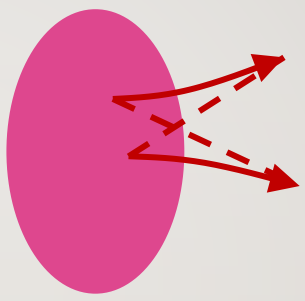
INTERACTIONS: THE COULOMB-EFFECT

- Plane-wave result, based on $\left|\Psi_2^{(0)}(r)\right|^2 = 1 + e^{iqr}$:

$$C_2(q,K) \cong \int D(r,K)\left|\Psi_2^{(0)}(r)\right|^2 dr = 1 + \int D(r,K)e^{iqr}dr$$

- If there is interaction:

$$\Psi_2^{(0)}(r) \to \Psi_2^{(\mathrm{int})}(r_1, r_2)$$



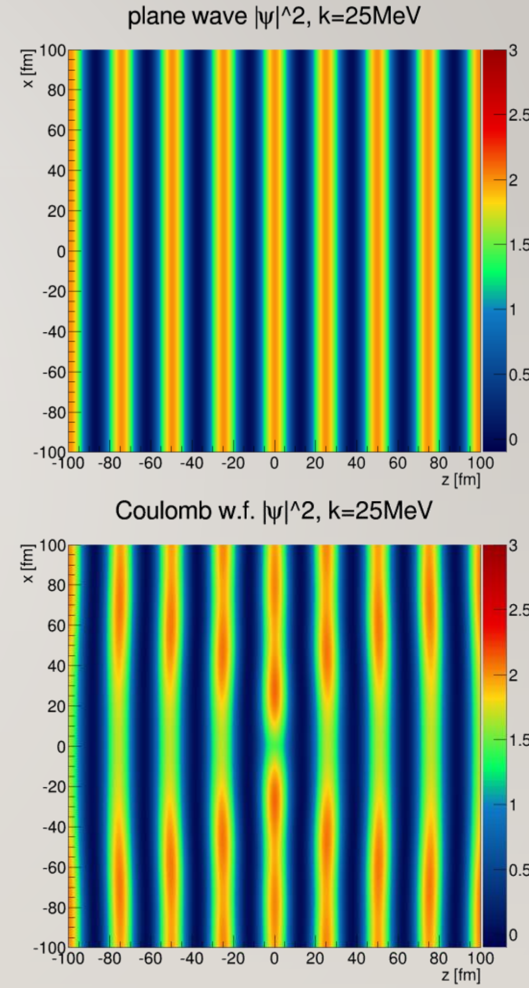
- For Coulomb:

$$\left|\Psi_2^{(C)}(r)\right|^2 = \frac{\pi\eta}{e^{2\pi\eta}-1}\cdot(\text{complicated hypergeometric expression})$$

- Direct fit with this, or the usual iterative Coulomb-correction:

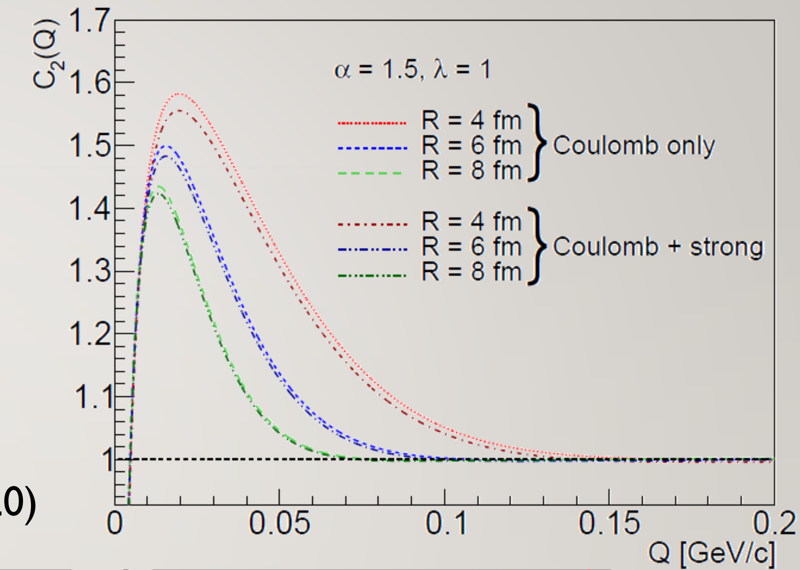
$$C_{\mathrm{Bose-Einstein}}(q)K(q), \text{ where } K(q) = \frac{\int D(r,K)\left|\Psi_2^{(C)}(r)\right|^2 dr}{\int D(r,K)\left|\Psi_2^{(0)}(r)\right|^2 dr}$$

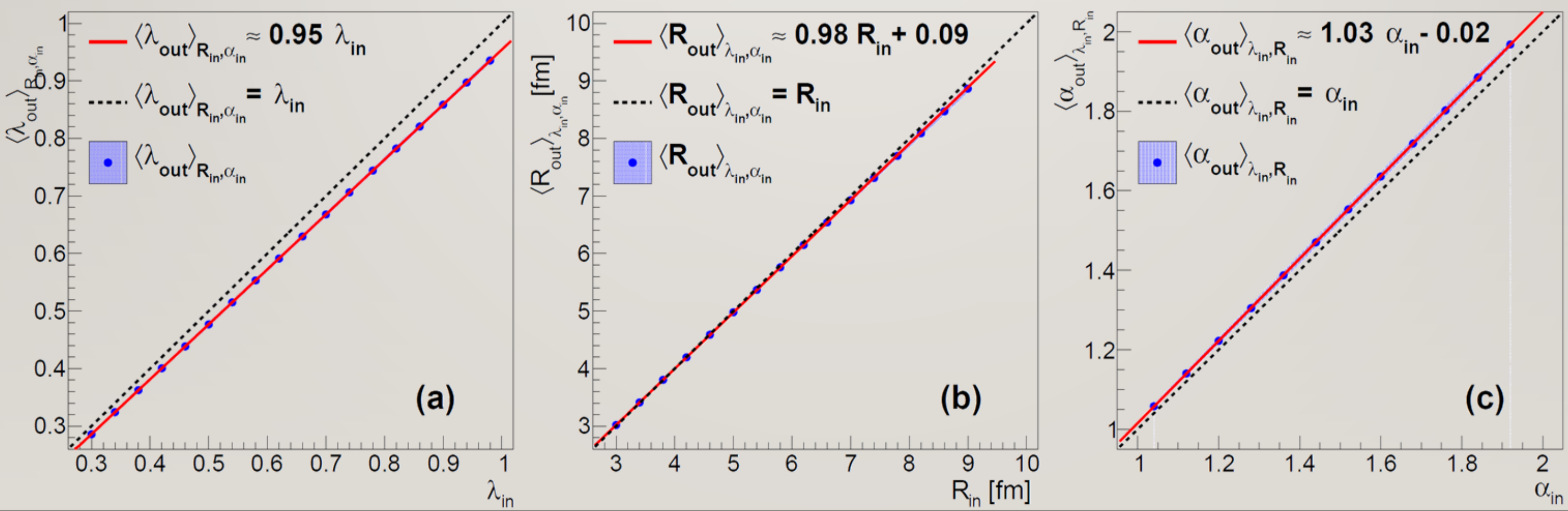
- Complication: need for integrating power-law tails
- Parametrization possible
  - MCs, S. Lökös, M. Nagy, Phys. Part. Nuclei 51 (2020) 238
  - MCs, S. Lökös, M. Nagy, Universe 5 (2019) 6, 133



28/25 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
  D. Kincses, M. I. Nagy, M. Cs. PRC 102, 064912 (2020)



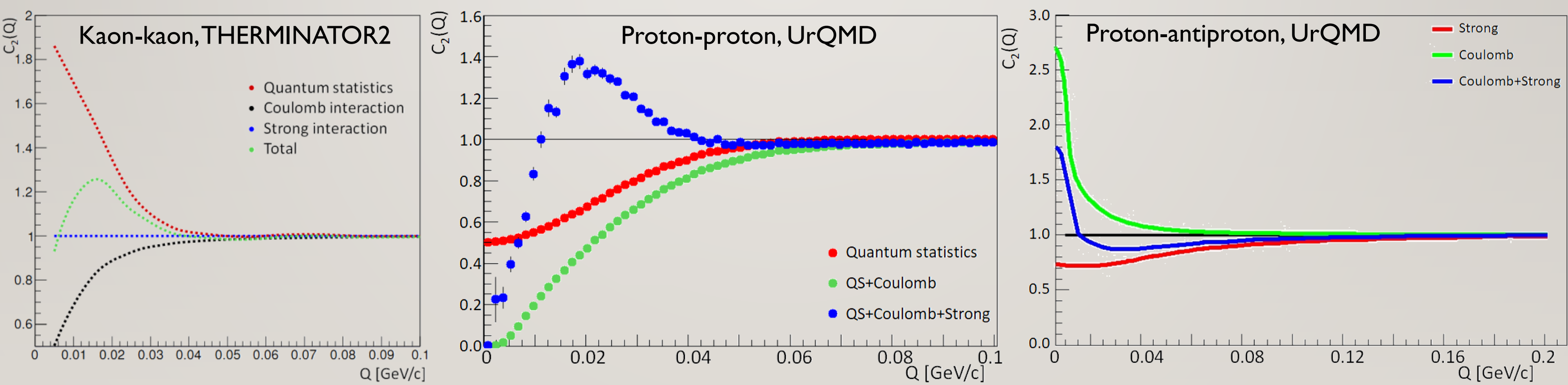


ROLE OF THE STRONG INTERACTION

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

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

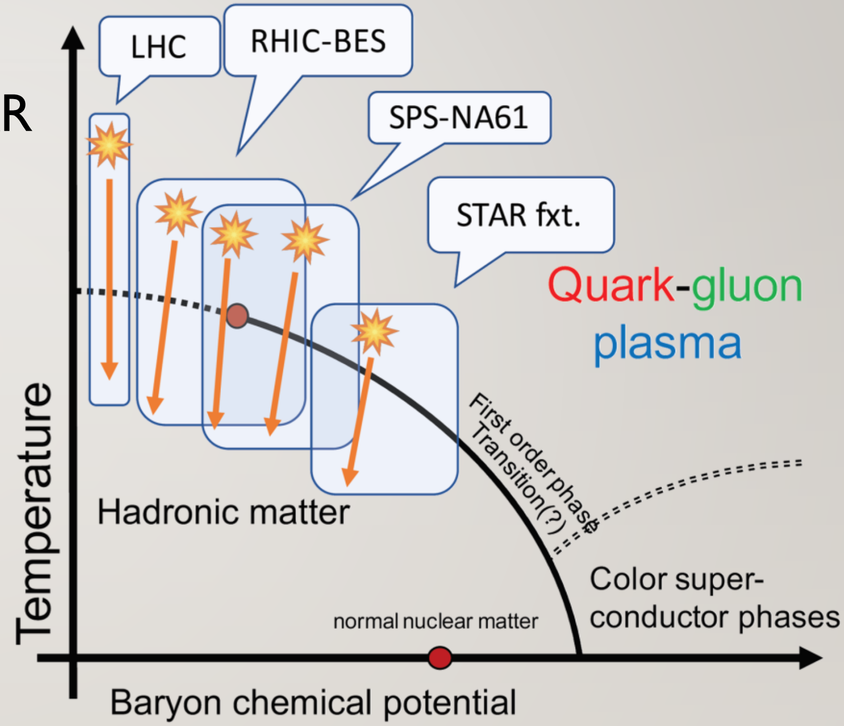
- Pair wave function determines $D \leftrightarrow C_2$ connection
- Mesons, baryons: strong interaction; fermions: anticorrelation
- Non-identical pairs: interaction modifies wave function



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

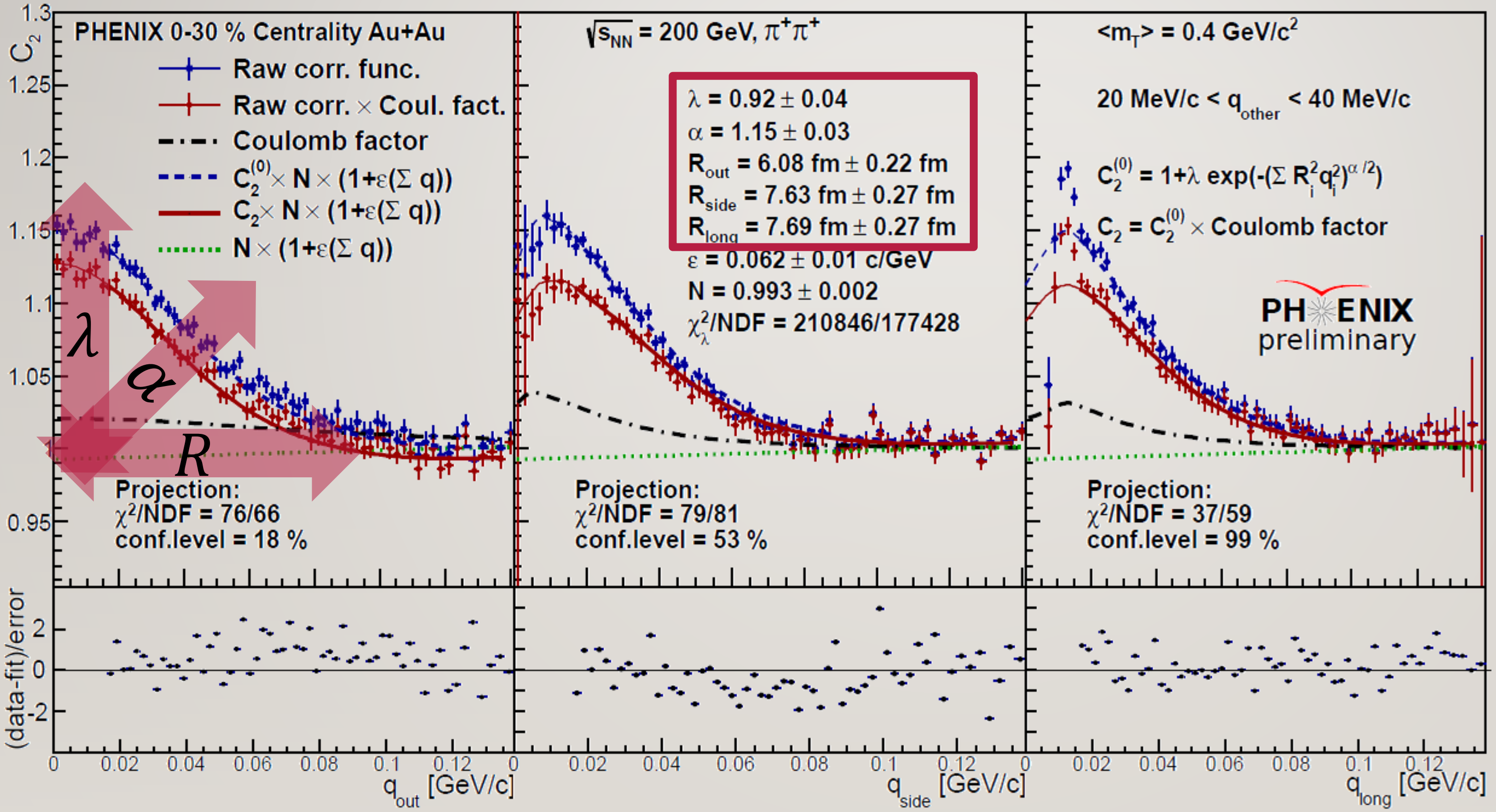
30/25 HBT MEASUREMENTS AND THE PHASE DIAGRAM

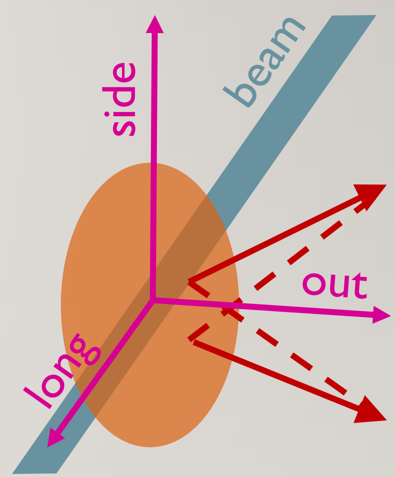
- LHC: measurement at CMS
  - 2-5 ATeV energy, p+p & Pb+Pb
- RHIC: measurement at PHENIX+STAR
  - 10-200 AGeV energy, Au+Au
- SPS: measurement at NA61
  - 17 AGeV energy, Be+Be
- Phase diagram can be investigated



31 /25 A CROSS-CHECK: 3D LÉVY FEMTOSCOPY

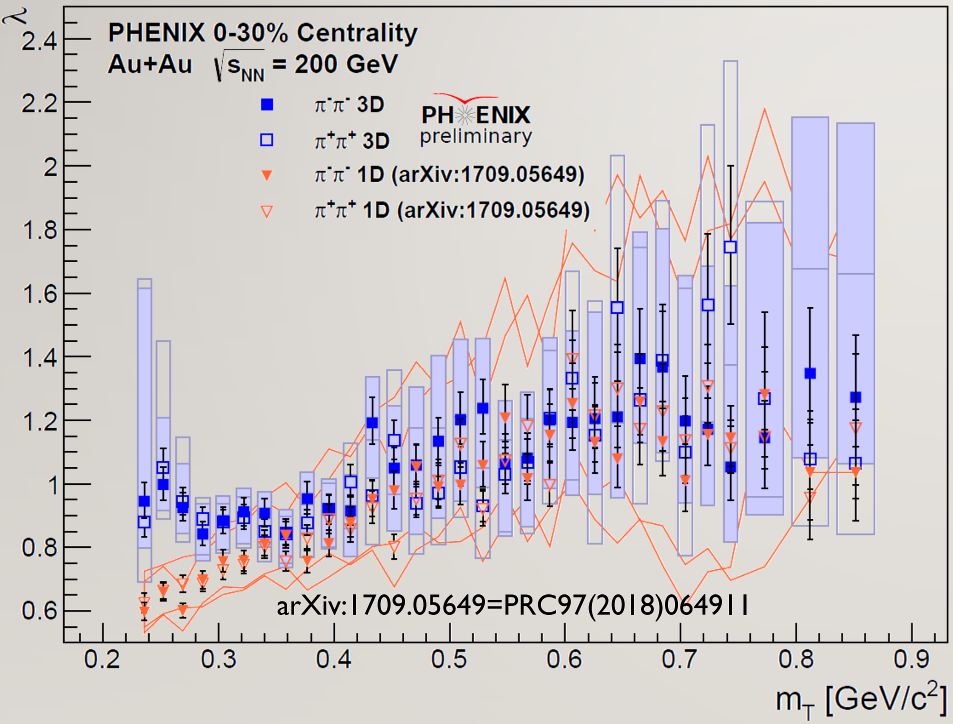
- Femtoscopy done in 3D: Bertsch-Pratt pair frame (out/side/long coordinates)
- Physical parameters: $R_{out/side/long}$ λ, α measured versus pair m_T
- Fit in this case: modified log-likelihood (small statistics in peak range)

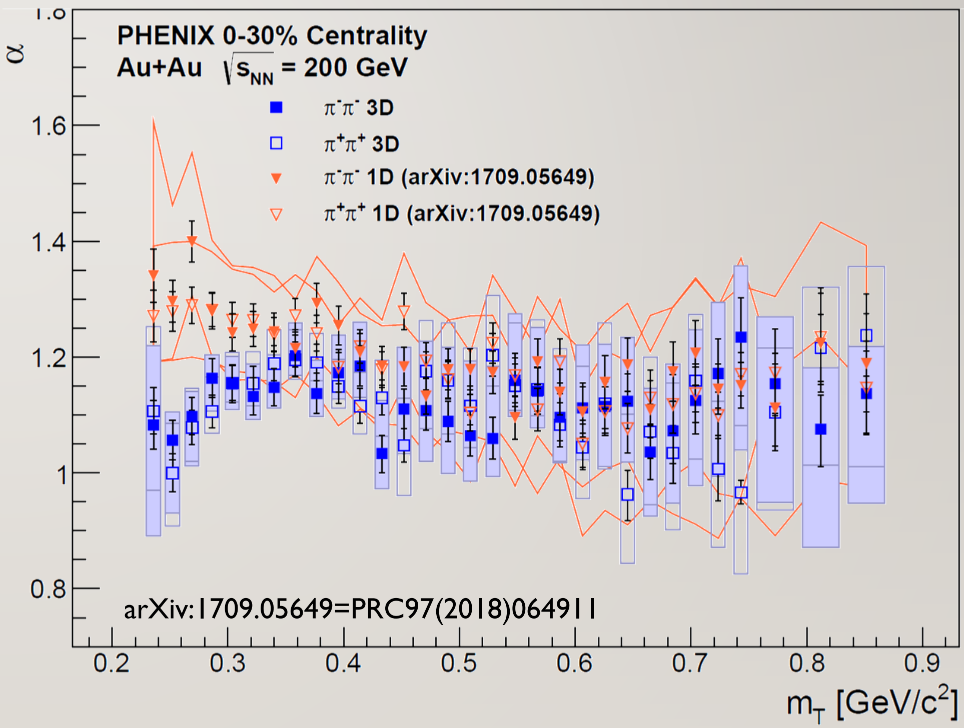




3D VERSUS 1D: STRENGTH λ AND SHAPE α

- Compatible with 1D (Q_{LCMS}) measurement of PRC97(2018)064911
- Small discrepancy at small mT: due to large Rlong at small mT?





OPEN QUESTIONS

- Collision energy and centrality dependence of Lévy parameters?
  - Non-monotonicity in $\alpha(\sqrt{s_{NN}})$ or $\alpha(\text{centrality})$?
  - Hole in $\lambda(m_T)$ at low $\sqrt{s_{NN}}$? Really due to η'?
- Reason for the appearance of Lévy distributions for pions?
  - What is the Lévy exponent for kaons?
  - Kaons have smaller total cross-section thus larger mean free path, heavier tail?
  - Does m_T scaling hold for Lévy scale R?
- Correlation strength versus core-halo picture: are there other effects?
  - Three-particle correlations may show if coherence or other effects play a role
  - Other effects may also play a role (finite meson sizes, random field phase shift, etc)