Messages about Collaboration meeting:

Adam:

Due to the fact that this week is an official holiday in Russia, I propose to move the MPD Convenors meeting from tomorrow (April 1st) to next Wednesday (April 8th).

In the meantime, please let me know if You have proposals for the presentations during the "Physics Discussions" session of the Collaboration Meeting. I hope that we can finalize the agenda for this session during the meeting next week.

Natalia:

On behalf of the Organizing Committee I would like to invite you to register for the V-th Collaboration Meeting of the MPD Experiment at the NICA Facility which will be held as a videoconference on April 23-24, 2020. Details of the connection procedure will be announced in advance before the conference.

The registration is available at the www-page of the meeting:

https://indico.jinr.ru/e/5mpd_meeting

Vth MPD Collaboration meeting
23-24 April 2020,JINR, Dubna

Correlation femtoscopy and factorial moments

on behalf of PWG3 (Correlations and Fluctuations)
Supported by the RFBR grant 18-02-40044

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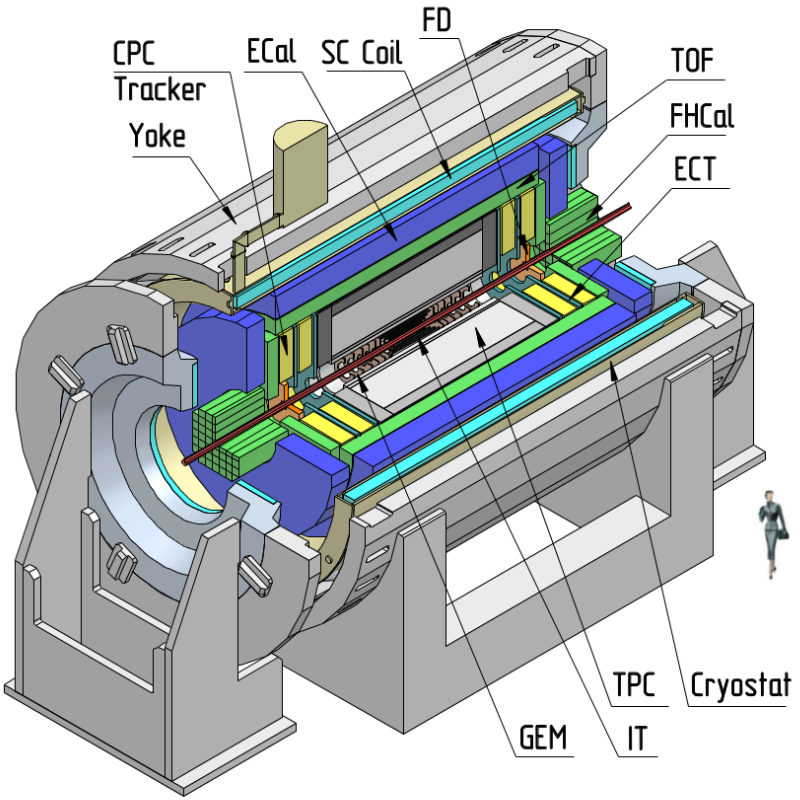
Outline

- Activities
- Femtoscopy & Motivation
- Hybrid vHLLE+UrQMD model
- Comparison with STAR BES
  - pions
  - first results with kaons
- First tests with reconstructed data
- Factorial Moments
- Other activities
- Plans for 20202
- Conclusion



Activities within RFBR grant 18-02-40044 (2019)

Aim of the project:
Study of collective effects and dynamics of quark-hadron phase transitions via femtoscopic correlations of hadrons and factorial moments of particle multiplicity at NICA energies

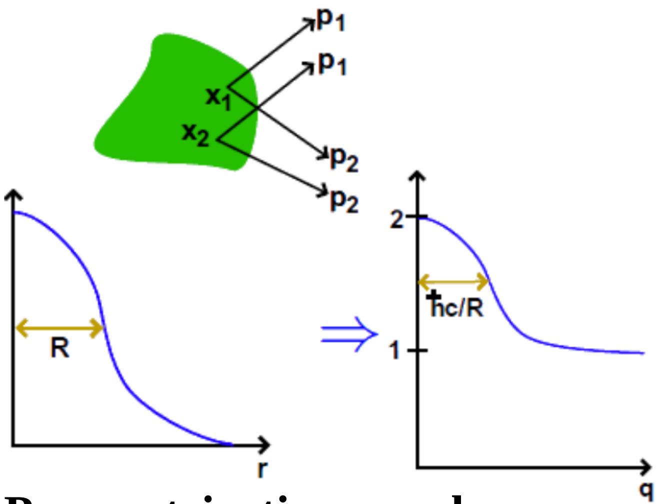
Goals:

- Development of the data analysis methods and software that will be integrated in the Multi-Purpose Detector (MPD) software environment
- Analysis of the simulated with different event generators (in particular, UrQMD and vHLLE) Au+Au collisions at NICA energies
- Study the dependence of femtoscopic radii and scaled factorial moments of particle multiplicity on the initial conditions and properties of nuclear matter equation of state

2019:

- Simulation of Au+Au collisions with UrQMD and vHLLE+UrQMD models for different collision energies (done)
- Software development for: (done)
  - femtoscopic analyses
  - factorial moments of multiplicity distributions
  - other activities
- Femtoscopic analysis (at one collision energy) and extraction of source functions for pions and kaons for models with different Equation of State (EoS): first-order phase transition (1PT), crossover (XPT), no phase transition. (done)
- Investigation of the detector effects (track-merging and track-splitting in TPC) on femtoscopic measurements (done)

Femtoscopy



Correlation femtoscopy :

Measurement of space-time characteristics **R**, **cτ** of particle production using particle correlations due to the effects of quantum statistics (QS) and final state interactions (FSI)

Two-particle correlation function:

theory: $$C(q)=\frac{N_2(p_1,p_2)}{N_1(p_1)\cdot N_2(p_1)}, C(\infty)=1$$

experiment: $$C(q)=\frac{S(q)}{B(q)}, q=p_1-p_2$$

$S(q)$ – distribution of pair momentum difference from same event

$B(q)$ – reference distribution built by mixing different events

Parametrizations used:

1D CF: $C(q_{inv})=1+\lambda e^{-R^2 q_{inv}^2}$

R – Gaussian radius in PRF,

λ – correlation strength parameter

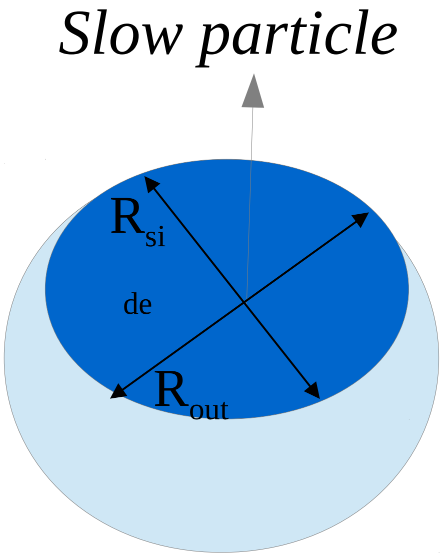
3D CF: $C(q_{out}, q_{side}, q_{long})=1+\lambda e^{-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2}$

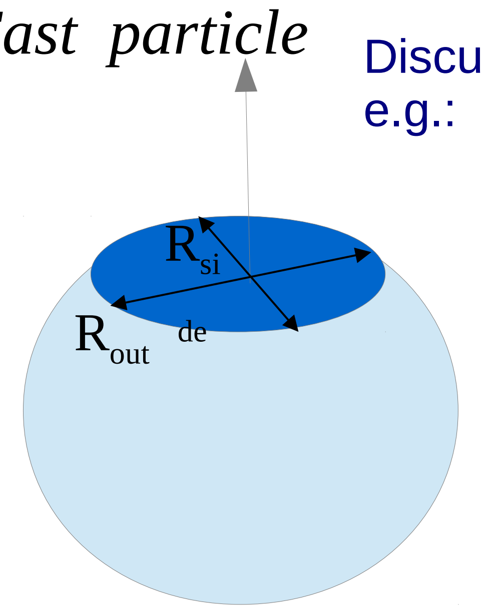
R and q are in Longitudinally Co-Moving Frame (**LCMS**)

long || beam; out || transverse pair velocity $\boldsymbol{v}_T$; side normal to out,long

Femtoscopy with expanding source → m_T-dependence

- **x-p** correlations → interference dominated by particles from nearby emitters.
- Interference probes only parts of the source at close momenta – **homogeneity regions.**
- Longitudinal and transverse expansion of the source -> significant reduction of the radii with increasing pair velocity, consequently with k_T (or $m_T=(m^2+k_T^2)^{1/2}$)





Discussed in e.g.:

Kolehmainen, Gyulassy'86
Makhlin-Sinyukov'87
Pratt, Csörgö, Zimanyi'90

$R_{side} \sim R/(1+m_T\beta_T^2/T)^{½}$

β_T collective transverse flow

assuming a longitudinal boost invariant expansion

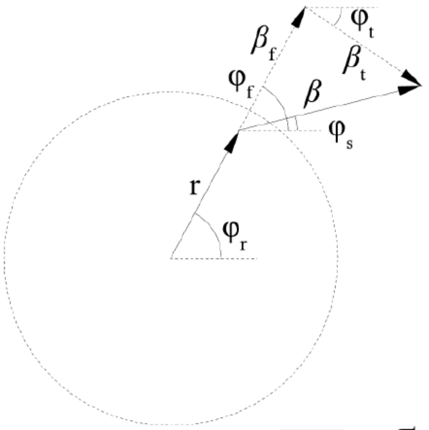
$R_{long} = \tau\,(T/m_T)^{1/2}$

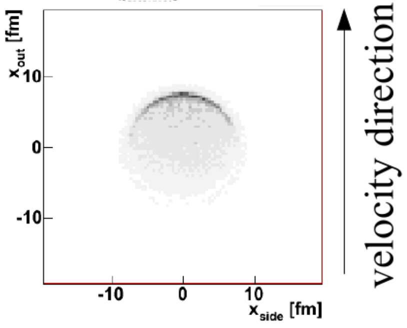
$R^2_{out} \sim R^2_{side} + 1/2(T/m_T)^2\beta_T^2\tau^2$

Femtoscopy with expanding source

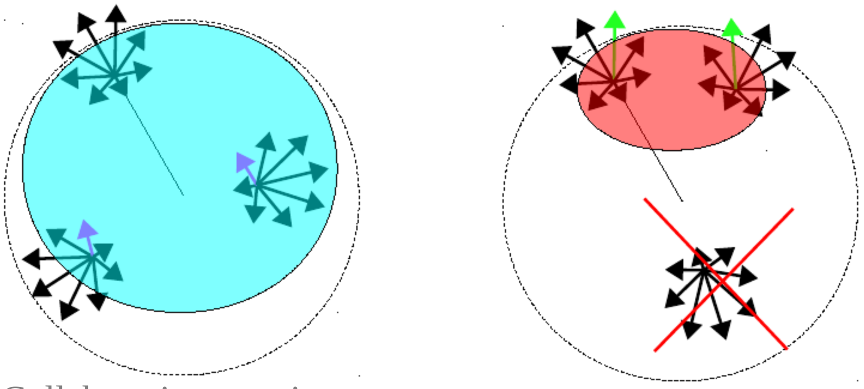
Interference probes only parts of the source at close momenta – **homogeneity regions.**

[Yu.M. Sinyukov, Nucl. Phys. A 566, 589 (1994);]
Figures and consideration from A. Kisiel Phys.Rev. C81 (2010) 064906





- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source



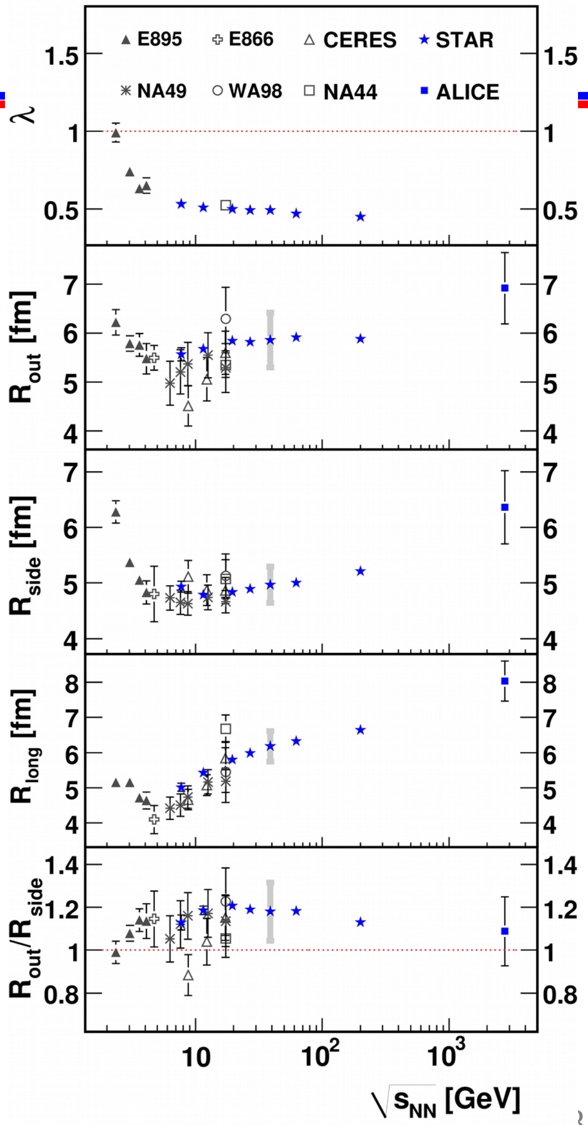
Motivation

- **Femtoscopy allows one:**

  - To obtain spatial and temporal information on particle-emitting source at kinetic freeze-out
  - To study collision dynamics depending on EoS

- RHIC Beam Energy Scan program (BES-I):
  $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39 GeV
  - The search for the onset of a first-order phase transition in Au + Au collisions
  - Measured pion and kaon femtoscopic parameters:
    m_T -dependence of radii,
    flow-induced $x - p$ correlations

- NICA energy range: $\sqrt{s_{NN}}$ = 4 – 11 GeV measurements with great accuracy



Femtoscopy with vHLLE+UrQMD

Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015)

Pre-thermal phase → Hydrodynamic phase → Hadronic cascade

Pre-thermal phase	Hydrodynamic phase	Hadronic cascade
UrQMD	vHLLE (3+1)-D viscous hydrodynamics	UrQMD

Parameters τ_0 , $R_\perp$, R_η and η/s adjusted using basic observables in the RHIC BES-I region.

$\sqrt{s_{NN}}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_η [fm]	η/s
7.7	3.2	1.4	0.5	0.2
8.8 (SPS)	2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
17.3 (SPS)	1.42	1.4	0.5	0.15
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08
200	0.4	1.0	1.0	0.08

Model tuned by matching with existing experimental data from SPS and BES-I RHIC

EoS to be used in the model

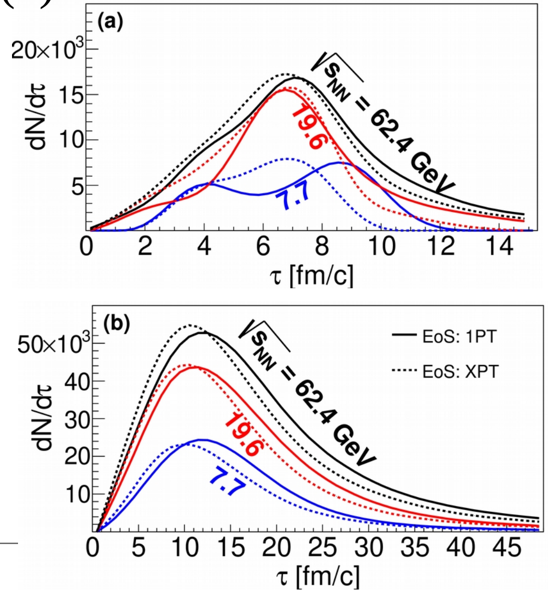
- Chiral EoS — crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model
  1st-order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

Hydrodynamic phase lasts longer with 1PT, especially at lower energies but cascade smears this difference.

Pion emission time

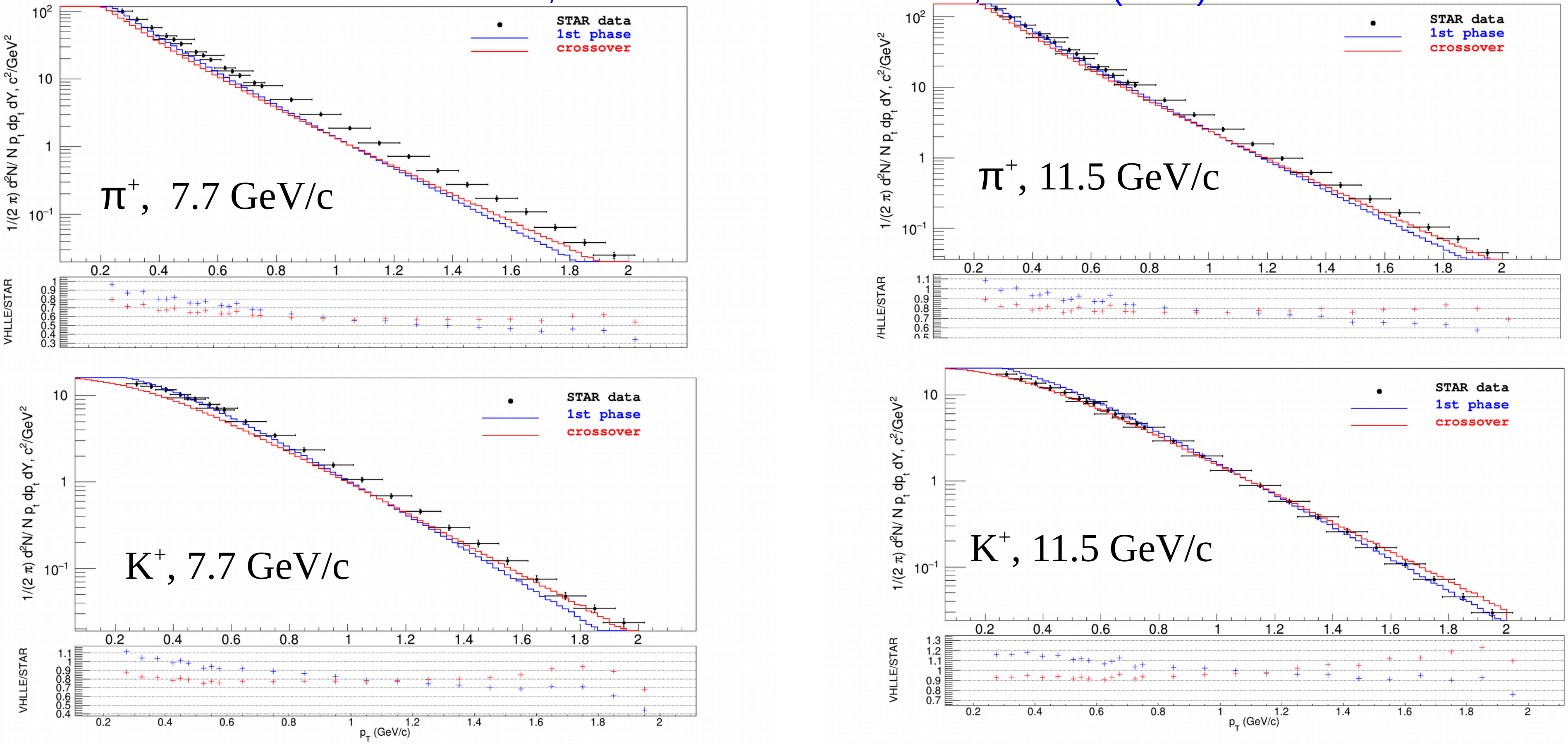
(a) - after hydrodynamic phase

(b) - after cascade



p_T- spectra of π and K with vHLLE+UrQMD

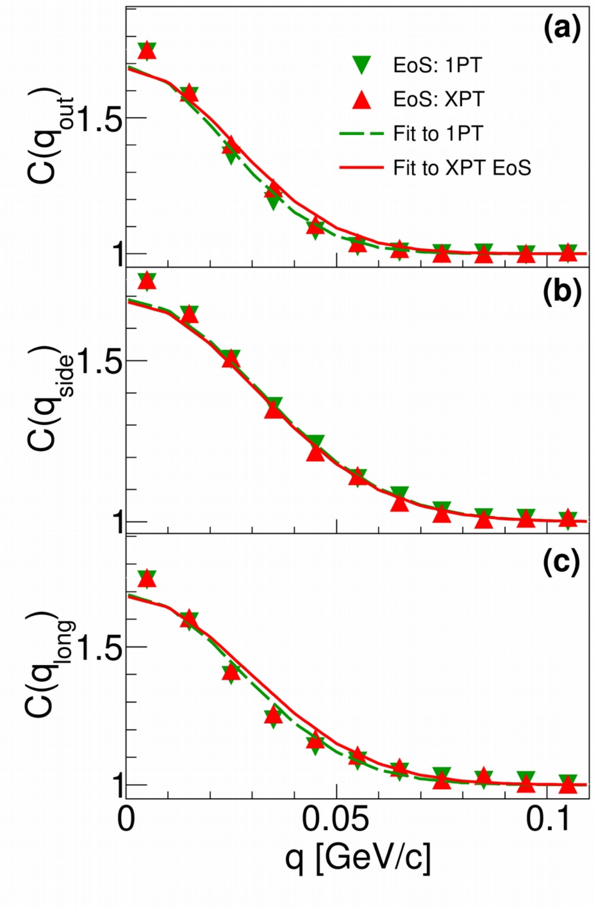
STAR, PHYSICAL REVIEW C 96, 044904 (2017)



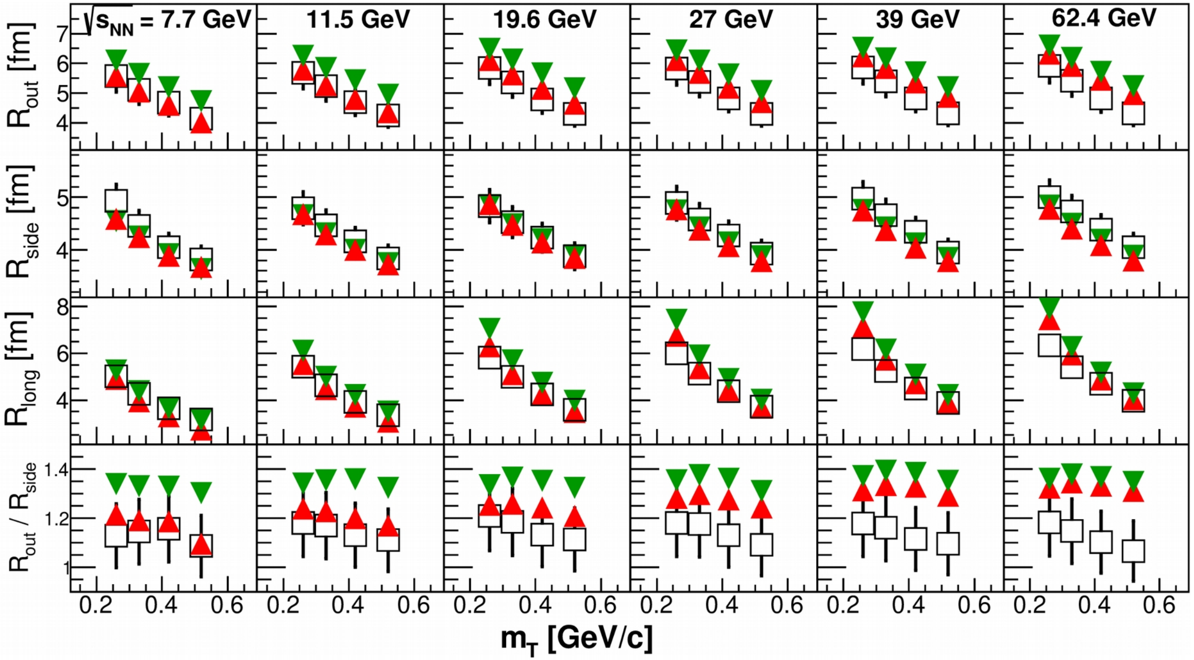
vHLEE+UrQMD model with both EoS describe reasonably (<20%) pT-spectra of pions and kaons at pT< 1 GeV/c

3D Pion radii versus m_T with vHLLE+UrQMD

Model CF



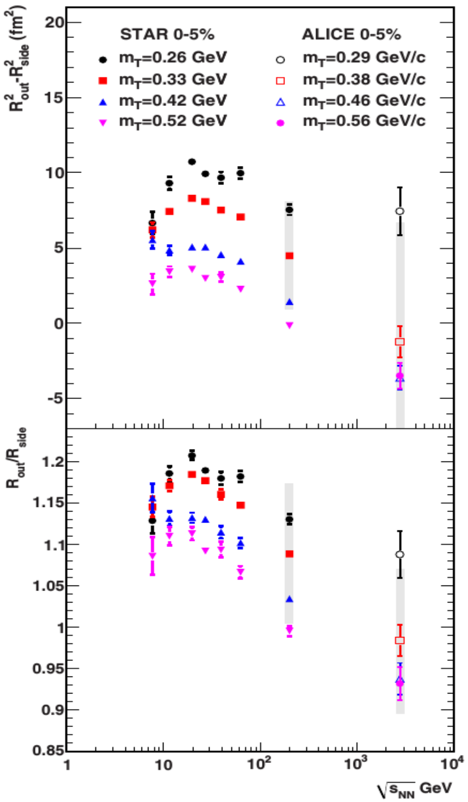
Comparison of extracted radii with the STAR data[PRC 96, 024911(2017)]



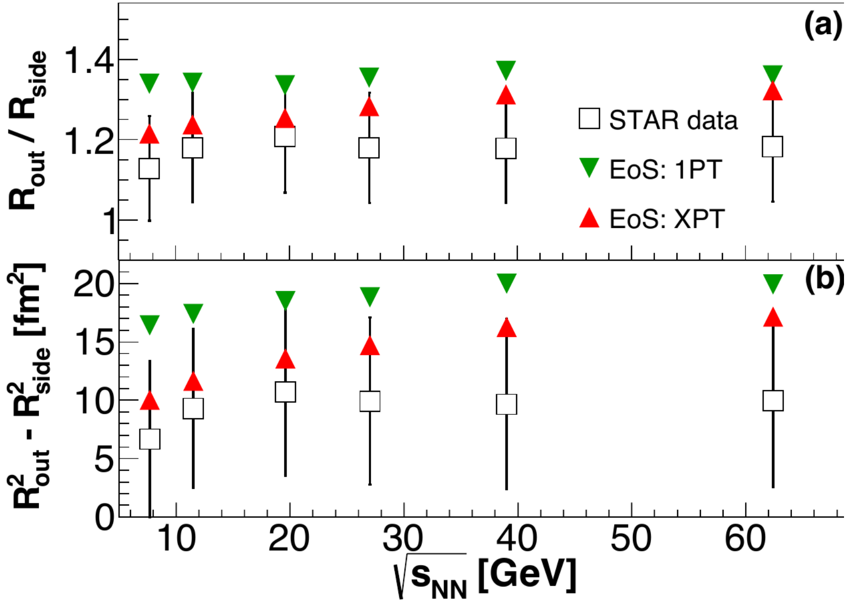
- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS does better job at lowest collision energies.
- R_{out} (XPT) at high energies and R_{out} (1PT) at all energies are slightly overestimated
- $R_{out,long}$ (1PT) > $R_{out,long}$ (XPT) by value of ∼1-2 fm.

R_{out} /R_{side} with vHLLE + UrQMD model

Exp. data: R_{out} /R_{side} and R^2_{out} - R^2_{side} as a function of $\sqrt{s_{NN}}$ at a fixed m_T demonstrate a wide maximum near $\sqrt{s_{NN}} \approx 20$ GeV

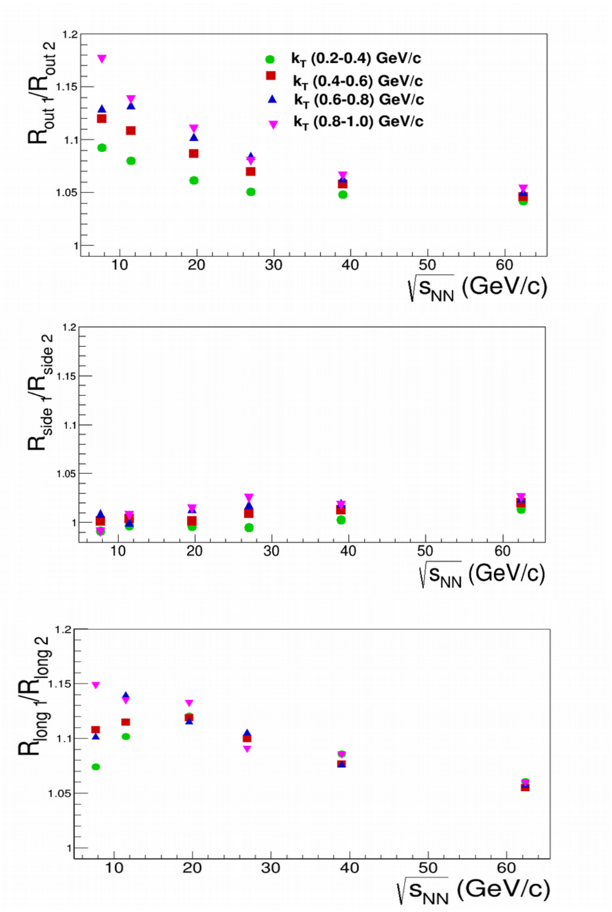


Present vHLLE+UrQMD calculations:



- R_{out} /R_{side} (XPT) agrees with almost all STAR data points within rather large systematic errors, while R_{out} /R_{side} (1PT) overestimates the data.
- XPT – a monotonic increase in both quantities

Ratio of $R_{out,side,long}(1PT)/R_{out,side,long}(XPT)$ vs. $\sqrt{s_{NN}}$



- Pion k_T divided into 4 bins
- R_{side} ratio practically coincide for both scenarios
- R_{out} and R_{long} ratios for 1PT EoS are greater than for XPT EoS and demonstrating a strong k_T -dependence at low energy

- The difference comes from a weaker transverse flow developed in the fluid phase with 1PT EoS as compared to XPT EoS and its longer lifetime in 1PT EoS

Kaon correlation functions with vHLLE+UrQMD (NEW!)

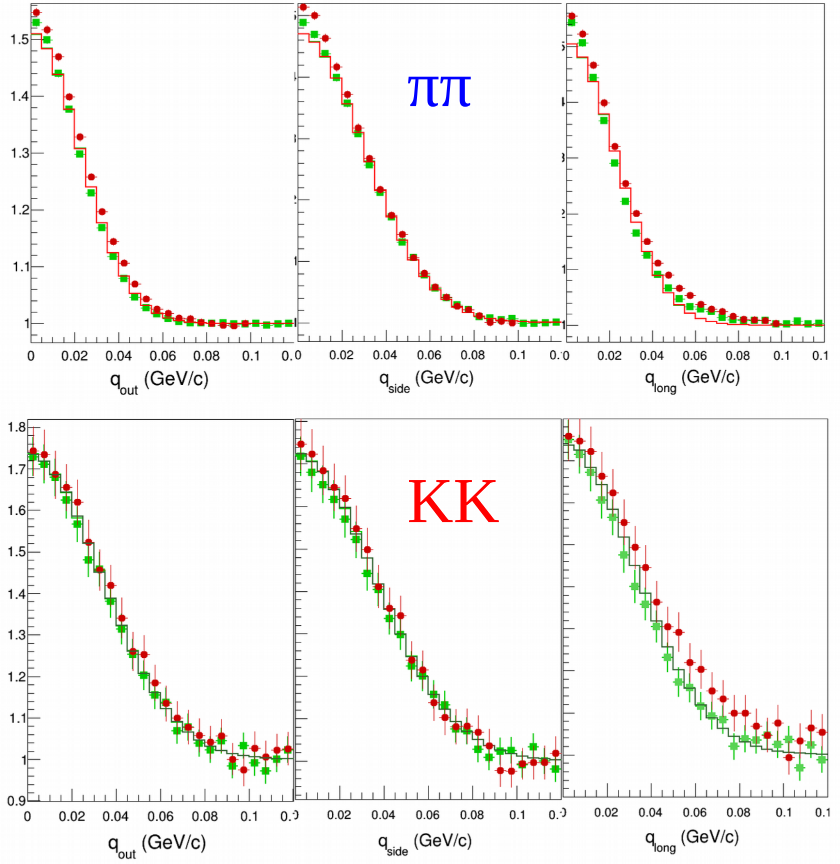
Analysis:

- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- $N_{events} \approx 4 \cdot 10^5$
- Standard 3D Gaussian fit used
- Our, side, long projections

- Projections of 3D kaon correlation functions on out-side-long directions are more Gaussian

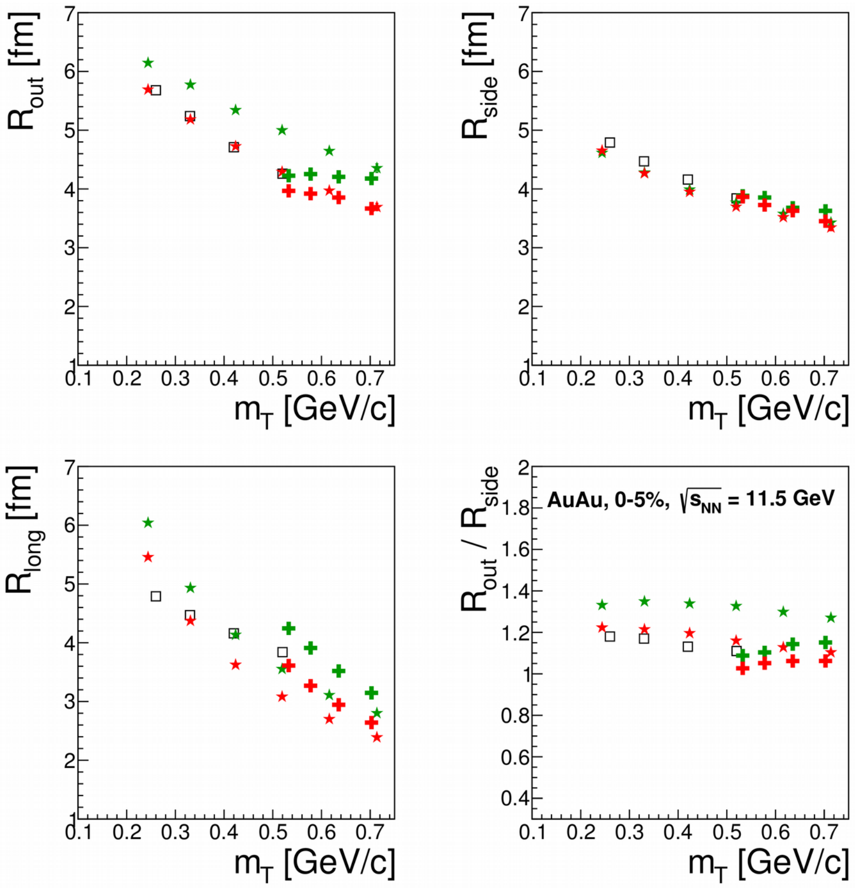
- XPT CF projections on long direction are visibly wider than 1PT especially for kaons

1PT -green dots; XPT – red dots



Radii π and K vs. mT with vHLLE+UrQMD

1PT -green dots; XPT – red dots



- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- As well as for π, kaon out and long radii greater for 1PT than for XPT
- Approximate m_T-scaling for pions and kaons observed only for “side” radii
- R_{out} almost flat for 1PT
- R_{long}(KK) is greater than R_{long}(ππ) kaons on average emitted later than pions
- Rout/Rside(KK) for kaons is less than for pions
- Approximately the same result is for Au+Au $\sqrt{s_{NN}}$ = 7.7 GeV

- It is important to measure both kaons and pions

Factorial moments

Proposed by A. Bialas and R. Peschanski (Nucl. Phys. B 273 (1986) 703) to study the dependence of the normalized factorial moments of the rapidity distribution on the size of the resolution

The scaled factorial moments are defined:

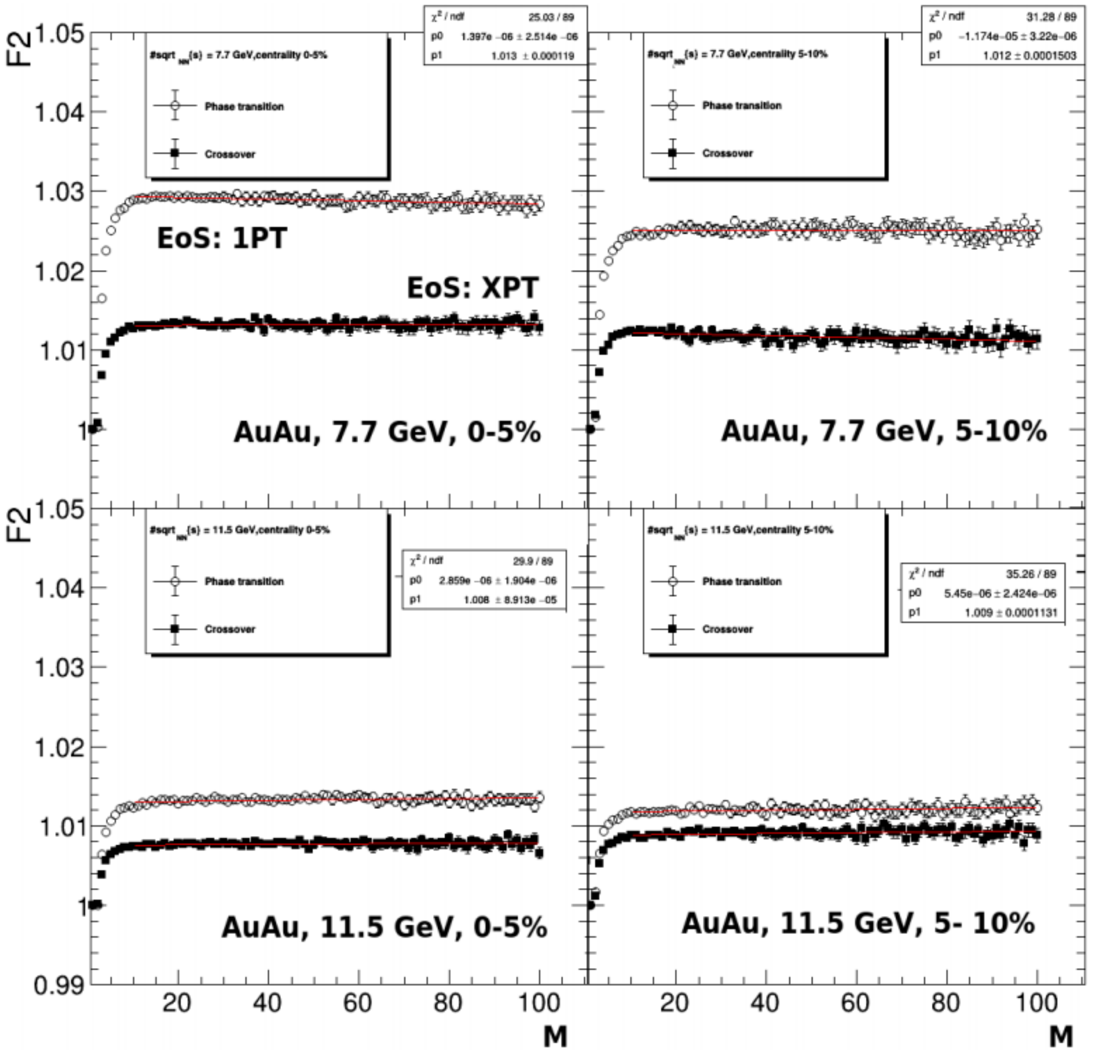
$$F_i = M^{i-1} \cdot \left\langle \frac{\sum_{j=1}^{M} k_j \cdot (k_j - 1) \cdot \ldots \cdot (k_j - i + 1)}{N \cdot (N-1) \cdot \ldots \cdot (N - i + 1)} \right\rangle$$

where brackets <> denote averaging over a sample of a selected class of events.
$N=k_1+\ldots+k_M$ is a total number of particles, and M is number of intervals in rapidity window.

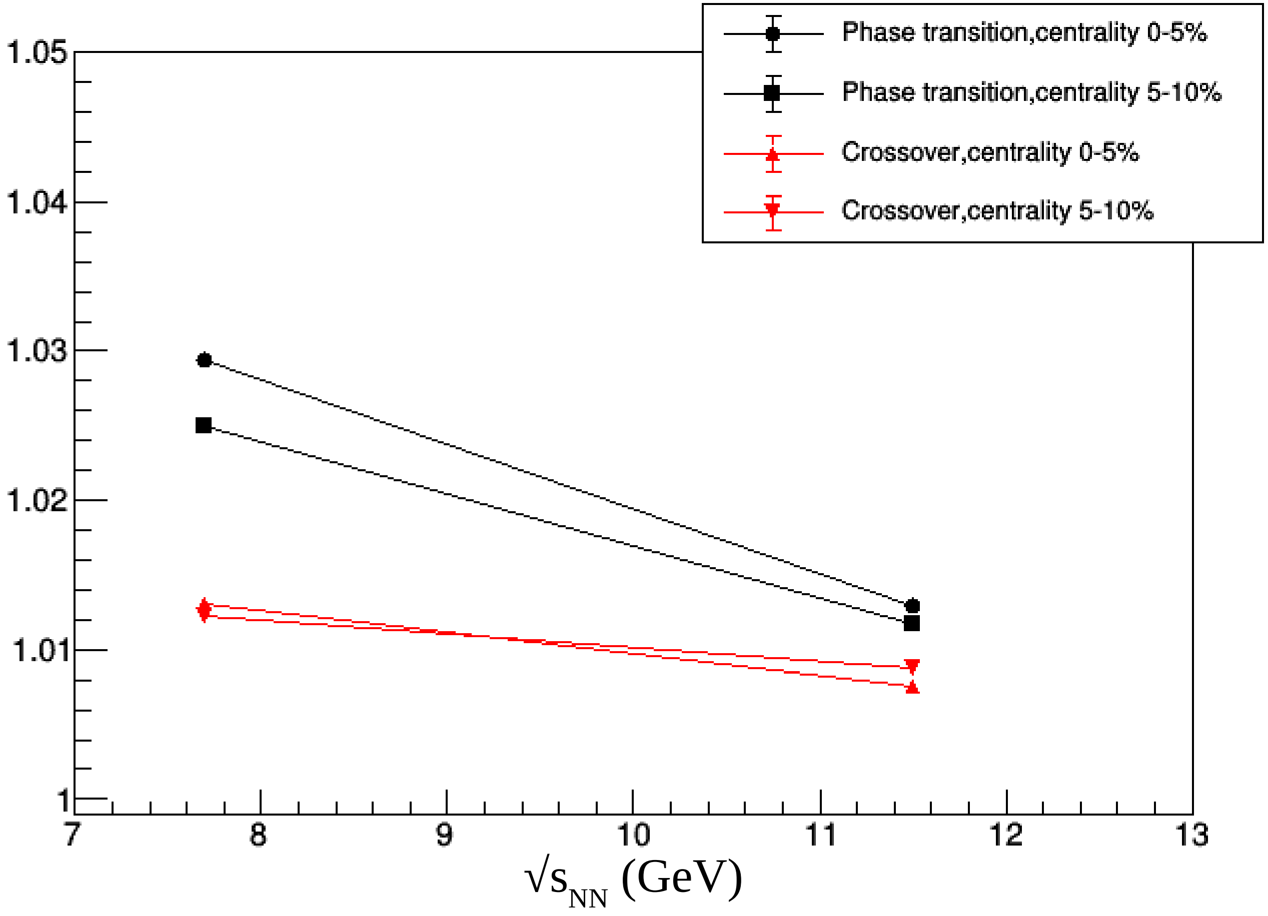
- Factorial moments do not depend on M in case of statistical fluctuation of rapidity distribution
- And F depend on M if fluctuation due to physical reason.

Factorial moments with vHLLE+UrQMD

- F2 as a function M for |y|<0.5
- Fit F2 by the first order polynomial: a+bM
  b is of the order of 10^{-6}
- F2 maximum is determined from fit



Energy dependence of F2 maximum



- Plot the F2 max as a function of energy.
- F2 energy dependence is expected for Crossover and 1st order phase transition

2020 plans

- Simulation of ion-ion collisions with different models and different EoS for $\sqrt{s_{NN}}$=4-11GeV energies to be continued
  - 3d CF analysis of $\pi\pi$ and KK
  - m_T dependence within MPD detector range
  - Factorial moment study
- New MpdFemto package
  - Test within MpdRoot
  - Two Track Cut tests (merging, splitting)
  - Finite Momentum Resolution tests
- New miniDST format
  - Compact reconstructed and generated information (ten times less than DST)
  - Reaction, track quality, TOF, Ecal and FHCal (first stage of MPD detector)
  - MiniDST created on-the-fly
- Software for factorial moment study will be developed

Conclusions

- Study of collective effects and dynamics of quark-hadron phase transitions via femtoscopic correlations of hadrons and factorial moments of particle multiplicity at NICA energies was performed

- First results look promising and this study is planned to be continued.

- Development of the data analysis methods and software integrated in the Multi-Purpose Detector (MPD) software environment was performed and will be continued

- Results were presented at WPCF, QFTHEP and NICA Days conferences
- Proceeding were published

Thank you for attention!

Title

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