

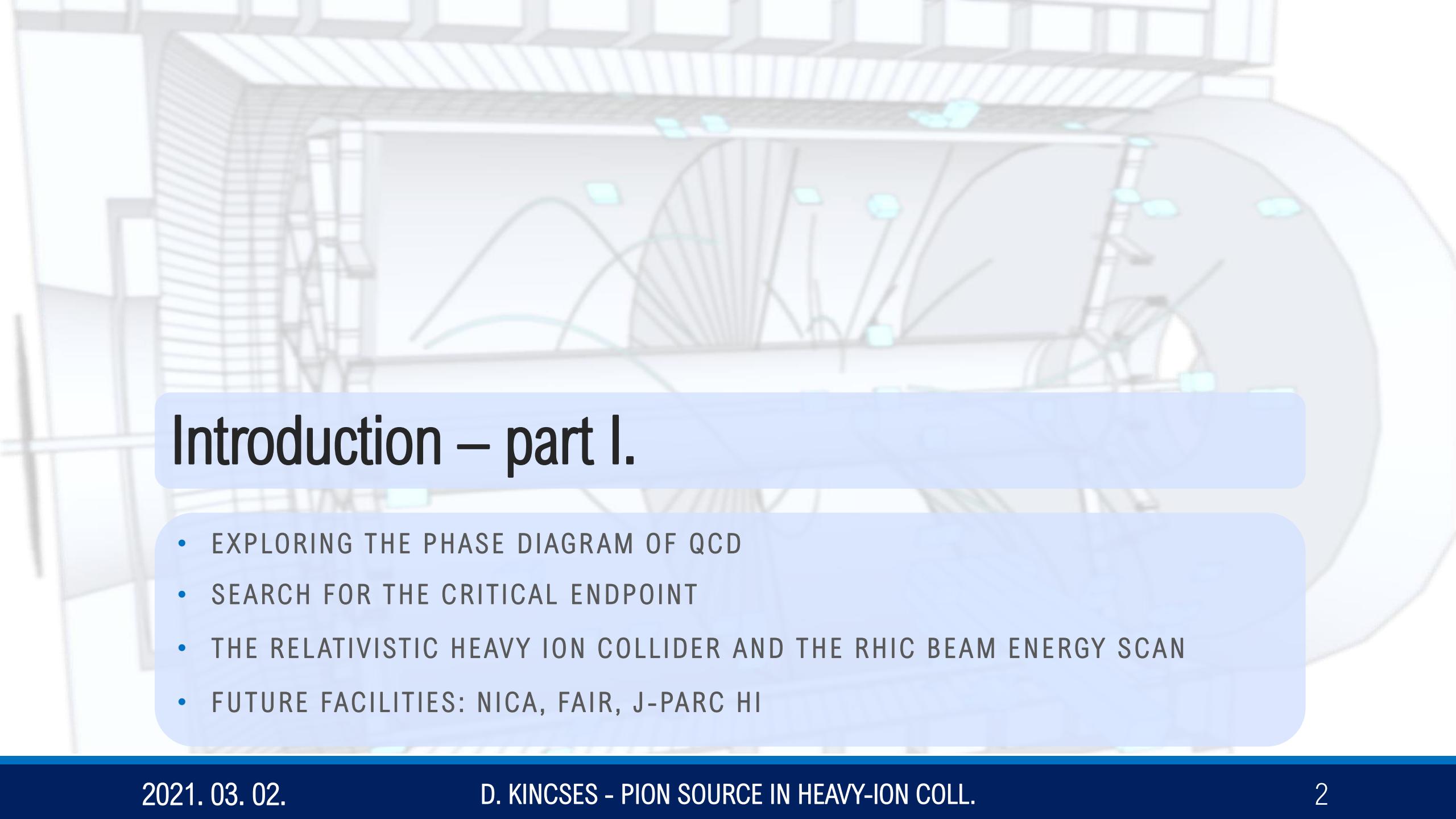
Investigating the pion source-function in heavy-ion collisions

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ELTE PARTICLE PHYSICS SEMINAR

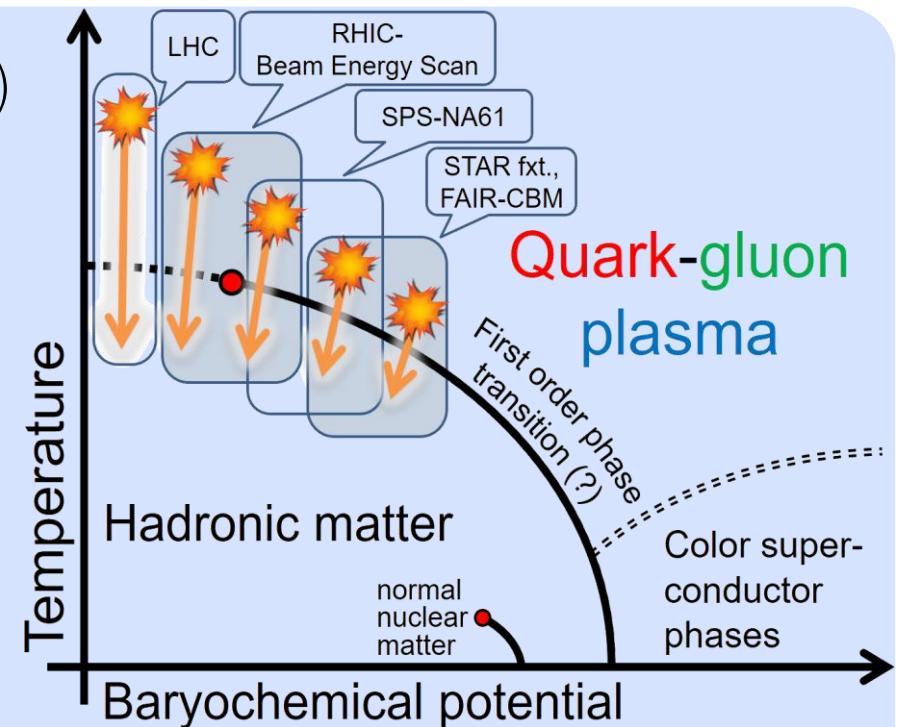


Introduction – part I.

- EXPLORING THE PHASE DIAGRAM OF QCD
- SEARCH FOR THE CRITICAL ENDPOINT
- THE RELATIVISTIC HEAVY ION COLLIDER AND THE RHIC BEAM ENERGY SCAN
- FUTURE FACILITIES: NICA, FAIR, J-PARC HI

Exploring the Phase diagram of QCD

- **Phase diagram:** temp. vs. matter excess (baryoch. pot. μ_B)
- **Control parameters:**
 - Collision energy, system
 - Collision geometry
- **Crossover at low μ_B** and $T \cong 170$ MeV
- Probably **1st order** p.t. **at high μ_B** (NJL, bag model, etc)
- **Critical End Point** (CEP) in between?
- High μ_B : nuclear matter, neutron stars, color superconductors...
- Phase transition importance: even in core-collapse supernovae!



The Relativistic Heavy Ion Collider

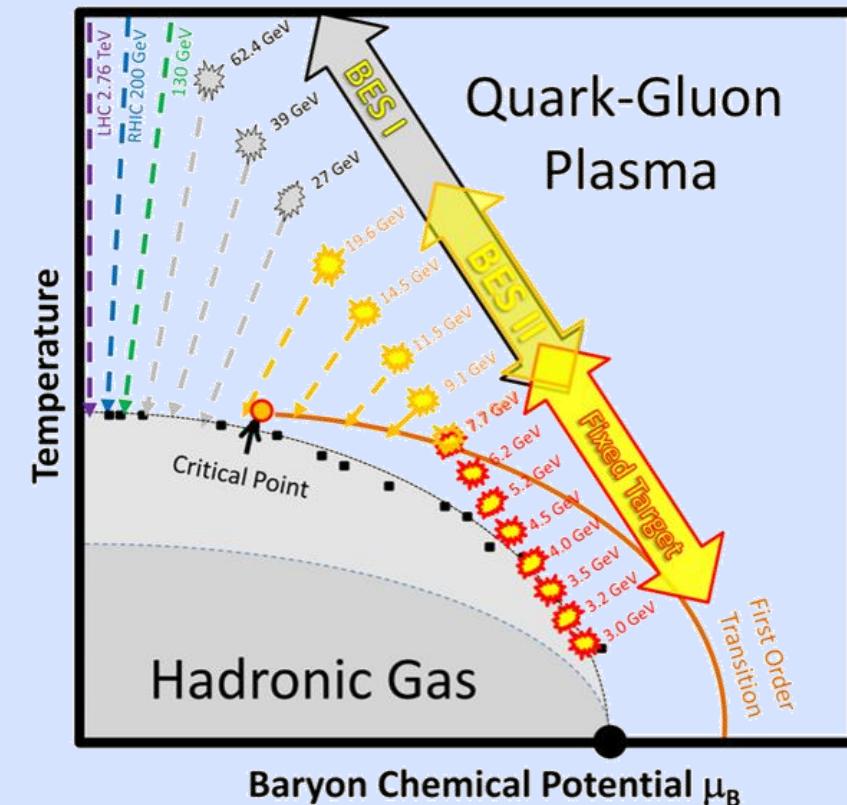
- Located at the **Brookhaven National Laboratory**, Long Island, New York, USA
- Collisions of p, d, ^3He , Al, Cu, Au, U
- Accelerator energies: 7.7-200 GeV/nucleon, even 0.51 TeV for p
- Experiments: **STAR**; future: **sPHENIX**; past: BRAHMS & PHOBOS & **PHENIX**



The RHIC Beam Energy Scan

- **BES-I**: 7.7-200 GeV; **BES-II**: 7.7-19.9 GeV, increased luminosity
- Small system scan: x+Au, 19.6-200 GeV
- STAR **fixed target** mode: down to 3 GeV

$\sqrt{s_{NN}}$ [GeV]	STAR Au+Au events [10^6]	PHENIX Au+Au events [10^6]	Year
200.0	2000	7000	2010
62.4	67	830	2010
54.4	1300	-	2017
39.0	130	385	2010
27.0	70	220	2011
19.6	36	88	2011
14.5	20	247	2014
11.5	12	-	2010
7.7	4	1.4	2010



The RHIC Beam Energy Scan

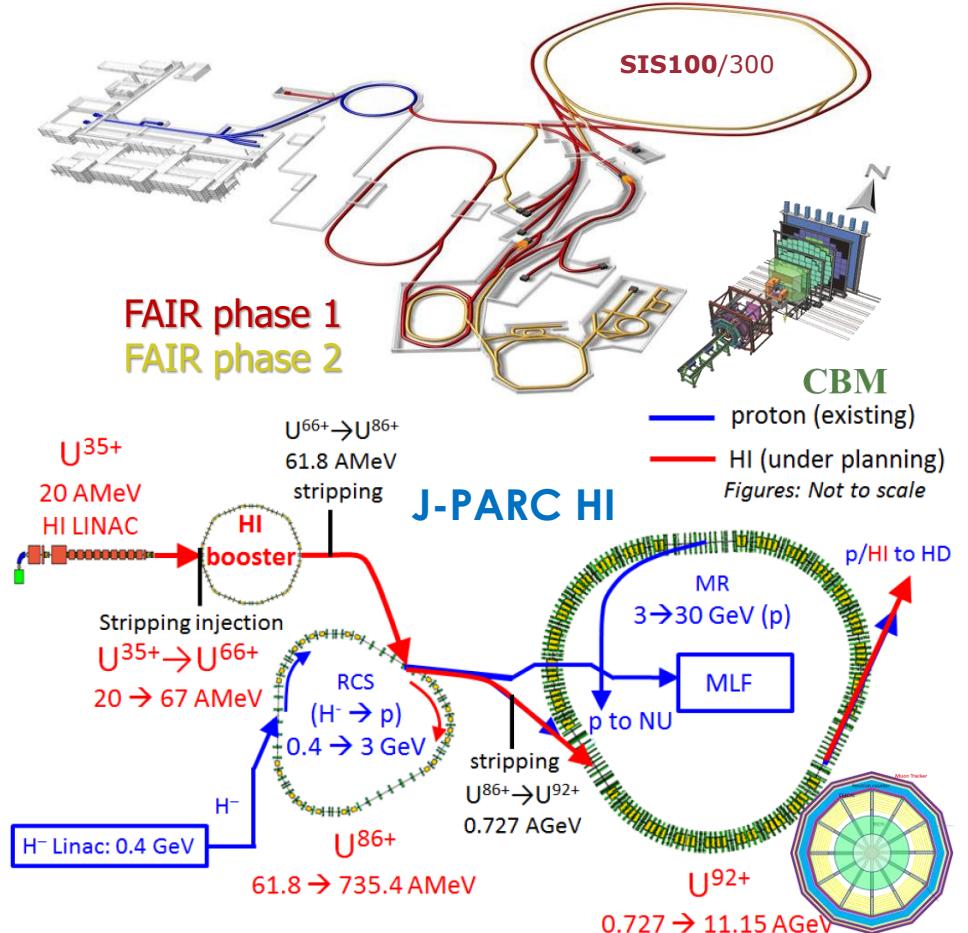
- **BES-I**: 7.7-200 GeV; **BES-II**: 7.7-19.9 GeV, increased luminosity
- Small system scan: x+Au, 19.6-200 GeV
- STAR **fixed target** mode: down to 3 GeV

Collider Energy	Fixed Target Coll. Energy	Single Beam C.M. Energy	Rapidity	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39.0	6.2	18.6	1.87	487
27.0	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721

Energies unreachable in collider mode

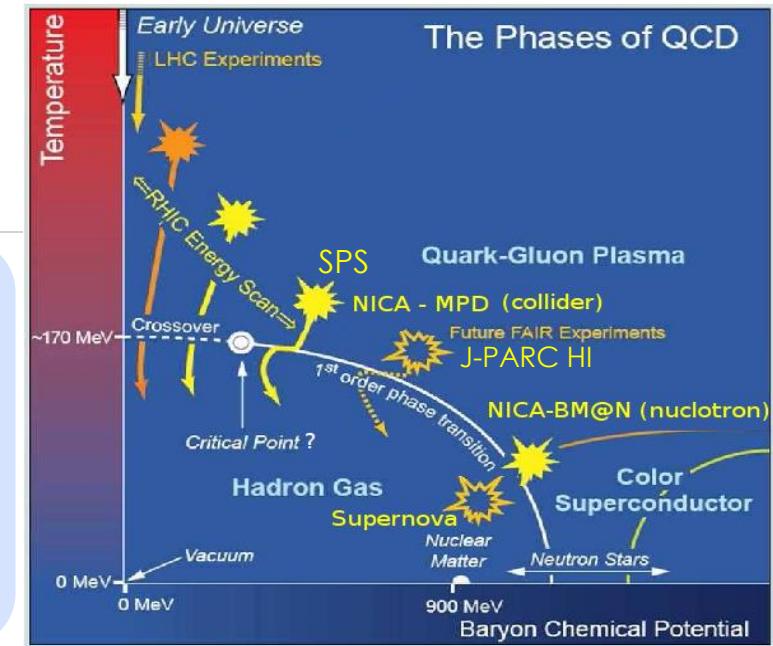
Future facilities: NICA, FAIR, J-PARC HI

- New facilities planned/built
- **NICA:** 2020, MPD&BM@N
- **FAIR:** 2022, CBM
- **J-PARC HI:** 2025, JHITS

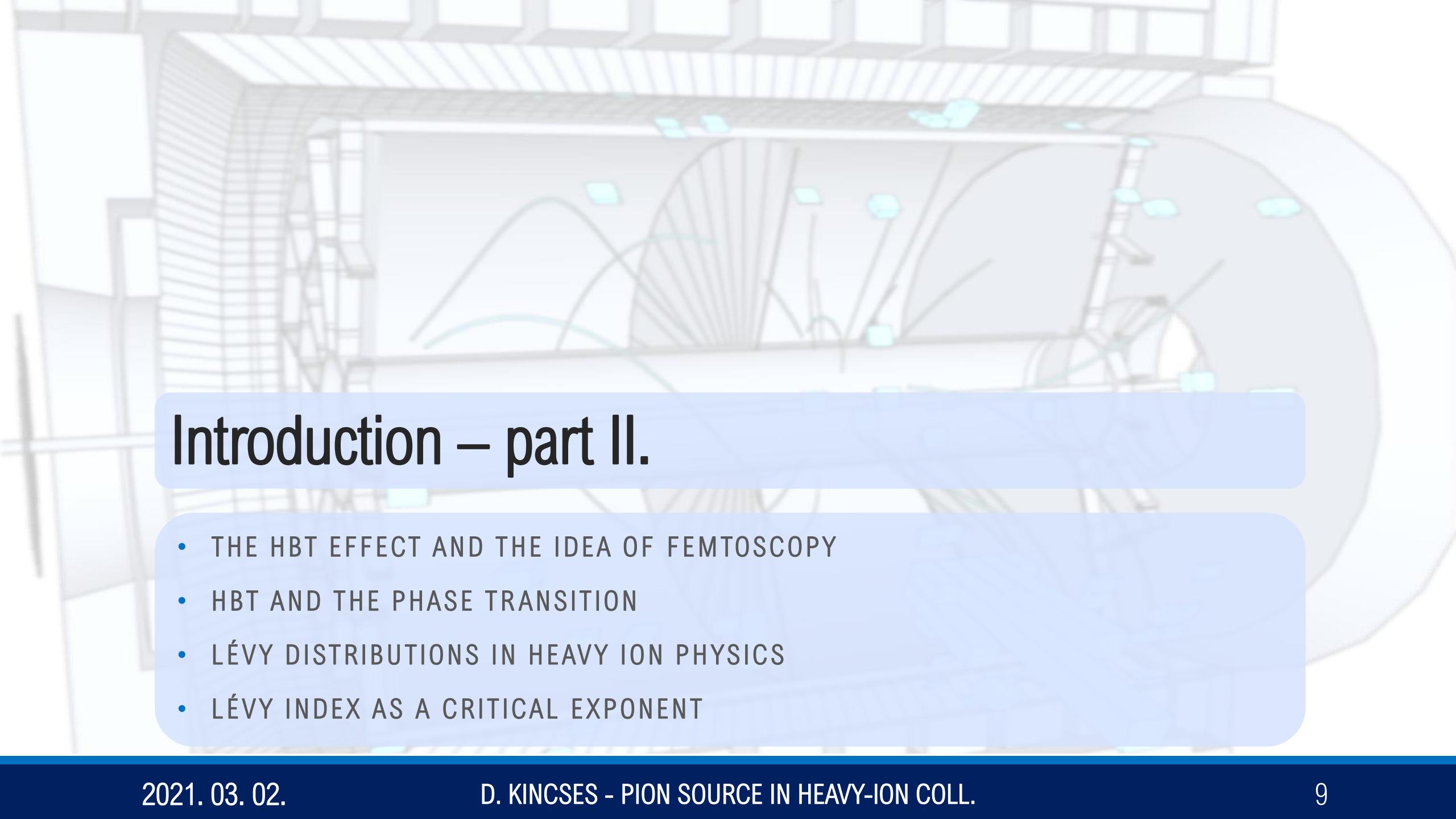


(Future) facilities comparison

- Many future facilities/experiments, SPS & RHIC already running
- RHIC, NICA: Collider and fixed target
- SPS, FAIR, J-PARC: fixed target
- Energy ranges from 2 to 20 GeV in $\sqrt{s_{NN}}$



Facility	RHIC BES-II & Fixed Target	SPS	NICA	FAIR	J-PARC HI
Experiment	STAR	NA61/SHINE	MPD & BM@N	CBM	JHITS
Start	2019	2009	2020-23	2025	2025
Energy ($\sqrt{s_{NN}}$, GeV)	2.9-19.6 GeV	4.9-17.3	2.0-11	2.7-8.2	2.0-6.2
Rate	100-1000 Hz	100 Hz	10 kHz	10 MHz	10-100 MHz
Physics	Critical Point Onset of Deconf.	Critical Point Onset of Deconf.	Onset of Deconfinement Compr. Hadronic Matter	Onset of Deconfinement Compr. Hadronic Matter	Onset of Deconfinement Compr. Hadronic Matter



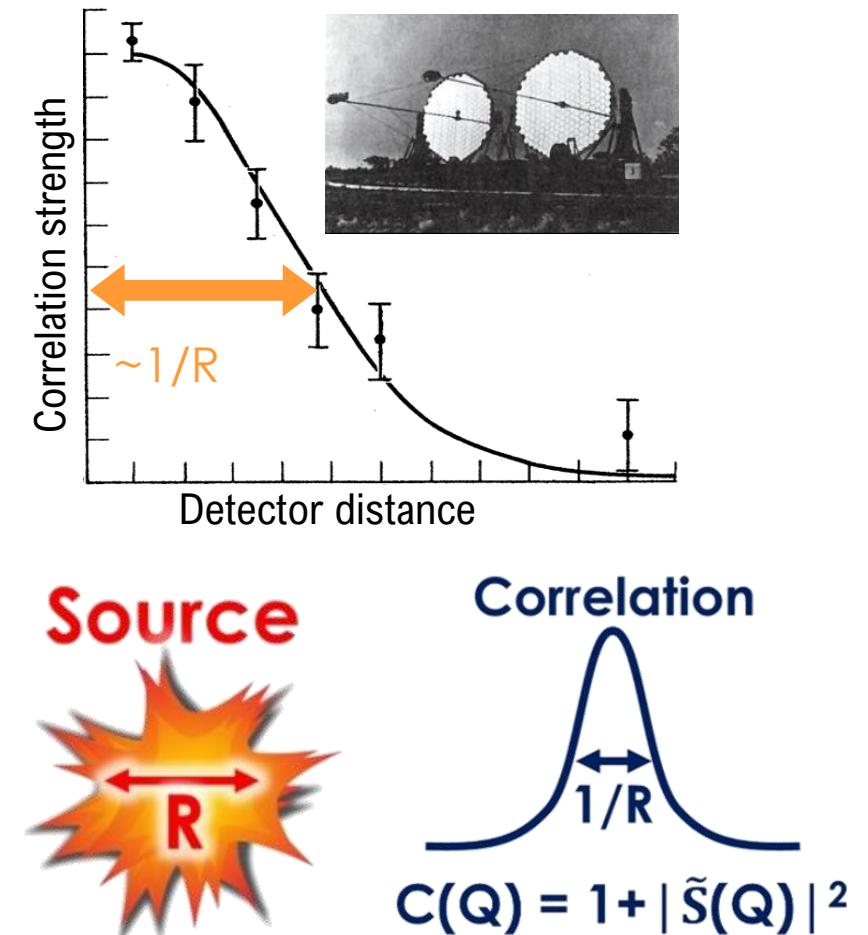
Introduction – part II.

- THE HBT EFFECT AND THE IDEA OF FEMTOSCOPY
- HBT AND THE PHASE TRANSITION
- LÉVY DISTRIBUTIONS IN HEAVY ION PHYSICS
- LÉVY INDEX AS A CRITICAL EXPONENT

The HBT effect and the idea of femtoscopy

- R. Hanbury Brown & R. Q. Twiss
 - **Intensity correlations** vs detector distance \Rightarrow source size
- Goldhaber et al: applicable in high energy physics
 - **Momentum correlations** of (non)identical particles
 - Possible to map out the source on the fm scale
 - $C(q) \cong 1 + |\int S(r)e^{iqr} dr|^2$ (under some assumptions)
or with the **pair-source distribution** (distance distr.) $D(r)$:
 - $C(q) \cong 1 + \int D(r)e^{iqr} dr$

Phys. Rev. Lett. 10, 84; Rev. Mod. Phys. 78 1267



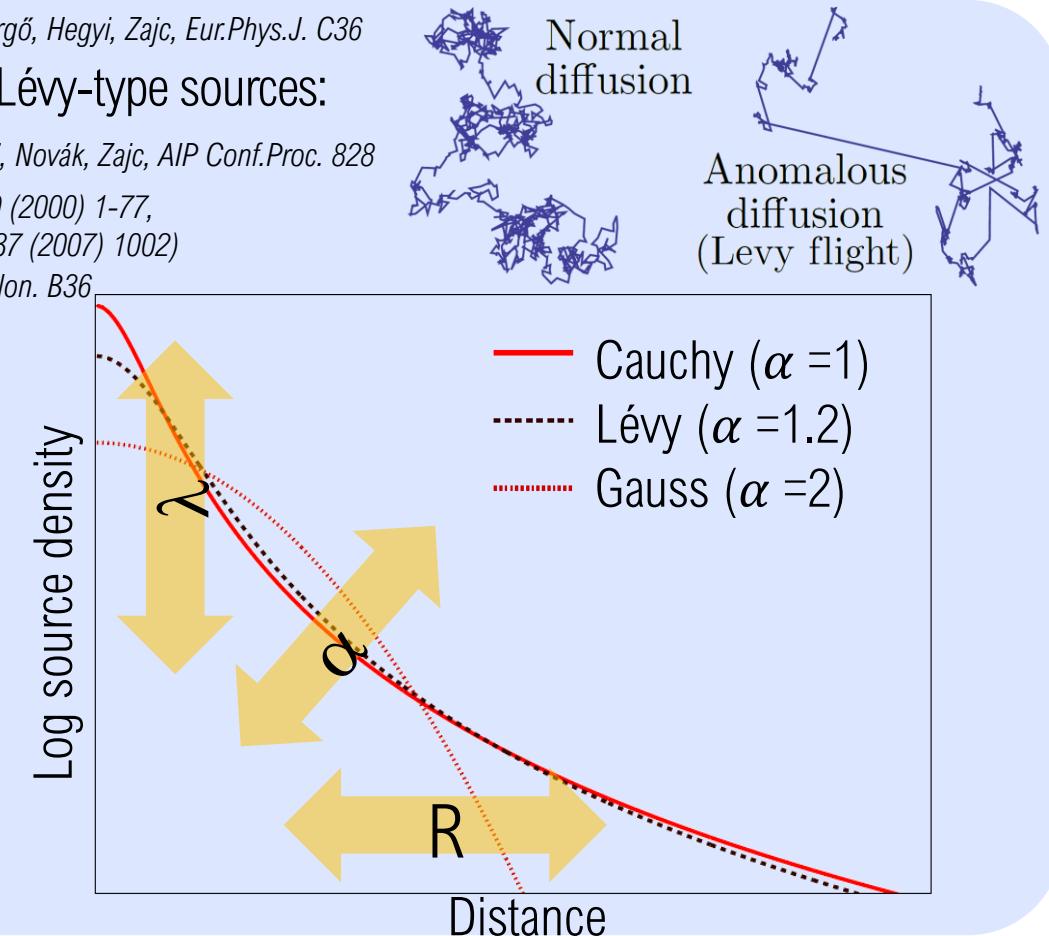
Basic definitions of femtoscopical correlation functions

- **Single particle distribution:** $N_1(p) = \int dx S(x, p)$
 - **Pair momentum distribution:** $N_2(p_1, p_2) = \int dx_1 dx_2 S(x_1, p_1)S(x_2, p_2)|\psi(x_1, x_2)|^2$
 - **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:** $D(r, K) = \int d^4\rho S\left(\rho + \frac{r}{2}, K\right)S\left(\rho - \frac{r}{2}, K\right)$
 - **No direct access to pair-source in experiments – correlation measurements provide access!**
- $$C(Q, K) = \frac{\int D(r, K)|\psi_Q(r)|^2 dr}{\int D(r, K)dr}$$
- relative pair momentum average pair momentum Pair wave function
- relative coordinate

Shape of the pair-source in heavy ion physics – Lévy?

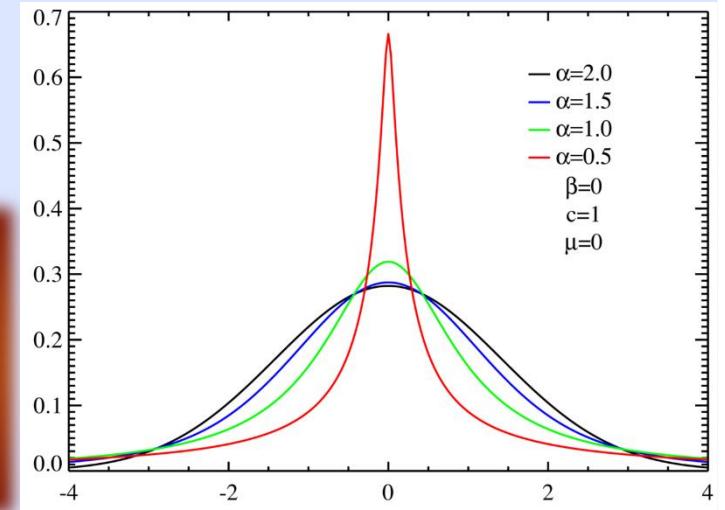
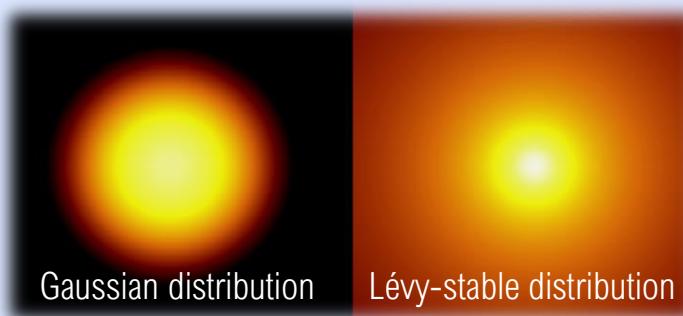
- Possible (competing) reasons for the appearance of Lévy-type sources:
 1. **Proximity of the critical endpoint** Csörgő, Hegyi, Novák, Zajc, AIP Conf. Proc. 828
 2. **Anomalous diffusion** (Metzler, Klafter, Physics Reports 339 (2000) 1-77, Csanad, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002)
 3. **Jet fragmentation** Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon. B36
- **Symmetric Lévy-stable distribution:**
- $\mathcal{L}(\alpha, R; r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$
 - From generalized central limit theorem, power-law tail $\sim r^{-(1+\alpha)}$
 - Special cases: $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy
- **Lévy-type corr. func.:** $C(Q) = 1 + \lambda \cdot e^{-(RQ)^\alpha}$
- No tail if $\alpha = 2$, power law if $\alpha < 2$; correlation between α and R, λ

Csörgő, Hegyi, Zajc, Eur.Phys.J. C36



Properties of univariate stable distributions

- **Univariate stable distribution:** $f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \varphi(q) e^{-ixq} dq$, where the characteristic function:
$$\varphi(q; \alpha, \beta, R, \mu) = \exp(iq\mu - |qR|^\alpha (1 - i\beta \operatorname{sgn}(q)\Phi))$$
$$\Phi = \begin{cases} \tan\left(\frac{\pi\alpha}{2}\right), & \alpha \neq 1 \\ -\frac{2}{\pi} \log|q|, & \alpha = 1 \end{cases}$$
- α : index of stability
- β : skewness, symmetric if $\beta = 0$
- R : scale parameter
- μ : location, equals the median,
if $\alpha > 1$: μ = mean

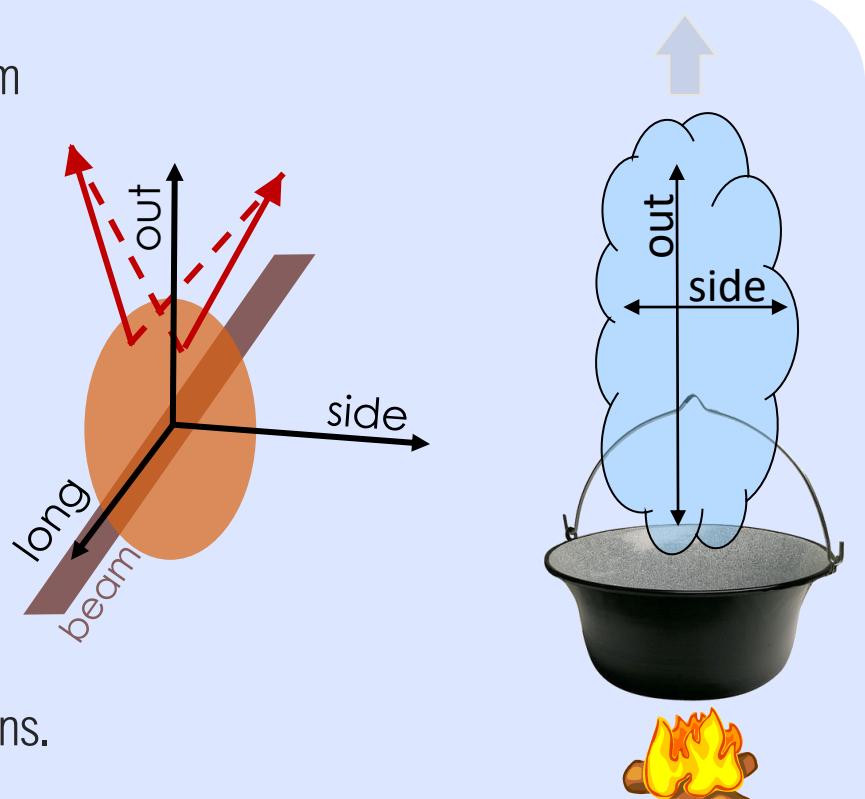


- **Important characteristics of stable distributions:**
 - The distributions retain the same α and β under convolution of random variables
 - Any moment greater than α isn't defined

HBT and the phase transition

S. Chapman, P. Scotto, U. Heinz, Phys.Rev.Lett. 74 (1995) 4400;
T. Csörgő and B. Lörstad, Phys.Rev. C54 (1996) 1390;
S. Pratt, Nucl.Phys. A830 (2009) 51C

- $C(q)$ usually measured in the Bertsch-Pratt pair coordinate-system
 - **out**: direction of the average transverse momentum
 - **long**: beam direction
 - **side**: orthogonal to the latter two
- $R_{out}, R_{side}, R_{long}$: HBT radii
- $\Delta\tau$ emission duration, i.e. $S(r, \tau) \sim e^{-\frac{(\tau - \tau_0)^2}{2\Delta\tau^2}}$
- From a simple hydro calculation:
$$R_{out}^2 = \frac{R^2}{1+u_T^2 m_T/T_0} + \beta_T^2 \Delta\tau^2, \quad R_{side}^2 = \frac{R^2}{1+u_T^2 m_T/T_0}$$
- RHIC, 200 GeV: $R_{out} \approx R_{side} \rightarrow$ no strong 1st order phase trans.
- Plus lots of other details: pre-equilibrium flow, initial state, EoS, ...

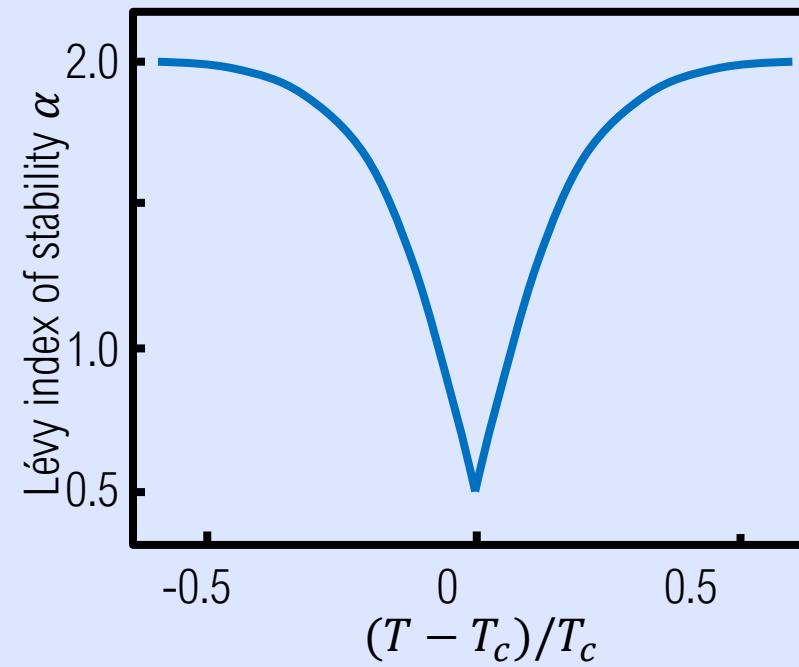


Second order phase transition?

- Second order phase transitions: **critical exponents**
 - **Near the critical point**
 - Specific heat $\sim ((T - T_c)/T_c)^{-\alpha}$
 - Order parameter $\sim ((T - T_c)/T_c)^{-\beta}$
 - Susceptibility/compressibility $\sim ((T - T_c)/T_c)^{-\gamma}$
 - Correlation length $\sim ((T - T_c)/T_c)^{-\nu}$
 - **At the critical point**
 - Order parameter $\sim (\text{source field})^{1/\delta}$
 - **Spatial correlation function** $\sim r^{-d+2-\eta}$
 - Ginzburg-Landau: $\alpha = 0, \beta = 0.5, \gamma = 1, \eta = 0.5, \delta = 3, \eta = 0$
- QCD \leftrightarrow 3D Ising model
- Can we measure the η power-law exponent?
- Depends on spatial distribution: measurable with femtoscopy!
- **What distribution has a power-law exponent? Levy-stable distribution!**

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 \leftrightarrow 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: $\eta = 0.50 \pm 0.05$
Rieger, Phys.Rev.B52 (1995) 6659
 - 3D Ising: $\eta = 0.03631(3)$
El-Showk et al., J.Stat.Phys. 157 (4-5): 869
- Motivation for precise Lévy HBT!
- **Change in α_{Levy} - proximity of CEP?**



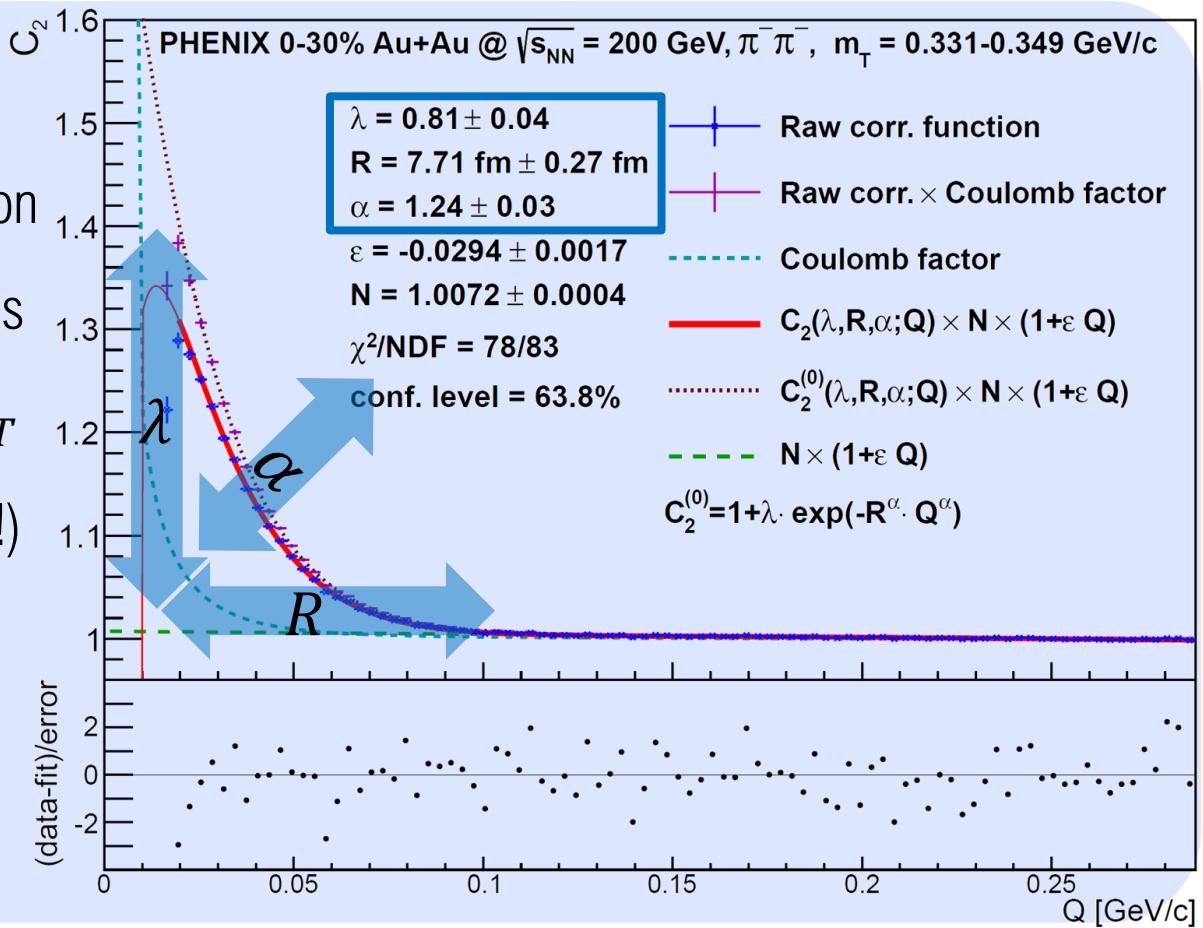
- Modulo finite size/time and non-equilibrium effects
- Other possible reasons for Lévy distributions:
anomalous diffusion, QCD jets, ...

Experimental results

- PHENIX RESULTS
(m_T , COLLISION ENERGY DEPENDENCE, 1D VS. 3D)
- STAR RESULTS

Example $C_2(Q_{LCMS})$ Correlation Function (PHENIX)

- Measured in m_T bins
- Fitted with Coulomb-incorporated function
- All fits converged, good confidence levels
- Physical parameters: R, λ, α vs. pair m_T
- Recall α : Lévy index, 0.5 at CEP (shape!)
- R : length of homogeneity (source size!)
- λ : correlation strength

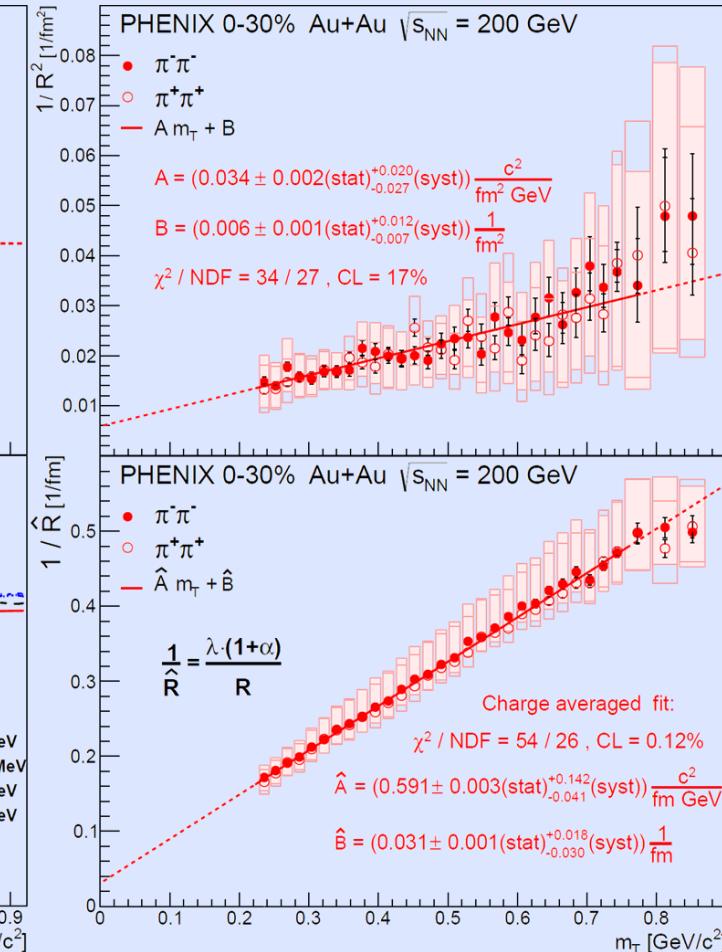
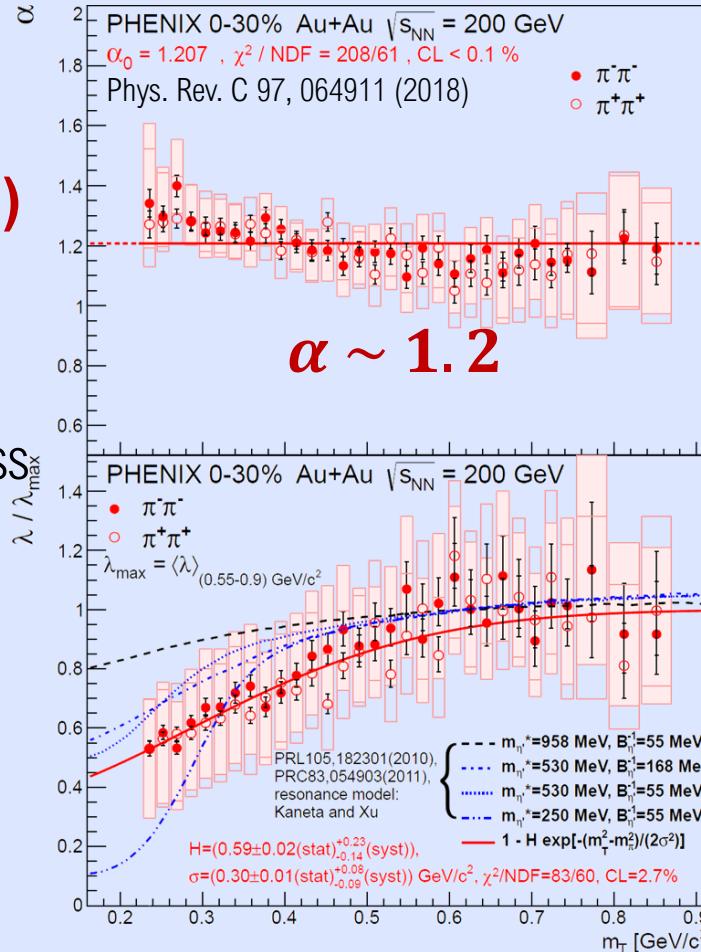


PHENIX, Phys. Rev. C97 (2018) no.6, 064911,
arXiv:1709.05649

PHENIX 200 GeV 1D Lévy HBT results

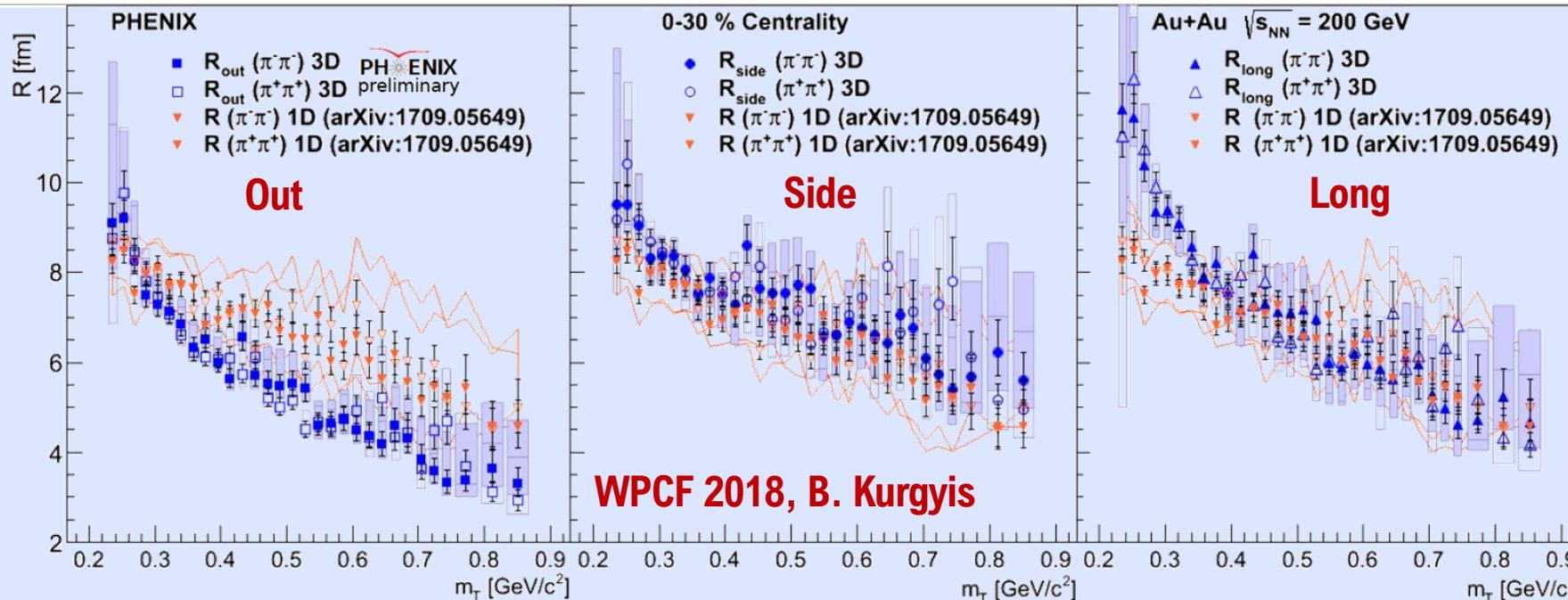
PHENIX, Phys.Rev. C97 (2018) no.6, 064911,
arXiv:1709.05649

- α : not 0.5 (CEP)
and not 2.0 (Gaussian)
- R : hydro scaling
- λ : „hole”,
not incompatible with mass
modification
- \hat{R} : new scaling variable

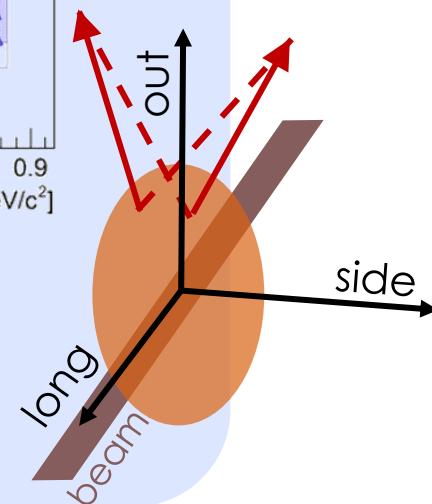


Cross-check with 3D versus 1D

B. Kurygis for the PHENIX Coll.,
Acta Phys. Pol. B Proc. Suppl. vol. 12 (2), pp. 477 - 482 (2019)



- **Compatibility with 1D Lévy analysis**
- Similar decreasing trend as Gaussian HBT radii, but it is not an RMS radius!
 - There is no 2nd moment (variance or root mean square) for Lévy distributions with $\alpha < 2$!
- Asymmetric source for small m_T , validity of Coulomb-approximation?

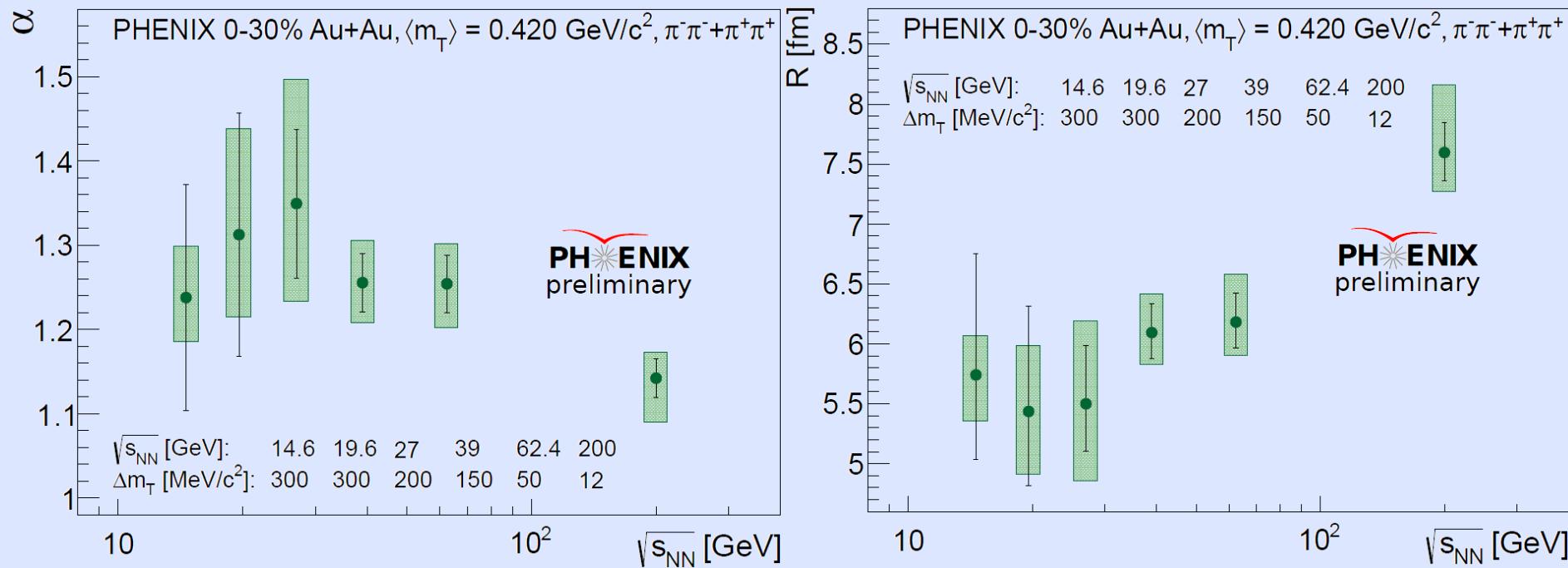


Collision energy dependence

D. Kincses for the PHENIX Coll.,
Acta Phys. Polon. Supp. 12 (2019) 445

- **Lévy exponent α still far from conjectured limit**, interesting trends in R
- Very much m_T bin width dependent, wait for final results...

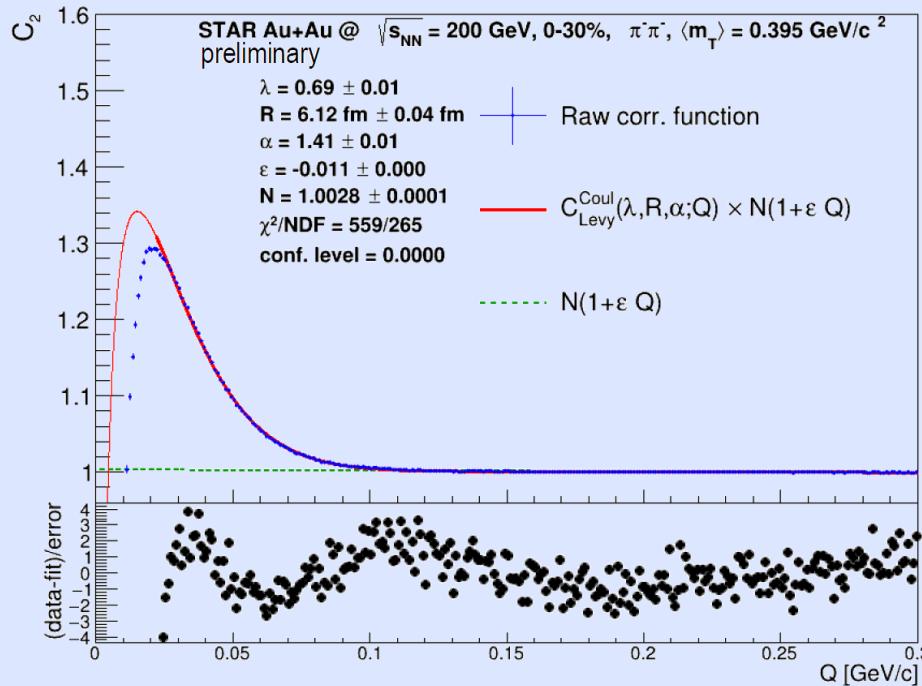
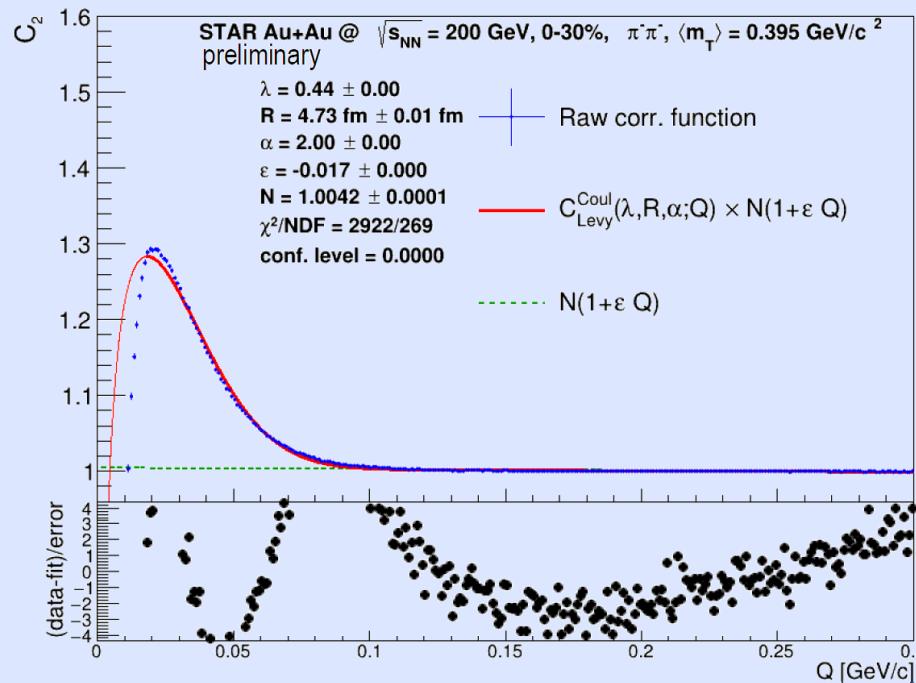
D. Kincses, QM18, WPCF18, CPOD18



Lévy Femtoscopy at STAR

D. Kincses for the STAR Coll.,
Phys.Part.Nucl. 51 (2020) 3, 267-269

- First 1D Lévy fits tested, preliminary results (presented at **WPCF19**)
- Higher precision than PHENIX – Low Q behavior not clear, Gaussian fits fail, Lévy fits also not perfect
- **refinements needed from phenomenology**



Developments in phenomenology – part I.

- FINAL-STATE COULOMB AND STRONG INTERACTIONS

**D. Kincses, M. I. Nagy, M. Csanad,
Phys.Rev.C 102 (2020) 6, 064912**

What do we need to calculate the correlation function?

$$C(Q) = \int D(r) |\psi_Q(\mathbf{r})|^2 dr$$

- Assumption on the **shape of the $D(r)$ pair-source function**
- Proper description of FSI enclosed in $\psi_Q(\mathbf{r})$ **symmetrized pair wave func.**

Final-state interactions in the pair wave function

- **Sommerfeld-parameter, Gamow-factor:** $\eta \equiv \frac{q_e^2}{4\pi\varepsilon_0} \frac{m}{\hbar^2 k}$ $|\mathcal{N}|^2 = \frac{2\pi\eta}{e^{2\pi\eta}-1}$ $\mathcal{N} = e^{-\pi\eta/2} \Gamma(1+i\eta)$
- **Coulomb wave-function (not yet symmetrized):** $\psi_{\mathbf{k}}^{(-)}(\mathbf{r}) = \mathcal{N}^* e^{-ikr} \mathbf{F}(1-i\eta, 1, i(kr+\mathbf{k}\cdot\mathbf{r}))$
Confluent hypergeometric function
- **How to include strong interaction?** Take partial wave expansion of the known Coulomb-scattering wavefunction, subtract the $l = 0$ term, and add this term back with strong phase-shift included:

$$\Psi_{\mathbf{k}}^{\text{cs}}(\mathbf{r}) = e^{-ikr} \left\{ \mathcal{N}^* \mathbf{F}(1-i\eta, 1, i(kr+\mathbf{k}\cdot\mathbf{r})) + \right.$$
$$\left. + 2i \sin \Delta_{k,0}^s e^{-i\Delta_{k,0}^s} e^{\pi\eta/2} e^{-2i\delta_{k,0}^c} U(1-i\eta, 2, 2ikr) \right\}$$

Strong phase shift Coulomb phase shift Tricomi's function

Final-state interactions in the pair wave function

- **Pair wave function with Coulomb + s-wave strong interaction:**

$$\Psi_{\mathbf{k}}^{\text{cs}}(\mathbf{r}) = e^{-ikr} \left\{ \mathcal{N}^* \mathbf{F}(1-i\eta, 1, i(kr+kr)) + \right. \\ \left. + 2i \sin \Delta_{k,0}^s e^{-i\Delta_{k,0}^s} e^{\pi\eta/2} e^{-2i\delta_{k,0}^c} U(1-i\eta, 2, 2ikr) \right\}$$

Confluent hypergeometric function:

$$\mathbf{F}(a, b, z) = \sum_{n=0}^{\infty} \frac{\Gamma(a+n)}{\Gamma(a)\Gamma(b+n)} \frac{z^n}{n!}$$

Tricomi's function (in case of integer b , l'Hospital's rule to be used...)

$$U(a, b, z) = \frac{\pi}{\sin(\pi b)} \left\{ \frac{\mathbf{F}(a, b, z)}{\Gamma(a+1-b)} - z^{1-b} \frac{\mathbf{F}(a+1-b, 2-b, z)}{\Gamma(a)} \right\}$$

- Effect of strong interaction appears through **s-wave strong phase-shift $\Delta_{k,0}^s$**
- Different parametrizations for $\Delta_{k,0}^s$ exist in the literature, see e.g. *Nucl. Phys. B 508, 26; Nucl. Phys. B 603, 12; Phys. Rev. D 83, 07400*

R. Lednický, *Phys. Part. Nucl.* 40, 307 (2009).

G. Colangelo, J. Gasser and H. Leutwyler,
Nucl. Phys. B 603, 125 (2001)

Final-state interactions in the pair wave function

- Effect of strong interaction appears through s-wave strong phase shift $\Delta_{k,l=0}^{(s)}$

$$\sin \Delta_{k,l=0}^{(s)} e^{i\Delta_{k,l=0}^{(s)}} = k \frac{2\pi\eta}{e^{2\pi\eta} - 1} \left(\frac{1}{K(k)} - 2k\eta \left(h(\eta) + \frac{i\pi}{e^{2\pi\eta} - 1} \right) \right)^{-1}$$

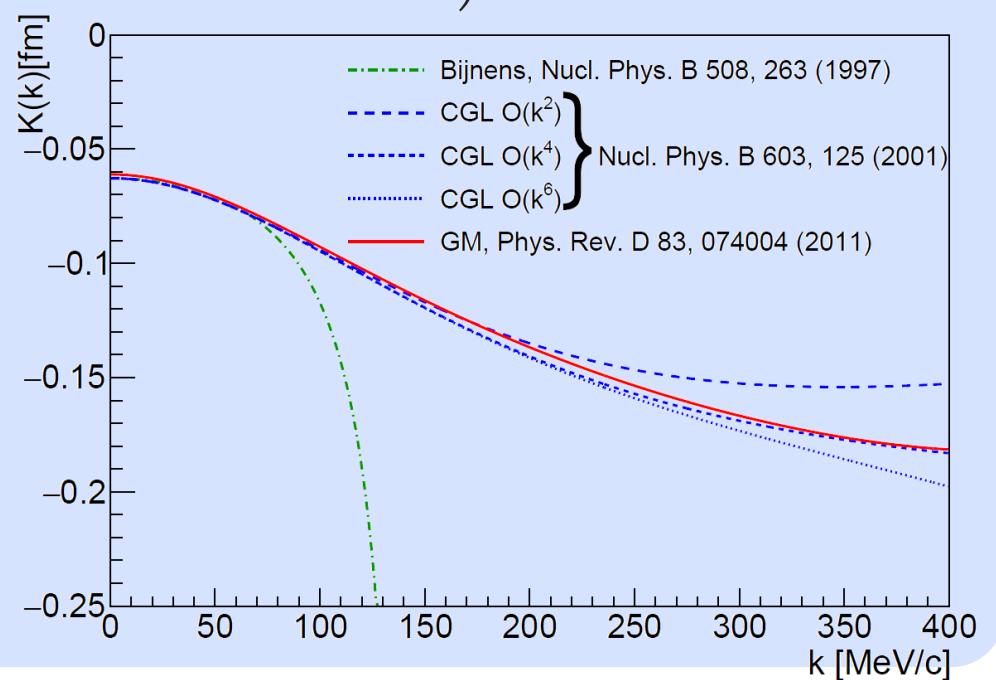
- Different parametrizations for $K(k)$:

Bijnens, Colangelo et al., Garcia-Martin

- Give identical result in the important range $k < 100$ MeV/c

- In the following, we utilized Garcia-Martin et al.

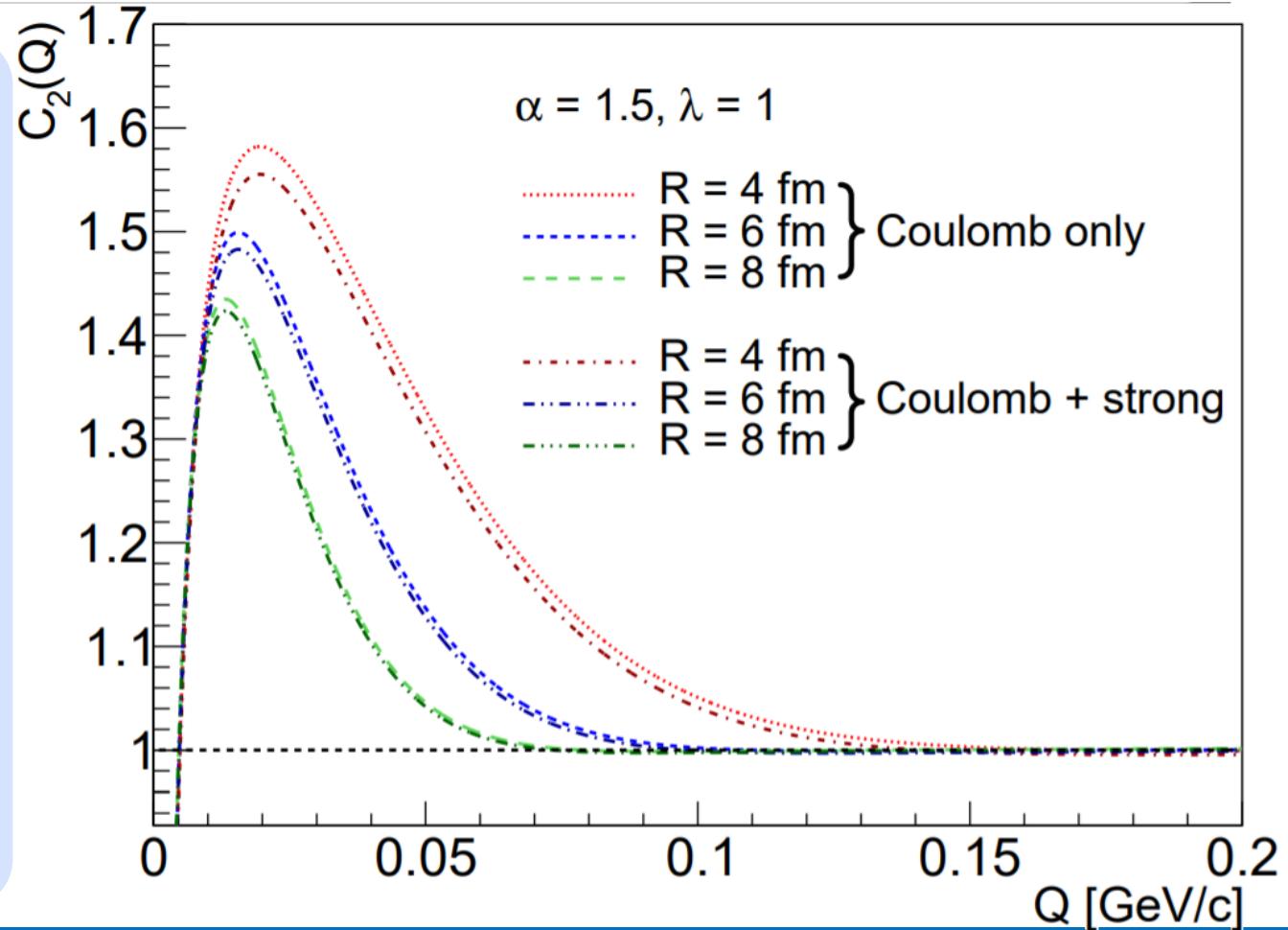
PRD83, 074004 (2011)



Two-pion correlation functions with Lévy-stable sources

- It seems that the strong interaction has a small but **non-negligible effect!**
- By eye it seems that it affects mostly the strength (λ), maybe R and α as well
- To investigate the effect in more details:

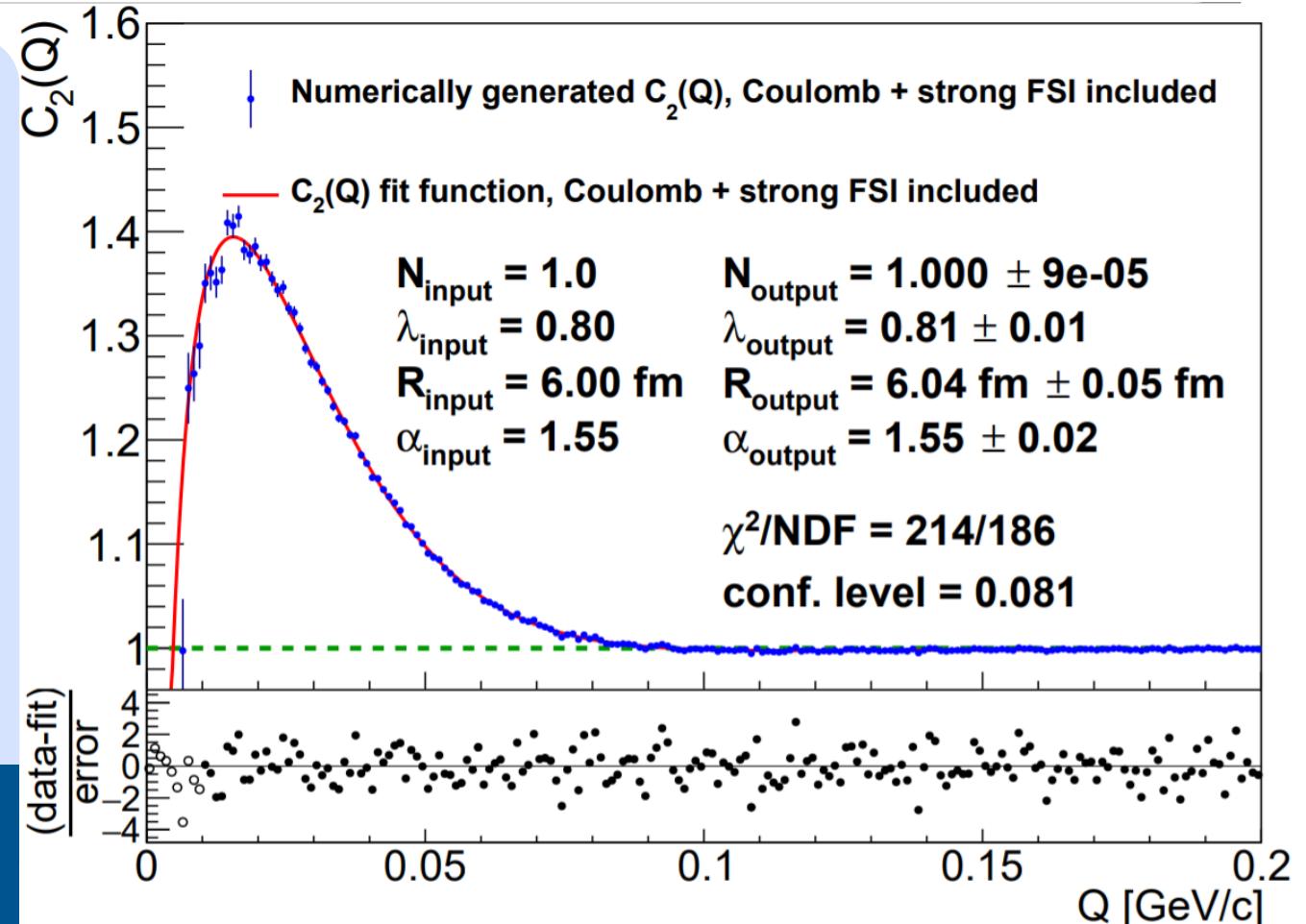
Let's generate data that resembles experimental $C(Q)$ by sampling the calculated functions containing C+S FSI



First check – fitting method

- Let's **generate data that resembles experimental corr. func.**, and see if the fit gives back the input
- **Fitting method is working well**, output is within errors the same as the input
- Test is repeated for multiple different input parameter combinations

C+S data fitted with C+S function example fit

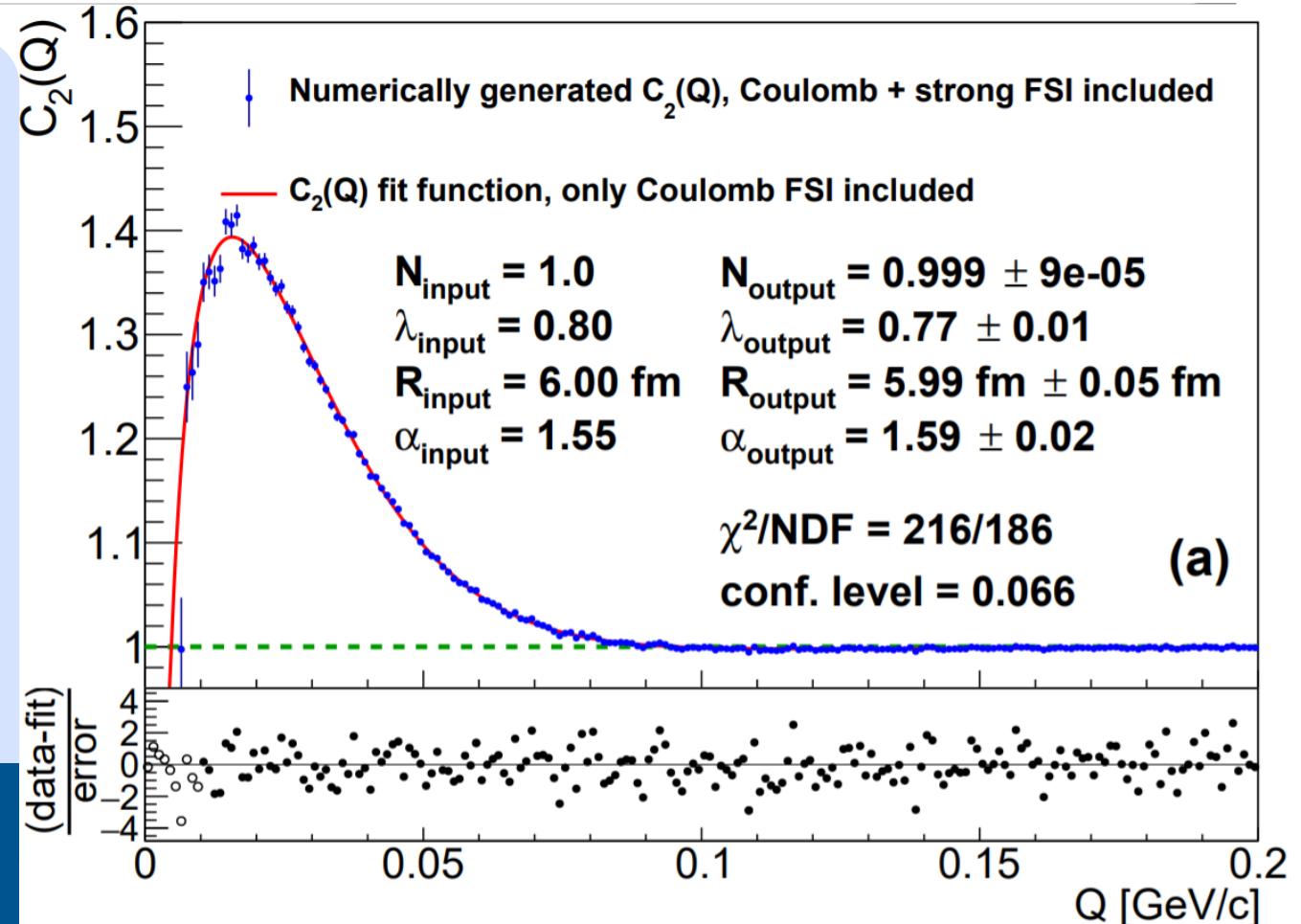


Second check – fitting C+S data with Coulomb only

(what people usually did for real data so far)

- Let's see what happens, if we **generate C+S data**, but **fit it with** a function containing **only the Coulomb interaction**
- Depending on the precision of the data, **we can get good / bad fits**
- Systematic change** in the parameters: $\lambda \downarrow$, $R \downarrow$, $\alpha \uparrow$

C+S data fitted with Coul. function
example fit – small statistics

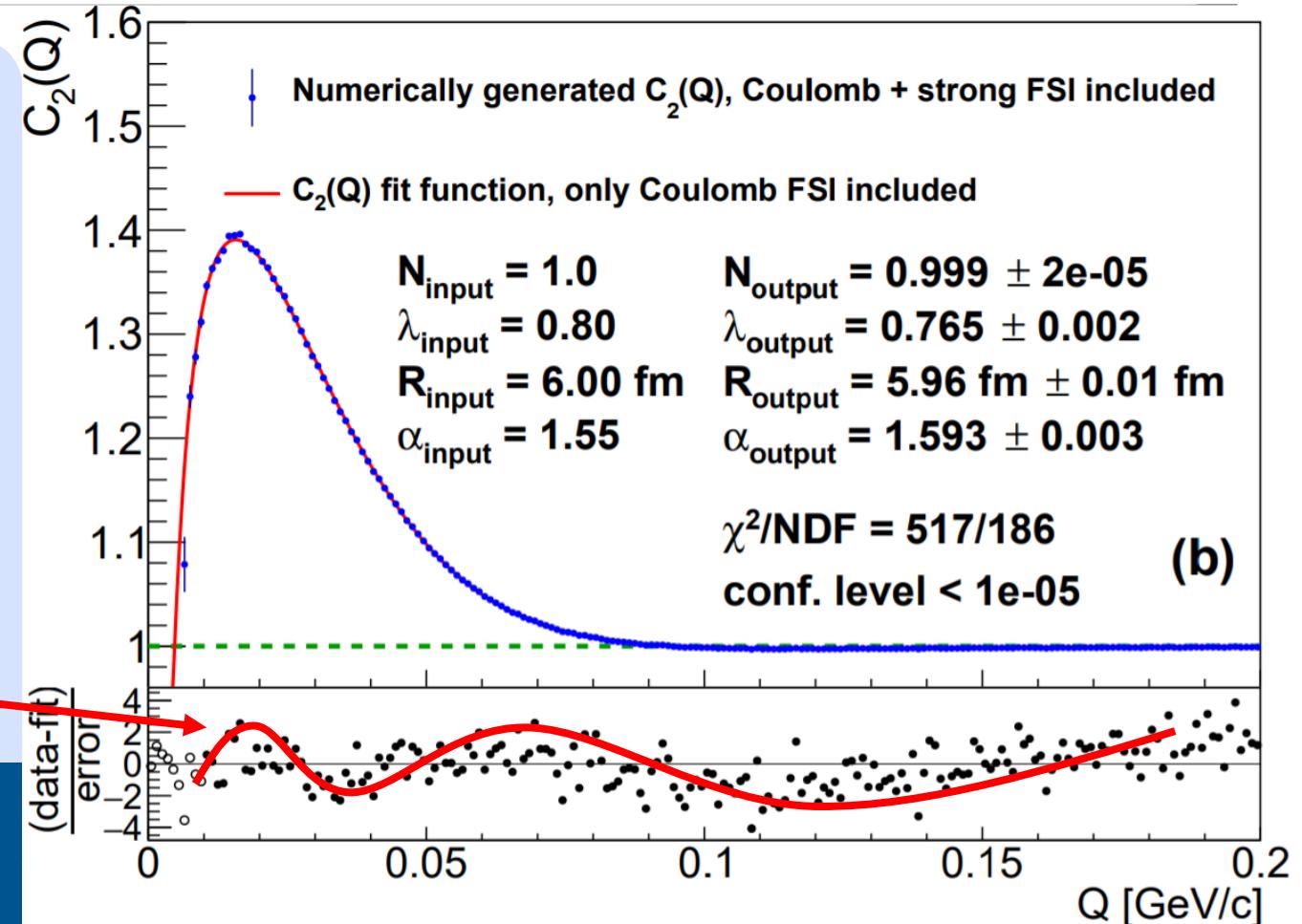


Second check – fitting C+S data with Coulomb only

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- Let's see what happens, if we **generate C+S data**, but **fit it with** a function containing **only the Coulomb interaction**
- Depending on the precision of the data, **we can get good / bad fits**
- **Systematic change** in the parameters: $\lambda \downarrow$, $R \downarrow$, $\alpha \uparrow$
- **(data-fit)/error** – characteristic **oscillation structure** appears

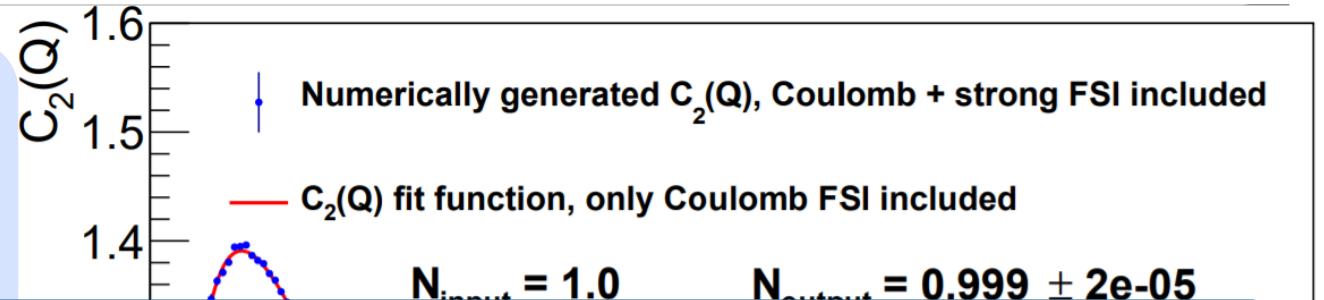
C+S data fitted with Coul. function
example fit – high statistics



Second check – fitting C+S data with Coulomb only

(what people usually did for real data so far)

- Let's see what happens, if we **generate C+S data**, but **fit it with** a function containing **only the Coulomb interaction**

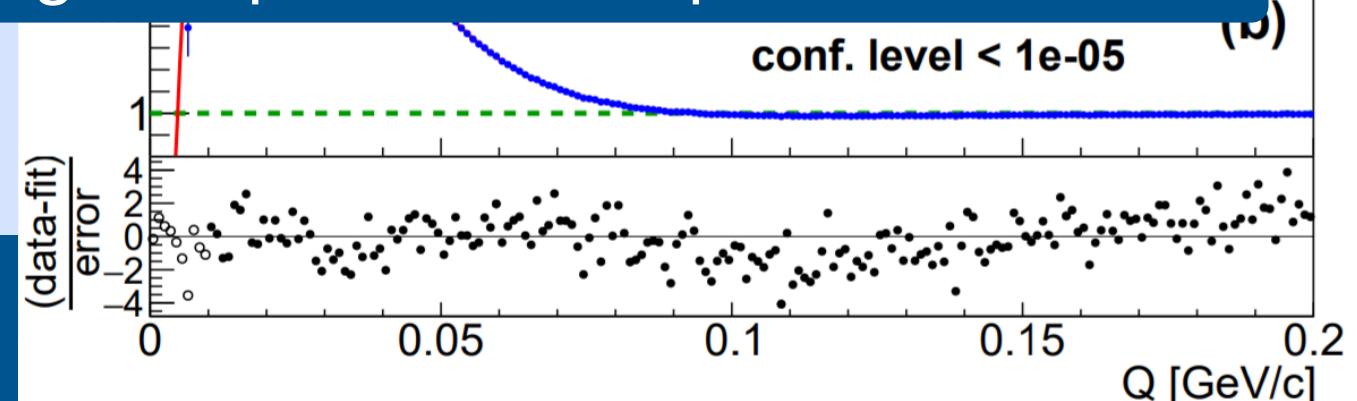


- Let's repeat this for many different input parameters,
spanning a wide range in parameter space!

parameters: $\lambda \uparrow$, $R \uparrow$, $\alpha \downarrow$

- (data-fit)/error** – characteristic **oscillation structure** appears

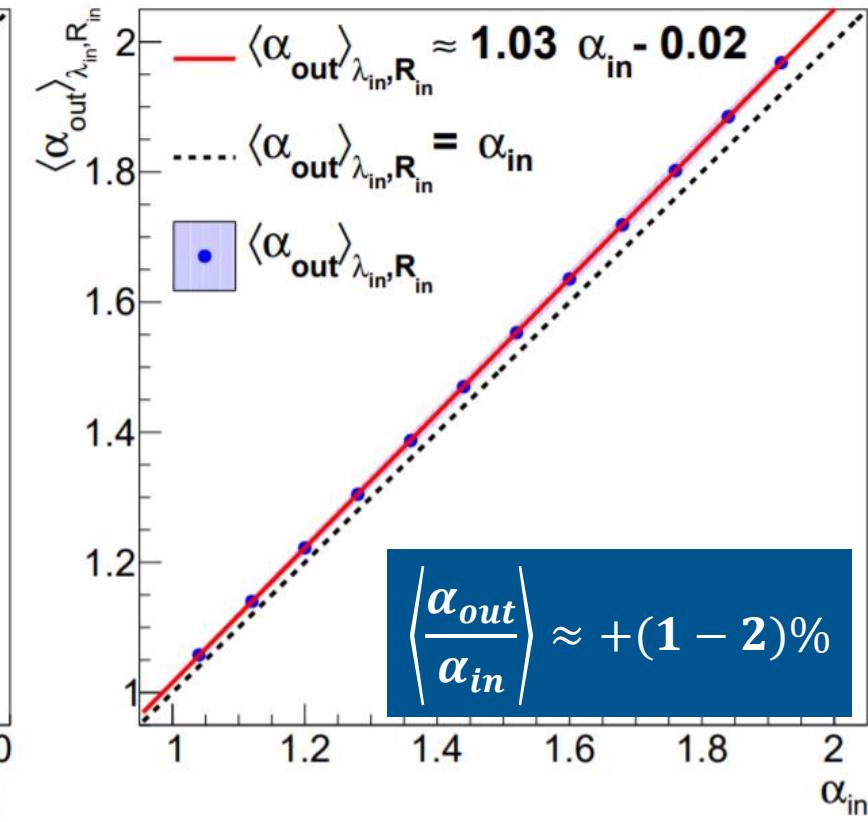
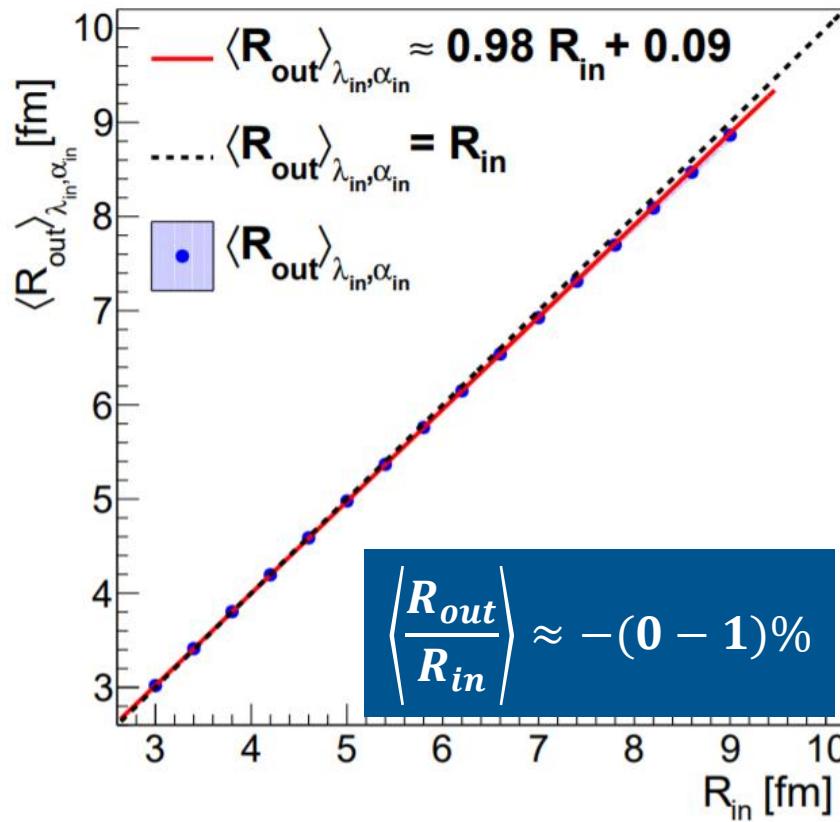
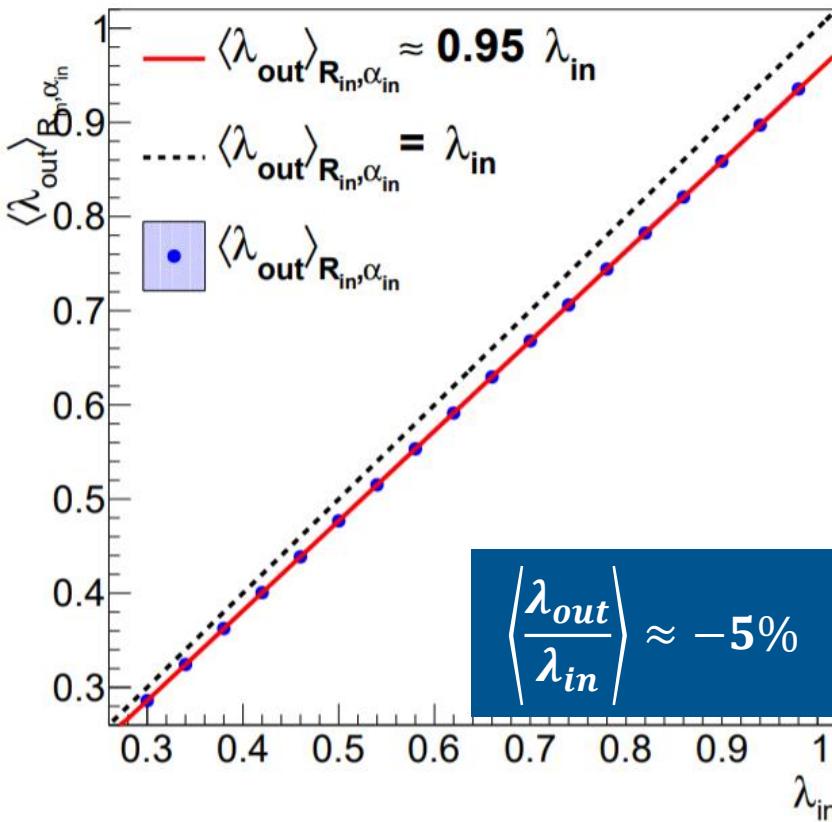
C+S data fitted with Coul. function
example fit – high statistics



Second check – fitting C+S data with Coulomb only

(what people usually did for real data so far)

Systematic change: $\lambda \downarrow / R \downarrow / \alpha \uparrow$



Summary – part I.

D. Kincses, M. I. Nagy, M. Csand,
Phys.Rev.C 102 (2020) 6, 064912

- Detailed calculation of $C(Q)$ with Lvy-type source and Coulomb + s-wave strong FSI included
- It seems that **strong interaction** can have a **non-negligible** effect **for pions**
- If the data is precise enough (could be achievable in today’s typical heavy-ion experiments),
fits neglecting strong interaction can become statistically unacceptable
- Two-pion HBT analyses not including SI probably slightly underestimate R , λ , and overestimate α
- **Outlook:** possibility to give constraints on strong interaction scattering length?

Developments in phenomenology – part II.

- PION SOURCE FUNCTION IN THE EPOS MODEL
- (FOR MOST RECENT RESULTS SEE CONTRIBUTION TO INITIAL STAGES 2021)

[HTTPS://INDICO.CERN.CH/EVENT/854124/CONTRIBUTIONS/4147083/](https://indico.cern.ch/event/854124/contributions/4147083/)

The two-particle source function

$$C(Q) = \int D(r) |\psi_Q(r)|^2 dr$$

- Experiments – no direct access to pair-source
 - Assumption on the **shape of the $D(r)$ pair-source function**
 - Proper description of FSI enclosed in $\psi_Q(r)$ **symmetrized pair wave func.**
- **Event generator models – direct access to pair-source!**
 - Phenomenological investigations of $D(r)$ possible

} Calculating $C(Q)$, then testing our assumption on experimental data

The EPOS model

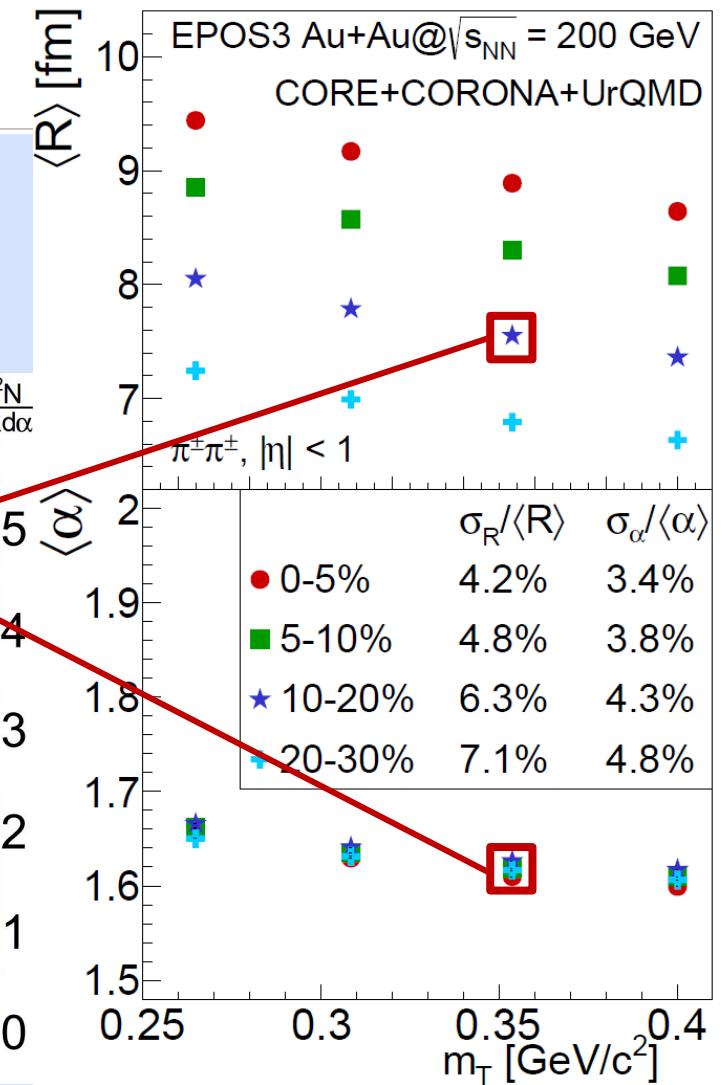
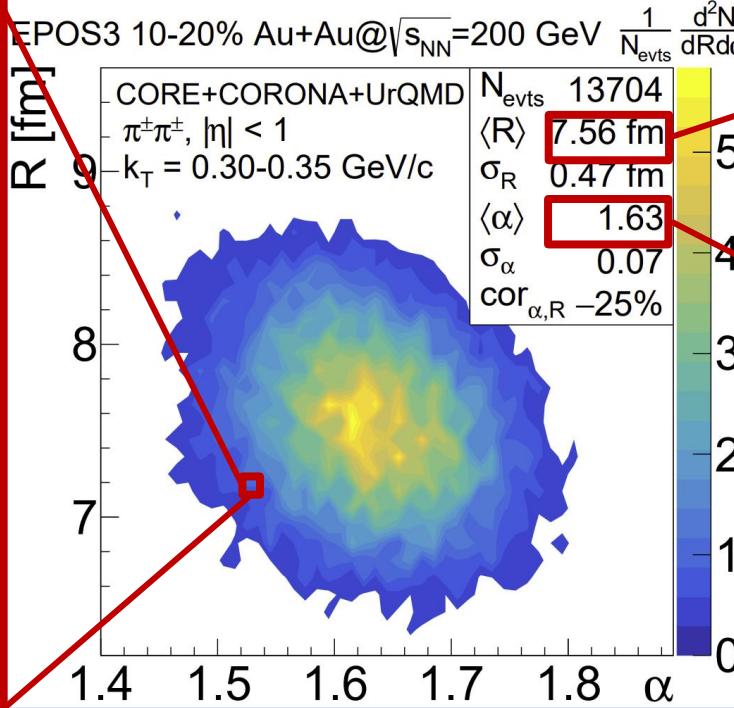
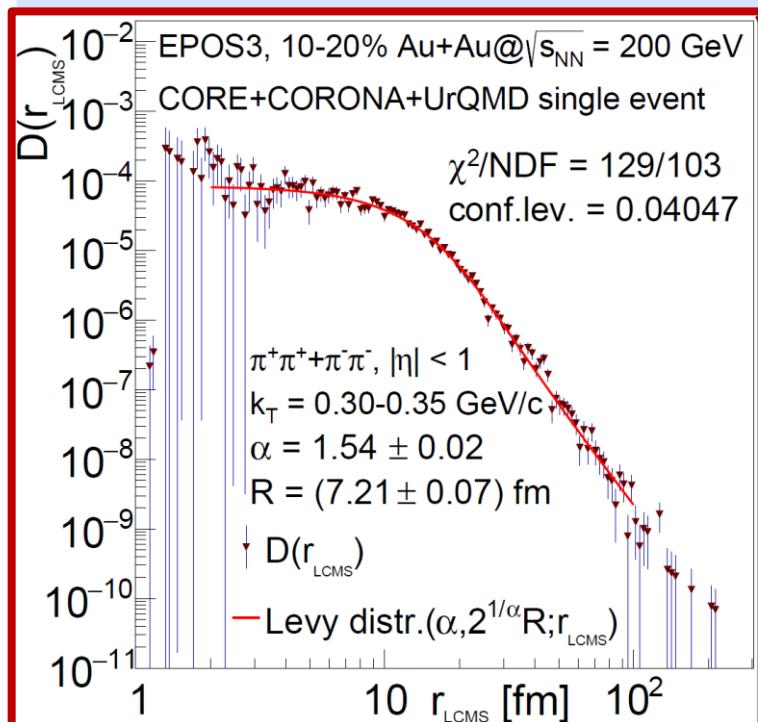
- Energy conserving quantum-mechanical multiple scattering approach, based on Partons (parton ladders), Off-shell remnants, and Splitting of parton ladders.
- The model is based on Monte-Carlo techniques
- Theoretical framework: parton-based Gribov-Regge theory (PBGRT)
- Three main parts of the model:
 - Core-Corona division (based on dE/dx of string segments)
 - Hydrodynamical evolution (vHLLE 3D+1 viscous hydrodynamics)
 - Hadronic cascades (UrQMD afterburner)

Details of the analysis

- **$\sqrt{s_{NN}} = 200 \text{ GeV Au+Au collisions generated by EPOS359}$**
- Investigating pions from the final stage of EPOS, after CORE+CORONA+UrQMD
- **event-by-event analysis!**
- Observable: **angle-averaged radial source distribution of like-sign pion pairs**
- $D(r_{1,2}^{LCMS}) = \int d\Omega dt D(r), \quad r_{1,2}^{LCMS} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (\Delta z_{LCMS})^2}$
- $\Delta z_{LCMS} = z_1 - z_2 - \frac{\beta(t_1 - t_2)}{\sqrt{1-\beta^2}}, \beta = (p_{z,1} + p_{z,2})/(E_1 + E_2)$

Results

- Pair-source containing CORE+CORONA+UrQMD fitted event-by-event!
- Extracted α and R parameters described with a normal distr.
- Similar trends as observed in experiments, higher α values



Summary – part II.

- Preliminary event-by-event analysis of EPOS 200 GeV Au+Au data
- **Angle averaged radial pair-source** of pions investigated
- **Lévy-distribution describes source $D(r)$**
- **event by event non-Gaussianity** – not because of averaging
- normal distribution of dN/dR and $dN/d\alpha$ in given kT & cent.
- Ongoing investigations:
 - pair-source in early phases of EPOS before rescattering
 - pair-source in multiple dimensions
 - pair-source of different particles
 - Reconstruct correlation functions from the measured pair-source distributions

Summary

- PHENIX, Phys.Rev. C97 (2018) no.6, 064911,
- Acta Phys. Pol. B Proc. Suppl. vol. 12 (2), 477 - 482 (2019)
- Acta Phys.Polon.Supp. 12 (2019) 445
- Phys.Part.Nucl. 51 (2020) 3, 267-269
- Phys.Rev.C 102 (2020) 6, 064912

- Investigation of the pion-pair source in heavy-ion collisions through HBT correlations

- **Experimental results**

- Levy fits yield acceptable description (within a certain precision), parameters R , λ , α measured
- Stability parameter $\alpha < 2 \leftrightarrow$ anomalous diffusion/CEP/QCD jets?
- Linear scaling of $1/R^2$ vs $m_T \leftrightarrow$ hydro (but non-Gaussian source!)
- Low- m_T decrease in $\lambda(m_T) \leftrightarrow$ core-halo model, in-medium η' mass?

- **Developments in phenomenology**

- Strong interaction might have a non-negligible effect for pions if the experimental precision is high
- Event-by-event non Gaussianity observed in the EPOS model

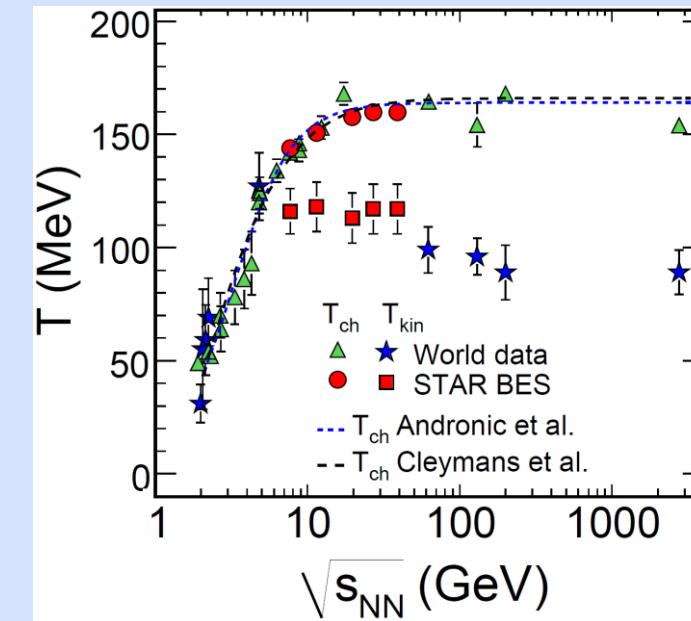
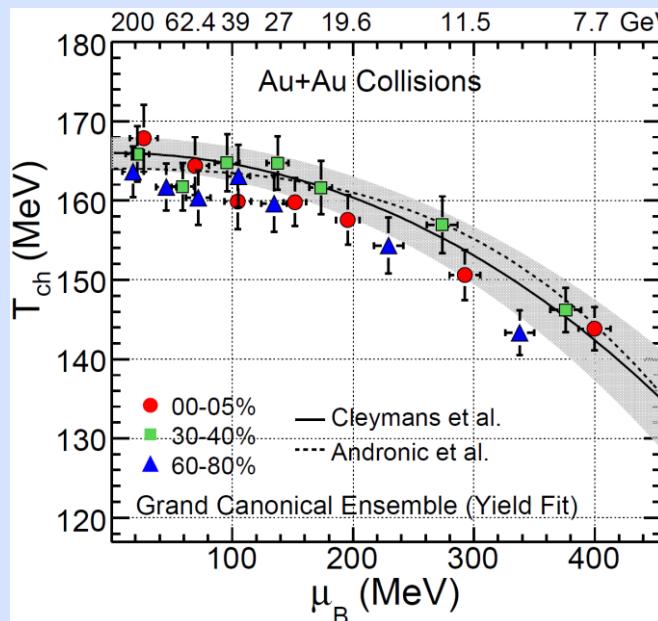
Thank you for your attention!

Backup slides

Freeze-out from particle yields

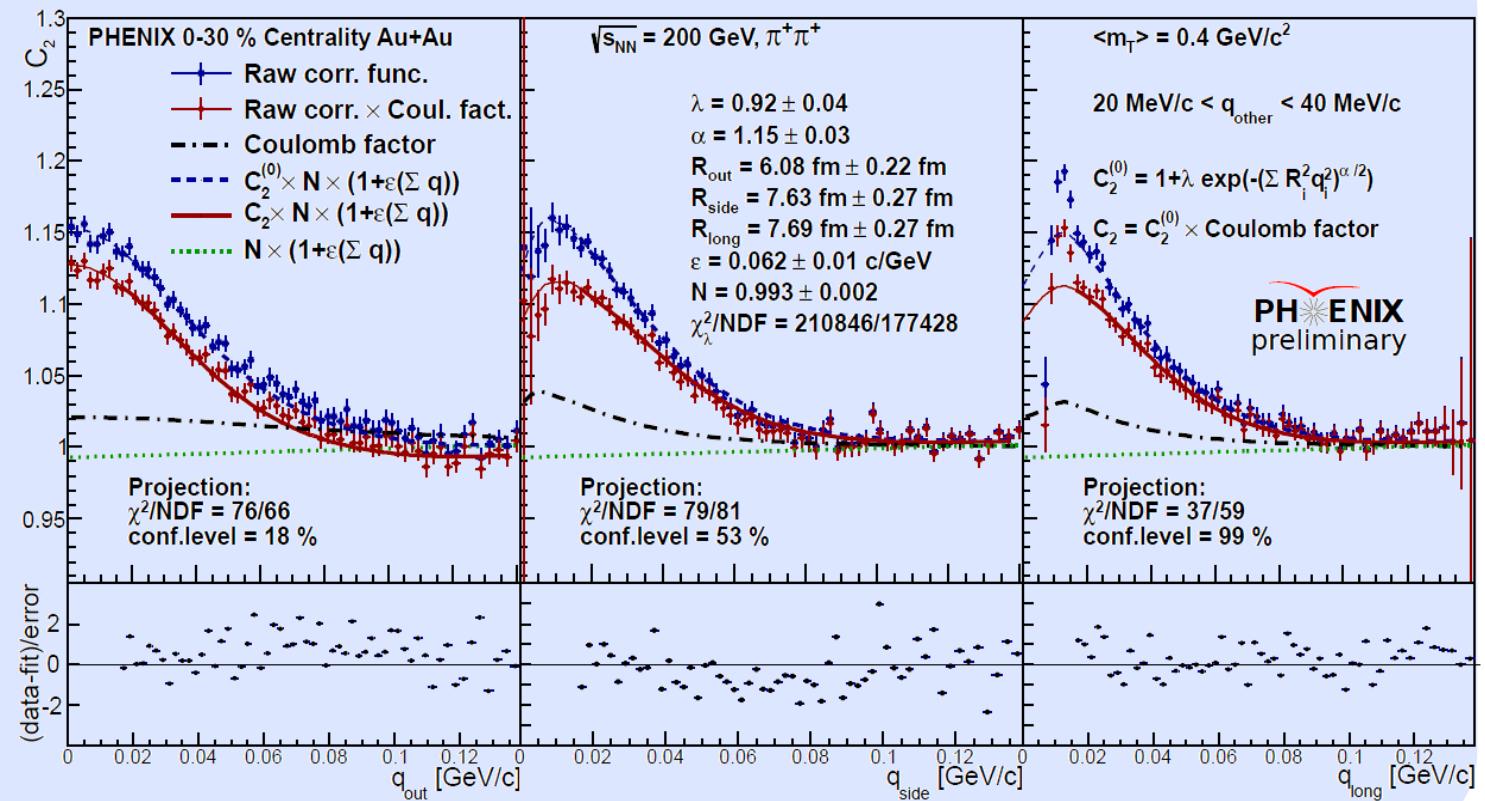
STAR Collaboration, Phys. Rev. C 96,
044904 (2017) [arXiv:1701.07065]

- Chemical and kinetic freeze-out parameters via THERMUS and BlastWave
- Thermal multiplicity assumption valid
- Systematics investigated (parameter constraints, included species)
- Separation of T_{ch} and T_{kin} around $\sqrt{s_{NN}} = 4-5$ GeV, T_{ch} flattens at ~ 10 GeV

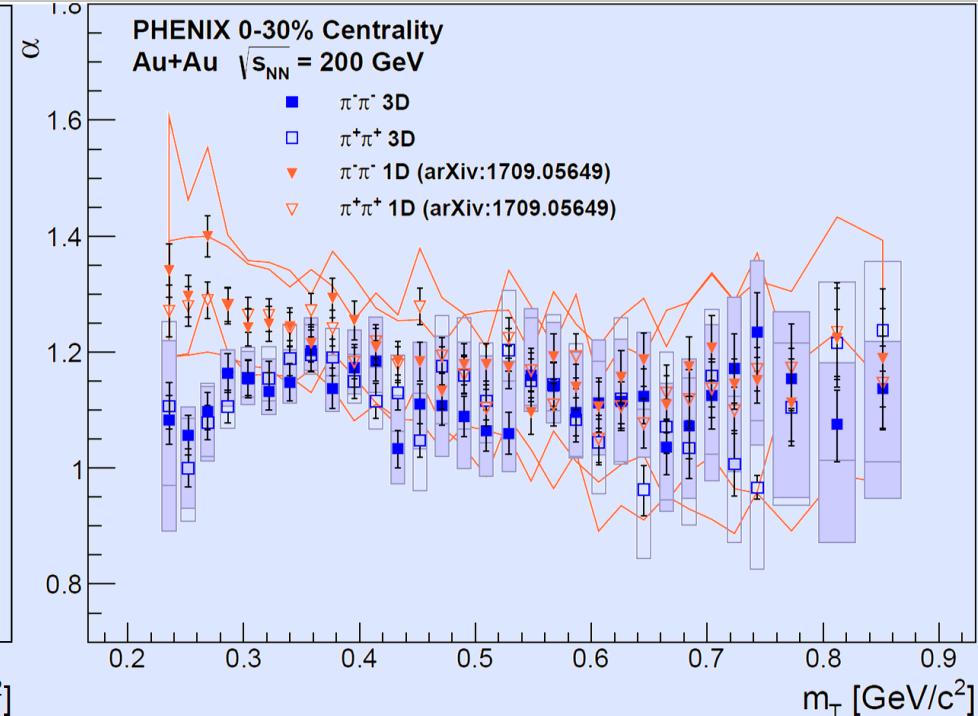
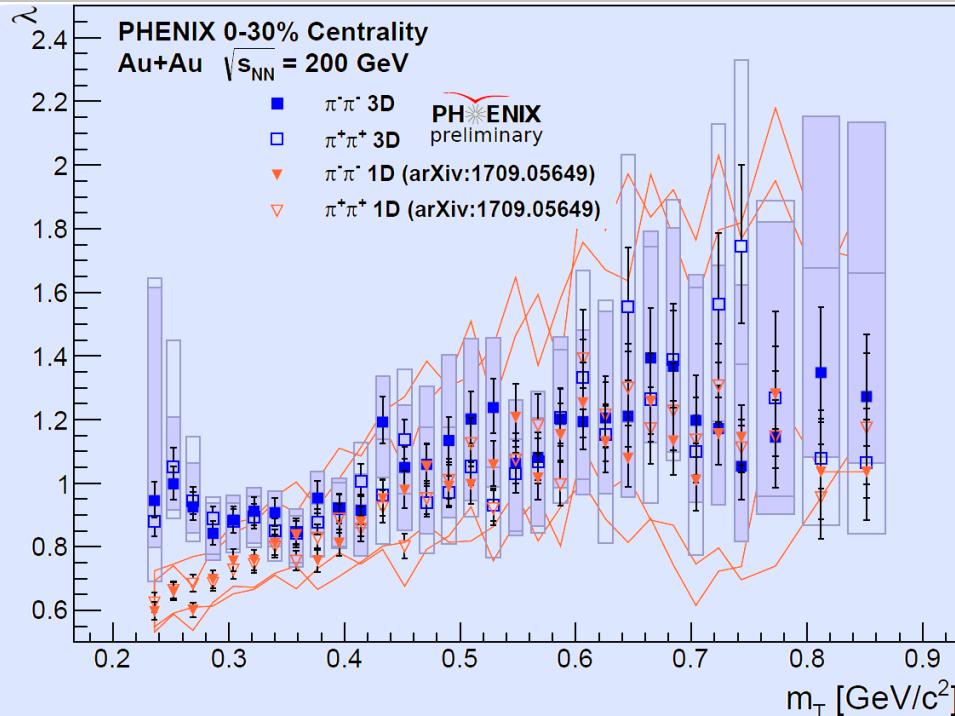


PHENIX 3D Lévy femtoscopy – example corr. functions

- 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 stat. in peak range)



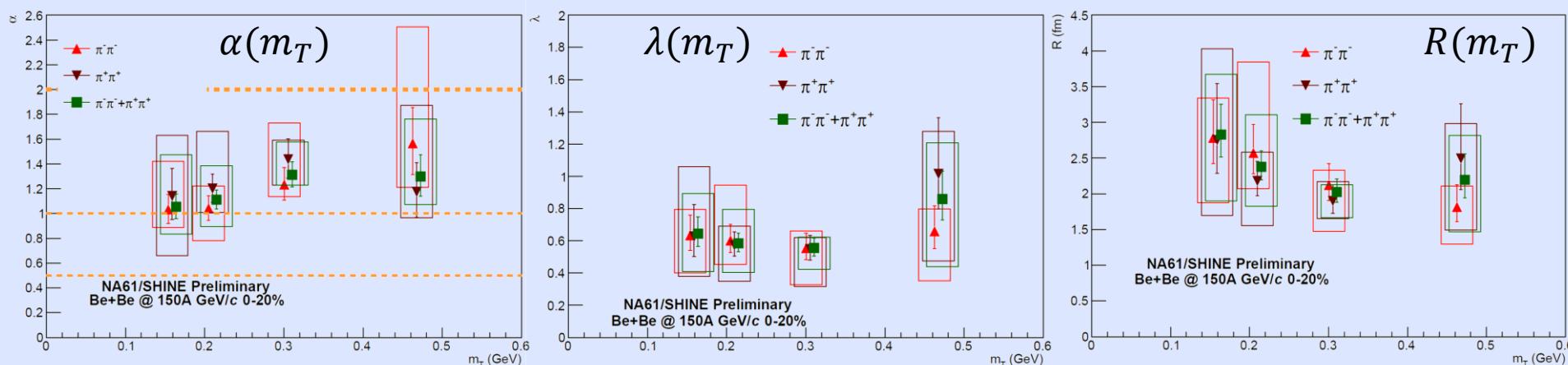
3D versus 1D: strength λ and shape α



- **Compatible with 1D (Q_{LCMS}) measurement** of Phys. Rev. C 97, 064911 (2018)
- Small discrepancy at small m_T : due to large R_{long} at small m_T ?

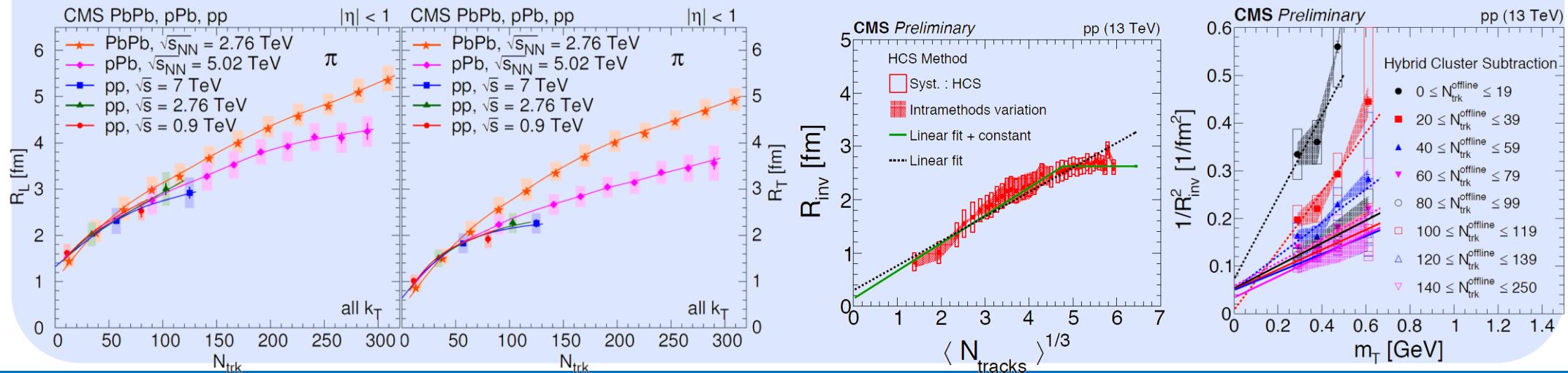
Lévy Femtoscopy at NA61/SHINE

- NA61/SHINE at SPS, 150A GeV/c Be+Be analysis
- Lévy fits statistically acceptable
- $R(m_T)$: Decreasing trend, transverse flow?
- $\lambda(m_T)$: Slight/no dependence with m_T , no „hole”
- $\alpha(m_T)$: **Not Gaussian, nearly Cauchy, around 1.0-1.5**



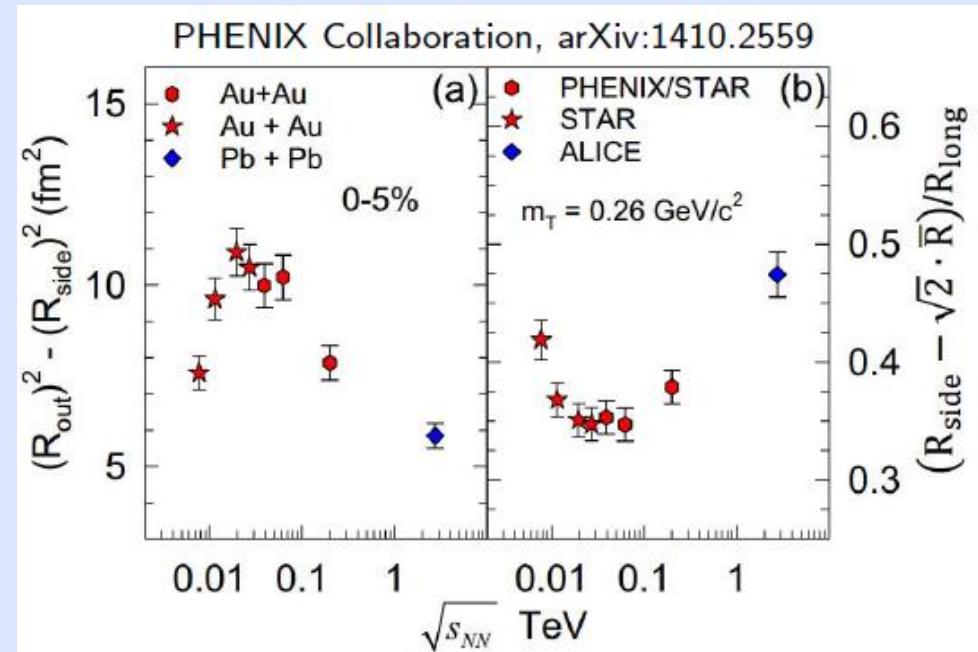
Results at CMS, touching different topics

- **Analysis performed at 0.9-13 TeV, Pb+Pb, p+Pb, p+p, using $\alpha = 1$ fixed**
- 3D analysis for 0.9-7 TeV
 - Detailed geometry exploration
 - Elongated source: p+p and p+Pb
- High multiplicity 13 TeV p+p: similar results as ion-ion
 - Geometric multiplicity scaling
 - Hydro type of m_T scaling?



HBT radii and the search for the CEP

- **Signals of QCD CEP: softest point, long emission**
- $R_{out}^2 - R_{side}^2$: related to emission duration
- $(R_{side} - \sqrt{2}\bar{R})/R_{long}$: related to expansion velocity, \bar{R} : initial transverse size
- Non-monotonic patterns
- **Indication of the CEP?**
- Further details in
Roy Lacey, arXiv:1606.08071 &
arXiv:1411.7931 (PRL114)
- How about finite size scaling?



Finite size effects taken into account

- Finite size scaling analysis with $L = \bar{R}$, peak position and height tell ν and γ
- Critical EndPoint location for $L \rightarrow \infty$: $\sqrt{s_{NN}} \approx 47.5$ GeV
- Scaling vs $t_T = (T - T_c)/T_c$, $t_{\mu_B} = (\mu_B - \mu_{B,c})/\mu_{B,c}$: **$T_c=165$ MeV & $\mu_B=95$ MeV**

