

Event-by-event analysis of the two-particle source function in heavy-ion collisions with EPOS

DÁNIEL KINCSES

IN COLLABORATION WITH
M. STEFANIAK, M. CSANÁD

EÖTVÖS UNIVERSITY,
BUDAPEST, HUNGARY

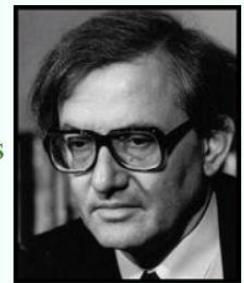


ZIMÁNYI SCHOOL 2021

21st ZIMÁNYI SCHOOL
WINTER WORKSHOP
ON HEAVY ION PHYSICS

December 6-10, 2021
Budapest, Hungary

József Zimányi (1931 - 2006)



Basic definitions of femtoscopical correlation functions

- Single particle distribution: $N_1(p) = \int dx S(x, p)$ phase-space density
 - Pair momentum distr.: $N_2(p_1, p_2) = \int dx_1 dx_2 S(x_1, p_1)S(x_2, p_2)|\psi(x_1, x_2)|^2$
 - Correlation function: $C(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)}$
 - Pair source/spatial correlation: $D(r, K) = \int d^4\rho S\left(\rho + \frac{r}{2}, K\right)S\left(\rho - \frac{r}{2}, K\right)$ relative coordinate
- $C(Q, K) = \frac{\int D(r, K)|\psi_Q(r)|^2 dr}{\int D(r, K)dr}$
- relative pair momentum average pair momentum Pair wave function
- Experiments: measuring $C(Q)$ to gain information about $D(r)$

The two-particle source function (spatial correlations)

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

- Experiments – no direct access to pair-source
 - Assumption on the **shape of the $D(r)$ pair-source function**
 - Proper description of FSI in $\psi_Q(r)$ **symmetrized pair wave function**
 - Calculating $C(Q)$, then testing the assumption on experimental data
 - Experimental indications – **power-law tail for pions, Lévy-type sources?**
- Event generator models (like EPOS) – direct access to pair-source!
 - Phenomenological investigations of $D(r)$ possible

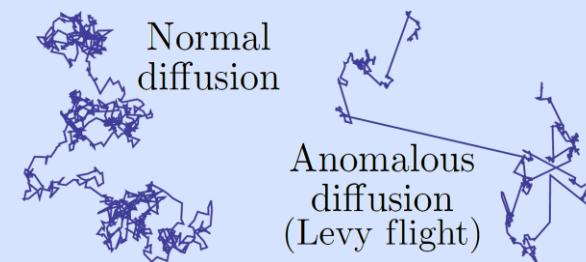
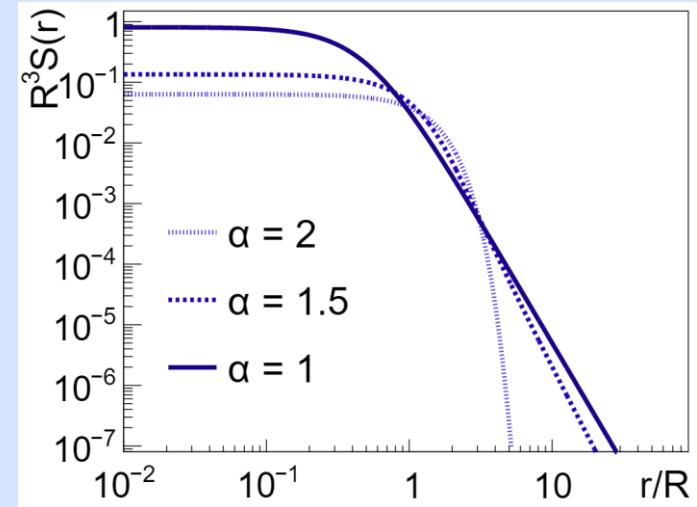
Lévy distributions in heavy ion physics

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

- Possible (competing) reasons for the appearance of Lévy-type sources:
 1. Proximity of the critical endpoint
 2. Anomalous diffusion
 3. Jet fragmentation
- Symmetric Lévy-stable distribution:

- From generalized central limit theorem, power-law tail (if $\alpha < 2$) $\sim r^{-(1+\alpha)}$
- $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy
- Retains the same α under convolution

$$S(r) = \mathcal{L}(\alpha, R; r) \Rightarrow D(r) = \mathcal{L}(\alpha, 2^{1/\alpha} R; r)$$



The EPOS model

- Energy conserving quantum-mechanical multiple scattering approach, based on **Partons** (parton ladders), **Off-shell remnants**, and **Splitting** of parton ladders.
- The model is based on **Monte-Carlo techniques**
- 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)

Details of the analysis

- $\sqrt{s_{NN}} = 200 \text{ GeV Au+Au}$ collisions generated by **EPOS359**
- Observable:
angle-avg. radial source distribution of like-sign pion pairs
$$D(r_{1,2}^{LCMS}) = \int d\Omega dt D(r)$$
- Investigated cases:
 1. **CORE, primordial pions – Gaussian source shape***
 2. CORE, decay products incl. – power-law structures appear*
 3. CORE+CORONA+UrQMD, primordial pions – Lévy-shape
 4. CORE+CORONA+UrQMD, decay products incl. – Lévy-shape

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

Details of the analysis

- $\sqrt{s_{\text{NN}}} = 200 \text{ GeV Au+Au}$ collisions generated by **EPOS359**
- Observable:
angle-avg. radial source distribution of like-sign pion pairs
$$D(r_{1,2}^{\text{LCMS}}) = \int d\Omega dt D(r)$$
- Investigated cases:
 1. CORE, primordial pions – Gaussian source shape*
 2. **CORE, decay products incl. – power-law structures appear***
 3. CORE+CORONA+UrQMD, primordial pions – Lévy-shape
 4. CORE+CORONA+UrQMD, decay products incl. – Lévy-shape

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

Details of the analysis

- $\sqrt{s_{NN}} = 200 \text{ GeV Au+Au}$ collisions generated by **EPOS359**
- Observable:
angle-avg. radial source distribution of like-sign pion pairs
$$D(r_{1,2}^{LCMS}) = \int d\Omega dt D(r)$$
- Investigated cases:
 1. CORE, primordial pions – Gaussian source shape*
 2. CORE, decay products incl. – power-law structures appear*
 3. **CORE+CORONA+UrQMD, primordial pions – Lévy-shape**
 4. CORE+CORONA+UrQMD, decay products incl. – Lévy-shape

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

Details of the analysis

- $\sqrt{s_{NN}} = 200 \text{ GeV Au+Au}$ collisions generated by **EPOS359**
- Observable:
angle-avg. radial source distribution of like-sign pion pairs
$$D(r_{1,2}^{LCMS}) = \int d\Omega dt D(r)$$
- Investigated cases:
 1. CORE, primordial pions – Gaussian source shape*
 2. CORE, decay products incl. – power-law structures appear*
 3. CORE+CORONA+UrQMD, primordial pions – Lévy-shape
 - 4. CORE+CORONA+UrQMD, decay products incl. – Lévy-shape**

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

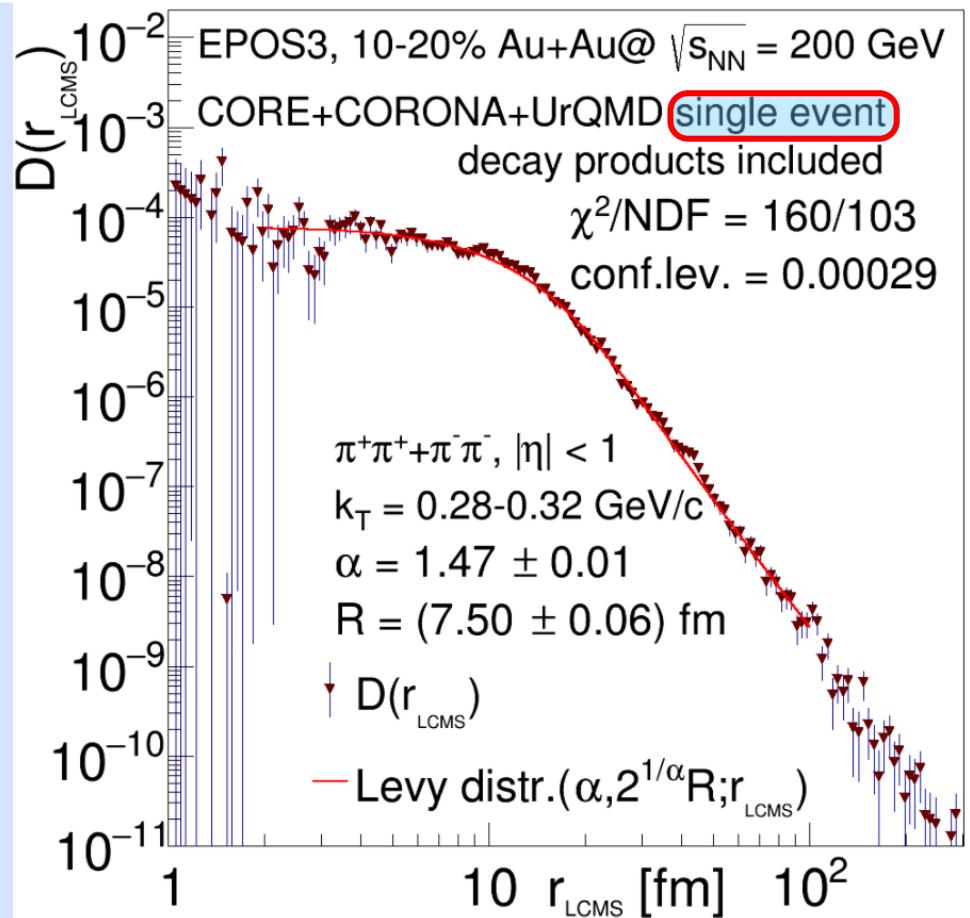
Details of the analysis

- $\sqrt{s_{NN}} = 200 \text{ GeV Au+Au}$ collisions generated by **EPOS359**
- Observable:
angle-avg. radial source distribution of like-sign pion pairs
$$D(r_{1,2}^{LCMS}) = \int d\Omega dt D(r)$$
- Investigated cases:
 1. CORE, primordial pions – Gaussian source shape*
 2. CORE, decay products incl. – power-law structures appear*
 3. **CORE+CORONA+UrQMD, primordial pions – Lévy-shape**
 4. **CORE+CORONA+UrQMD, decay products incl. – Lévy-shape**

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

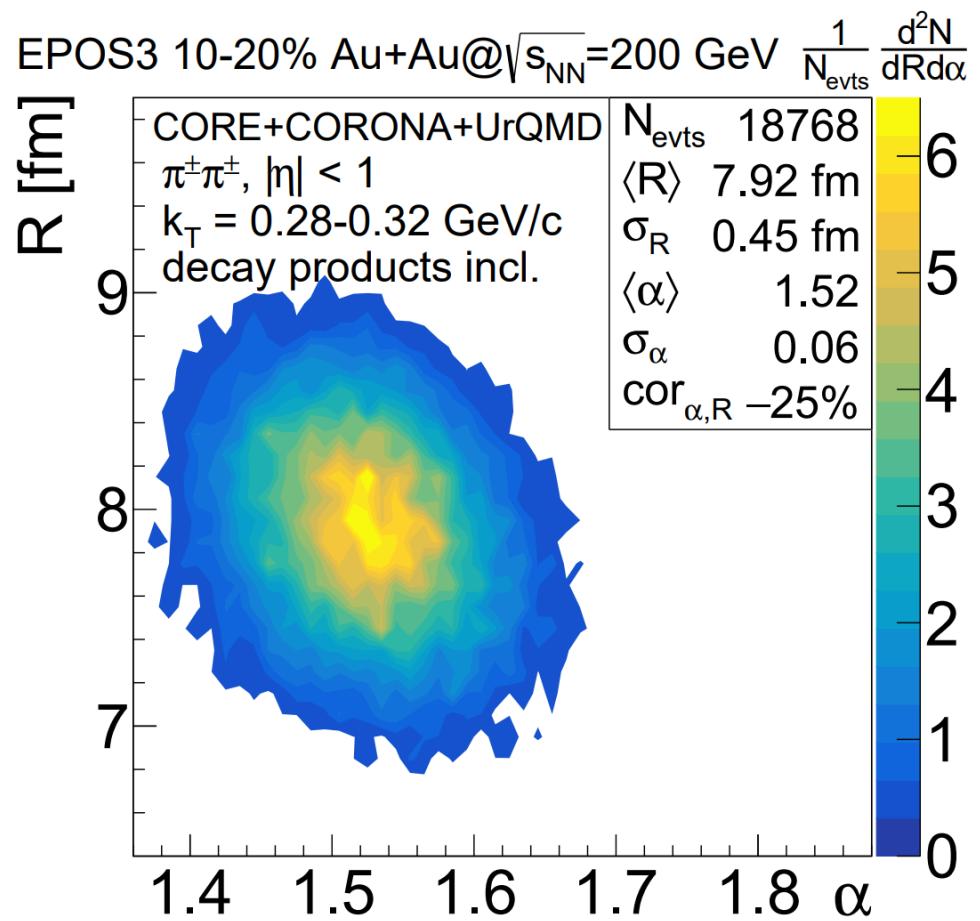
Example single evt. fit – CORE+CORONA+UrQMD with decay products included

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



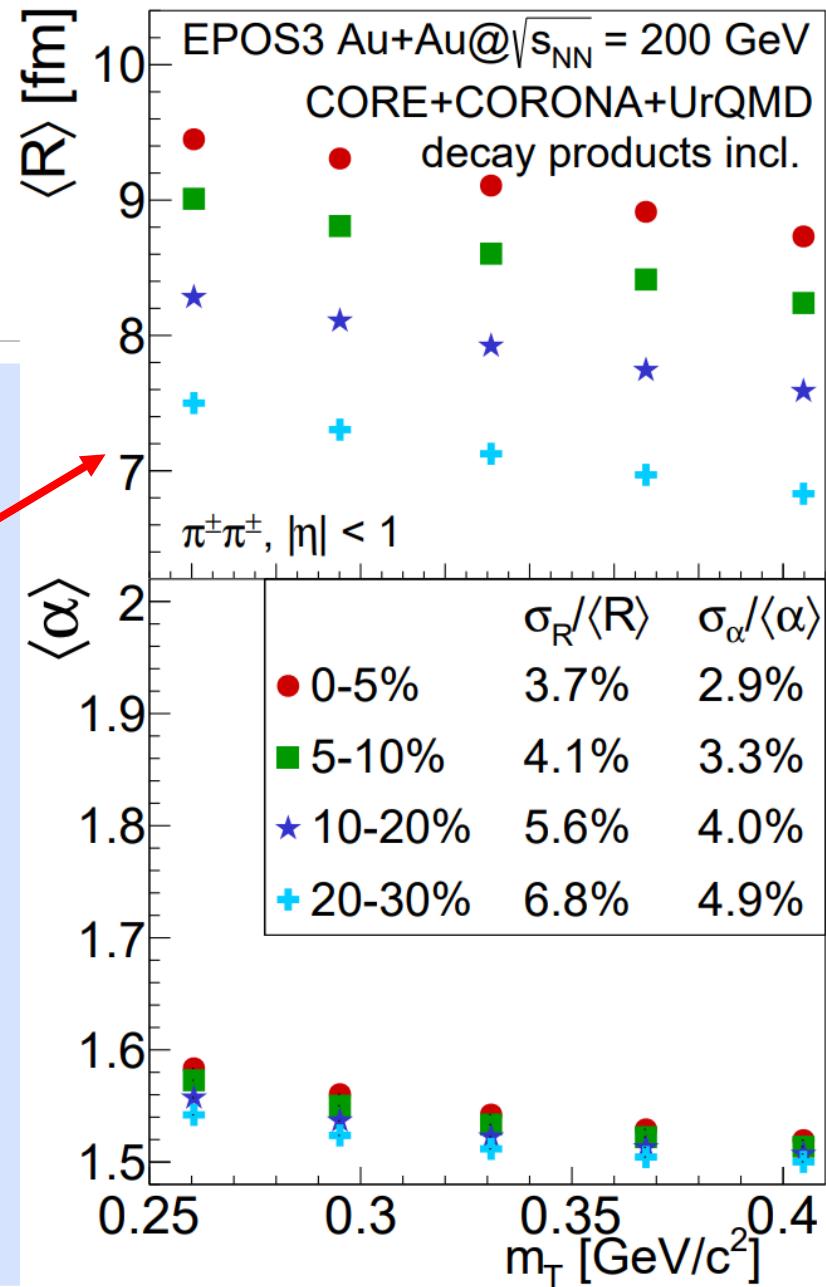
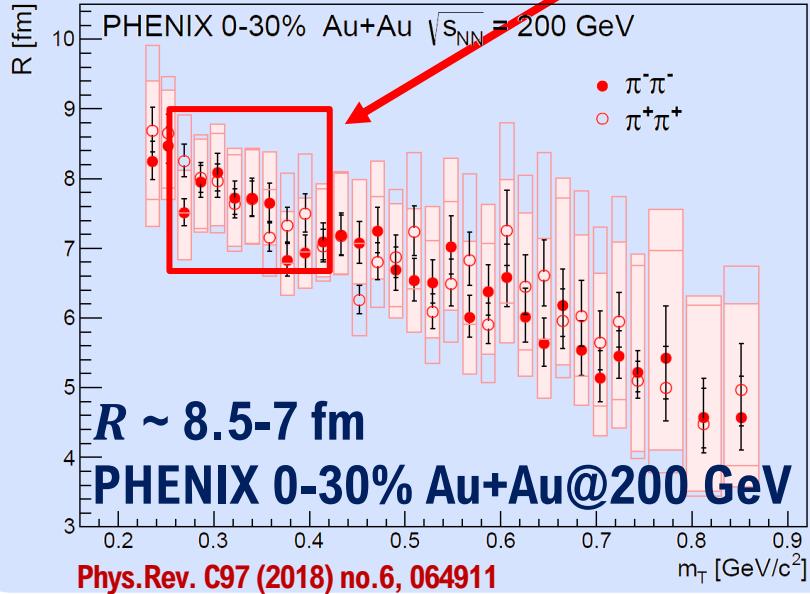
Example α, R distribution – CORE+CORONA+UrQMD with decay products included

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



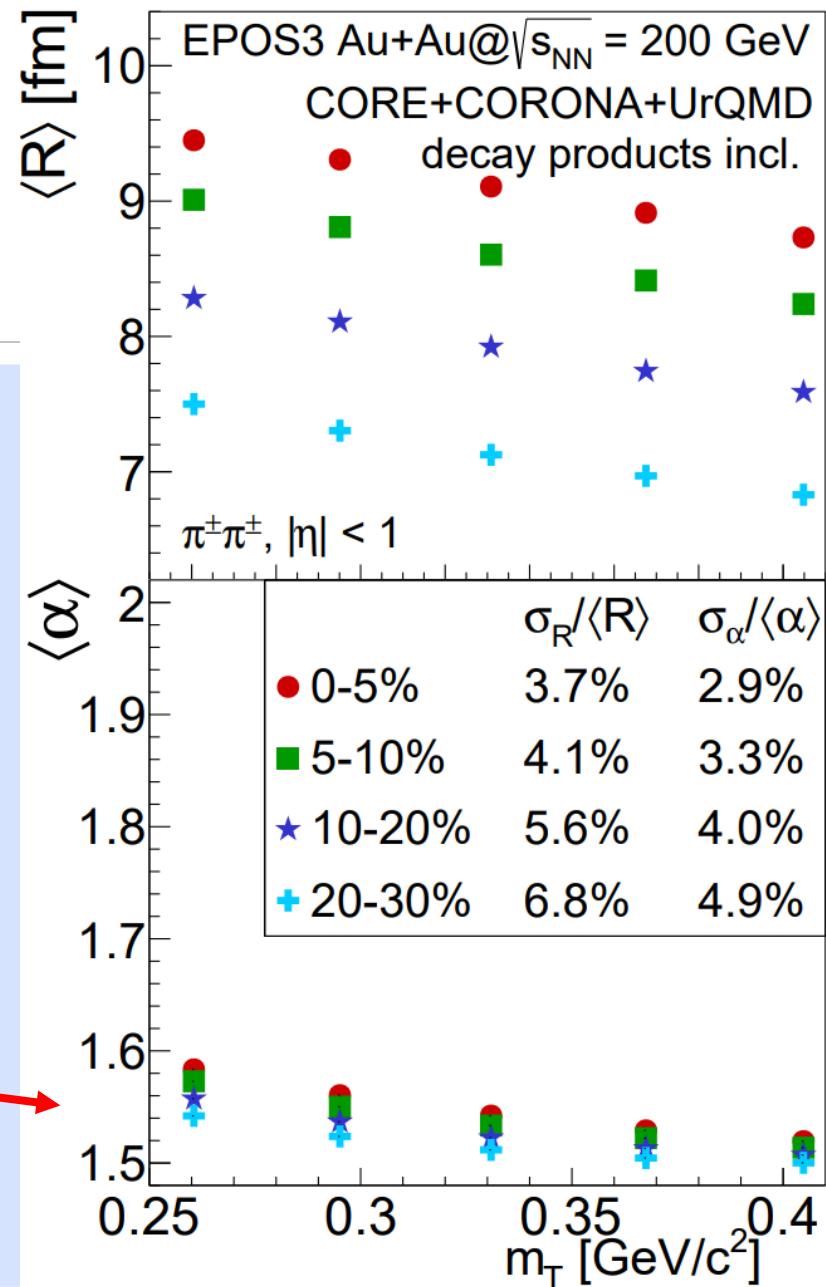
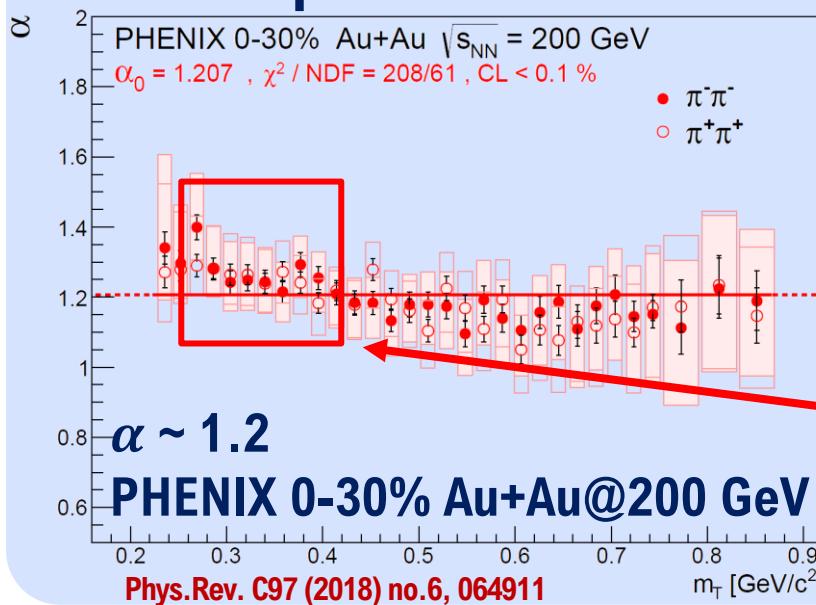
$\langle \alpha \rangle, \langle R \rangle$ vs. m_T , centr. CORE+CORONA+UrQMD decay products included

- Trends, magnitudes of R similar to experimental results
- Higher magnitudes of α than experimental results



$\langle \alpha \rangle, \langle R \rangle$ vs. m_T , centr. CORE+CORONA+UrQMD decay products included

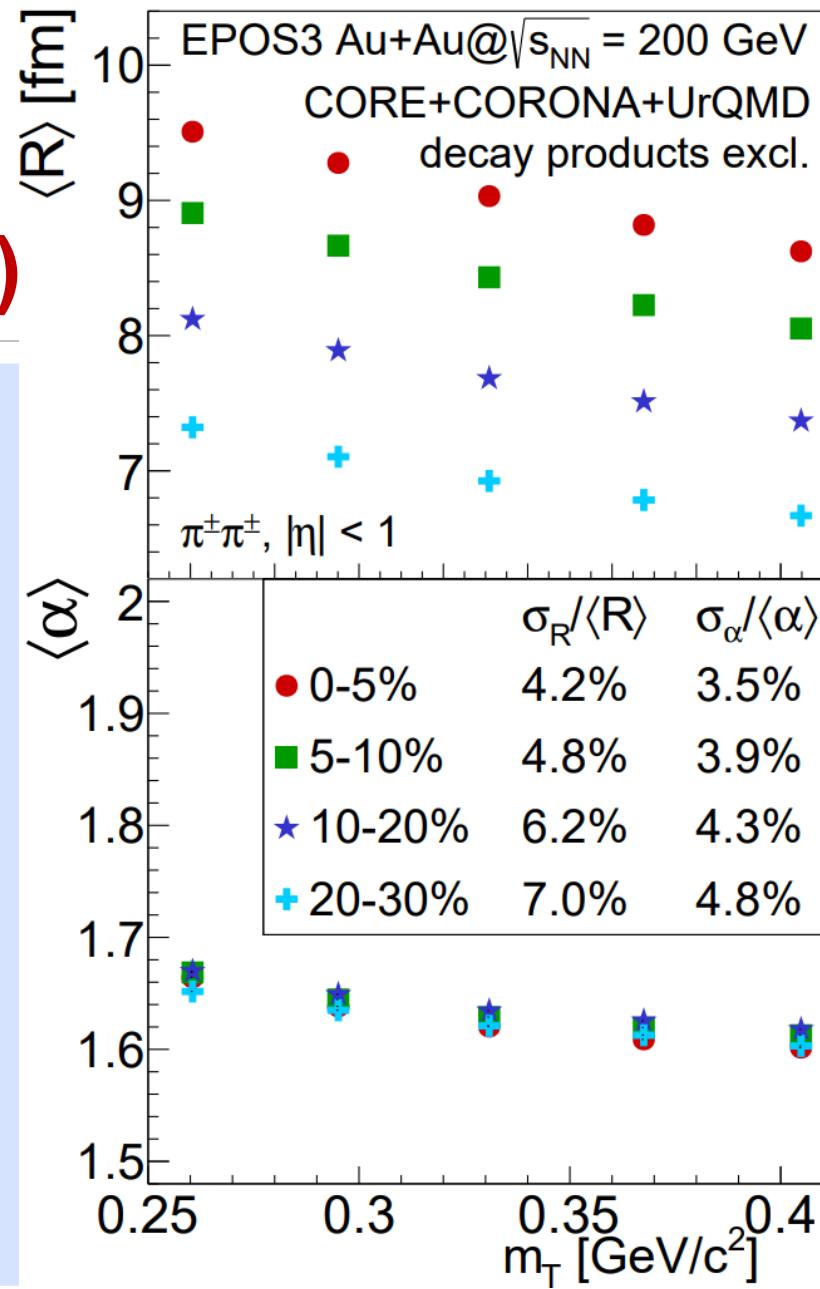
- Trends, magnitudes of R similar to experimental results
- Higher magnitudes of α than experimental results**



$\langle \alpha \rangle, \langle R \rangle$ vs. m_T , centr. CORE+CORONA+UrQMD decay products excluded(!)

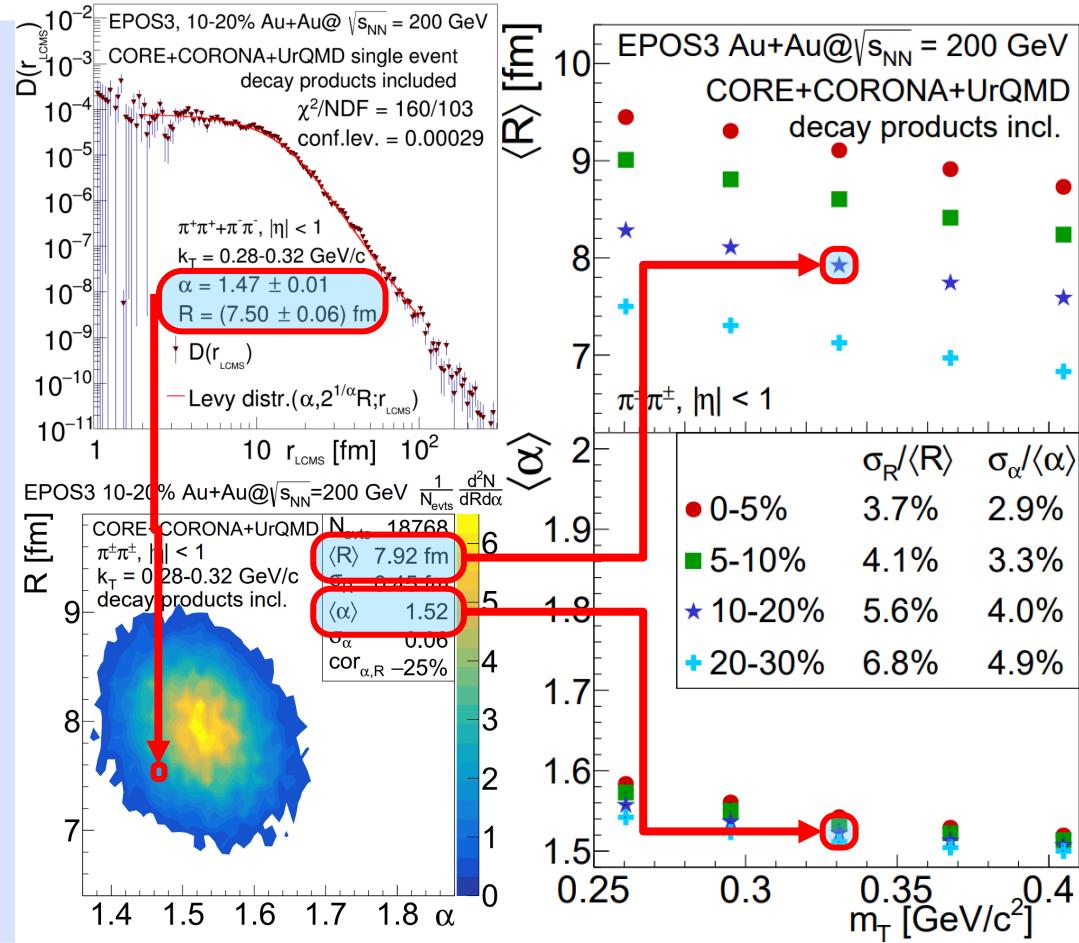
- Removing resonance decays decreases R, increases alpha (but still far from Gaussian)
- Resonances and rescattering both play an important role in the appearance of the power-law behavior

see also other phenomenological studies e.g.
Universe 5, 148, Phys. Part. Nucl. 51(3), 282–287



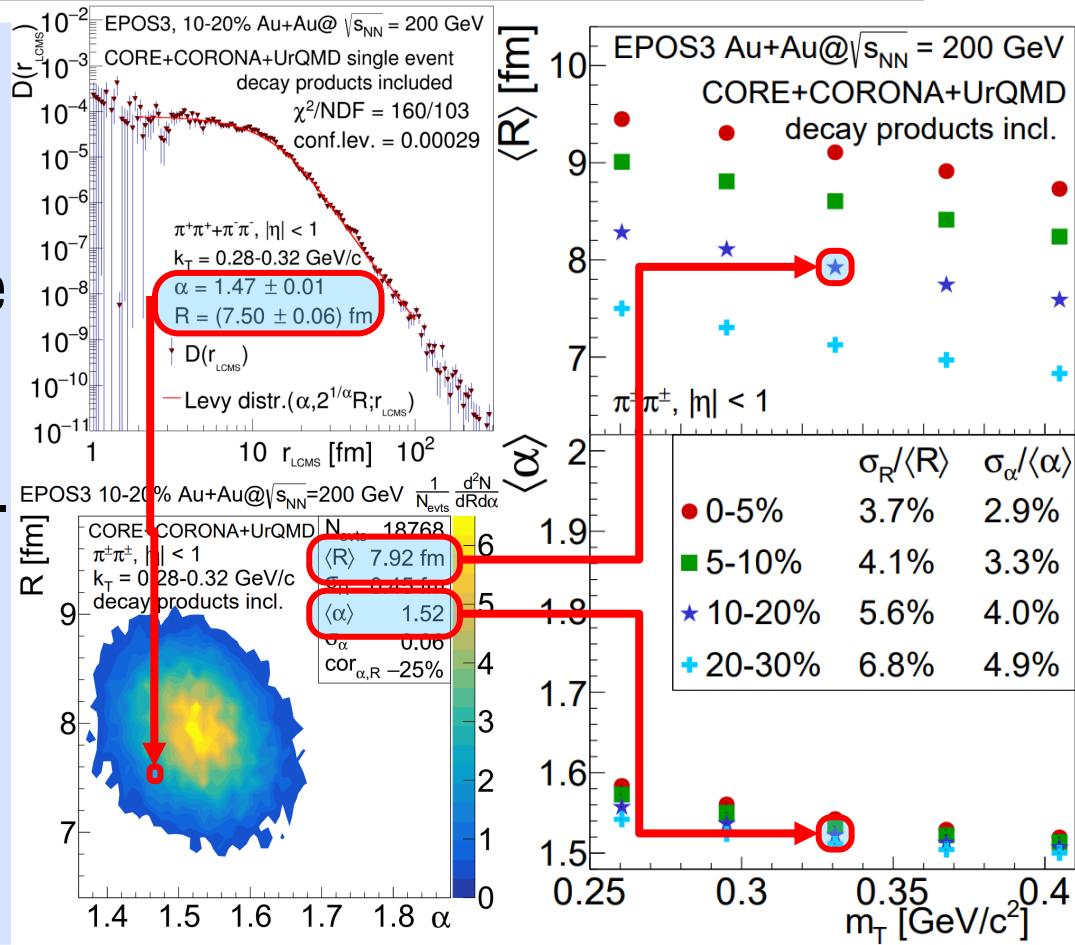
Summary – event by event analysis of the pion pair-source in EPOS 200 GeV Au+Au collisions

1. Single event Levy fits to angle-averaged $D(r)$ – **event-by-event non-Gaussianity**
2. Extracting the mean, std.dev. of R , α distr.
3. Investigating mT & centr. dependence
 - **Lévy fits provide good descr., power-law tail strongly affected by rescattering, decays**



Outlook

- Investigation of pair-source in multiple dimensions
- Investigating the pair-source of different particle species
- Reconstruct correlation func.
From measured pair-source
- Results to be uploaded to arXiv soon, stay tuned!



Backoff

