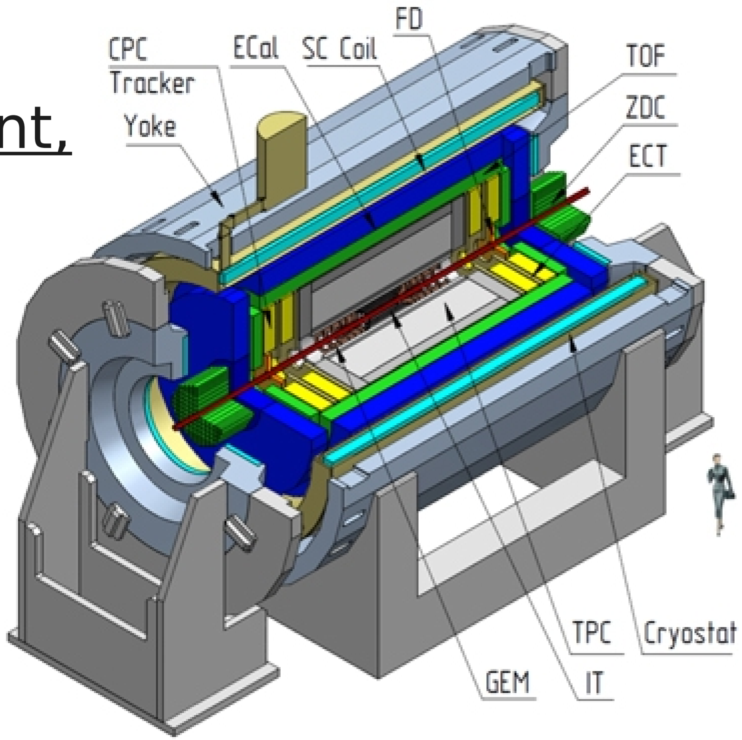
# Femtoscopy and correlations at MPD: physics case, people, projections

**within the RFBR Mega Grant # 18-02-40044**

**“Study of strongly interacting matter properties at the energies of the NICA collider using the methods of femtoscopy and factorial moments“**




**People:**

- Ludmila  Malinina (SINP MSU, JINR), (grant, PI)
- Konstantin  Mikhaylov (ITEP & JINR), co-convener
- Pavel Batyuk (JINR), co-convener
- Grigory Nigmatkulov (NRNU MEPhI),
- Olga Kodolova (SINP MSU),
- Igor Lokhtin (SINP MSU),
- Gleb Romanenko (student, MSU),
- Marya Cheremnova (student, MSU)

The 3rd MPD Collaboration Meeting
April 15, 2019

# Femtoscopy & correlations activities within RFBR mega grant

## “Study of strongly interacting matter properties at the energies of the NICA collider using the methods of femtoscopy and factorial moments“

**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

Plans for 2019:

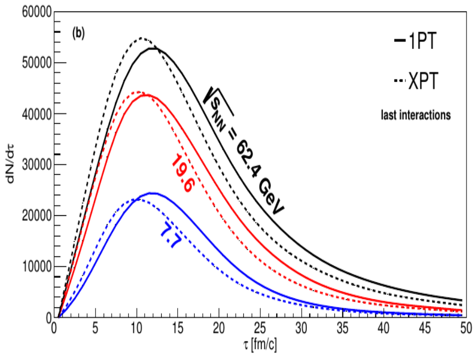
- Simulation of Au+Au collisions with UrQMD and vHLLE+UrQMD models for different collision energies
- Software development for:
  - Femtoscopic analyses
  - Factorial moments of multiplicity distributions
- Femtoscopic analysis (at one collision energy) and extraction of source functions for pions and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

# Correlation femtoscopy

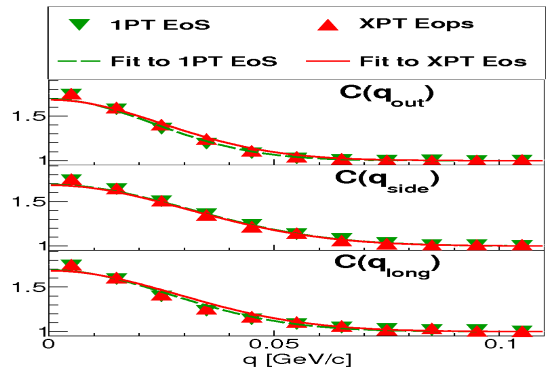
## Study of space-time properties of the particle-emitting source created in heavy-ion collisions with the MPD experiment at NICA

Emission times for the 1st-order phase transition are larger than those for the crossover. Study the possibilities to extract this difference experimentally at the MPD using femtoscopy technique

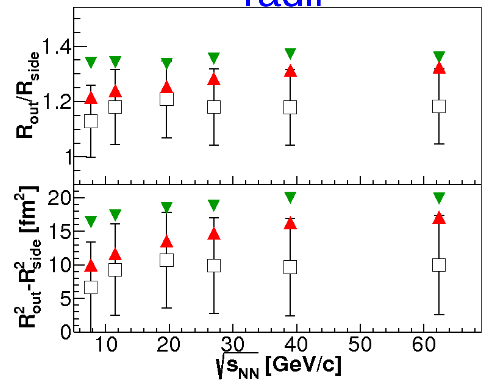
### Energy dependence of pion emission time




### Pion correlation functions




### 3D pion femtoscopic radii




*Green triangles* - 1st-order EoS,
*Red triangle* - crossover EoS,

*Open black square* - STAR data for beam energy scan.

"$R_{out}/R_{side}$" ratio for 1st-order > the one for crossover

"Correlation femtoscopy study at energies available at the JINR Nuclotron-based Ion Collider fAcility and the BNL Relativistic Heavy Ion Collider within a viscous hydrodynamic plus cascade model", Phys.Rev. C96 (2017) no.2, 024911
P. Batyuk, Iu. Karpenko, R. Lednicky, L. Malinina, K. Mikhaylov, O. Rogachevsky D. Wielanek

- Continue package development for femtoscopic studies which allows one to perform analyses of different particles types, study and elaborate criteria for minimization of the two-track effects (splitting & merging) & provide a good particle identification in order to avoid distortions of CF

- 3D CF analysis using different particles heavier than pions, e.g. kaons have more Gaussian shape of source function and less influenced by resonances

- Different particle pairs: πK, $K^+K^-$, πp, πΛ, ΛΛ - different influence of cascade phase, study of emission asymmetries

# vHLLE+UrQMD model

Pre-thermal phase → hydrodynamic phase → hadronic cascade

UrQMD | vHLLE (3+1)-D viscous hydrodynamics | UrQMD

Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978,1509.3751 , talk QM2015

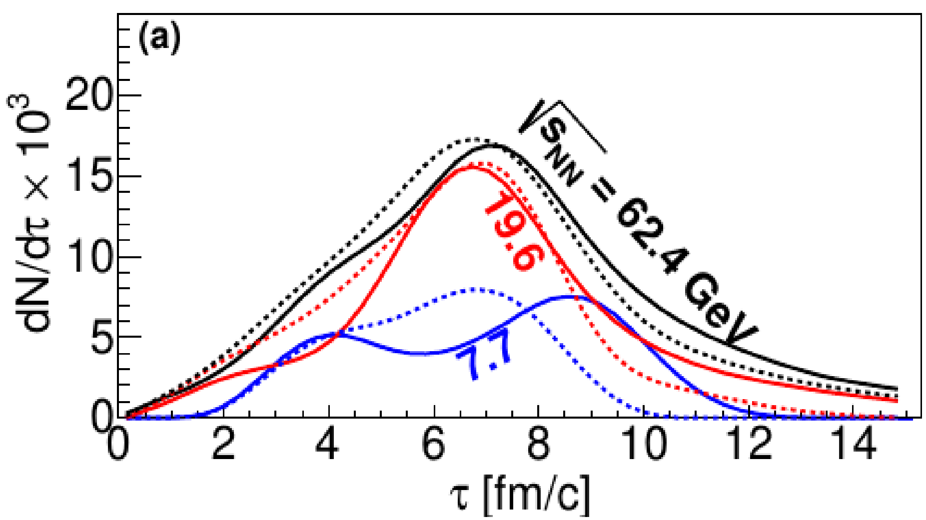
vHLLE code: free and open source, https://github.com/yukarpenko/vhlle, Comput. Phys. Commun. 185 (2014), 3016

Model tuned by matching with the experimental data of SPS and BES RHIC.

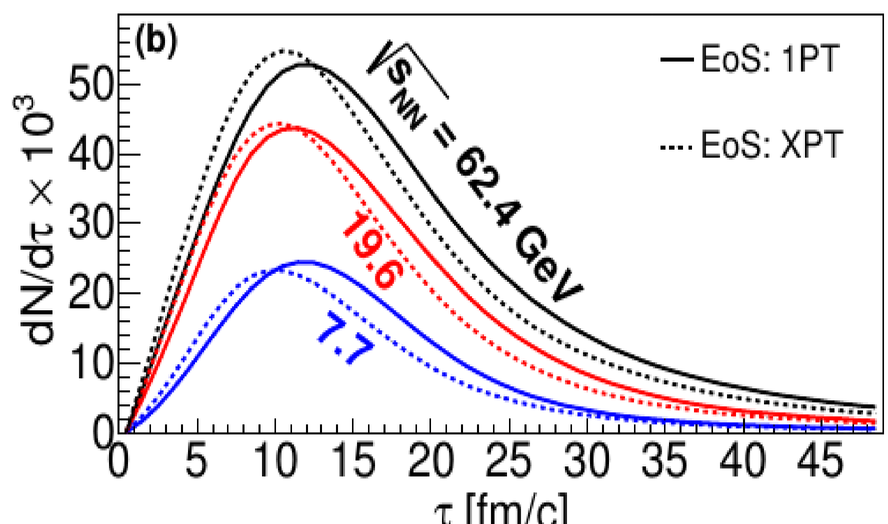
Chiral EoS → crossover PT (XPT)
J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

HadronGas + Bag Model → 1[st]-order PT (1PT)
P.F. Kolb, et al, Phys.Rev. C 62, 054909 (2000)

Pion emission times at the particlization surface




and at the last interaction points




We already started simulations with vHLLE+UrQMD with different Equation of States (EoS): first order phase transition (1PT), Crossover (XPT): 7.7 GeV & 11.5 GeV

# Factorial Moments

Factorial moments of the multiplicity distributions in rapidity and azimuthal angle intervals are sensitive to the deviation of the particle production from the independent case on event by event basis

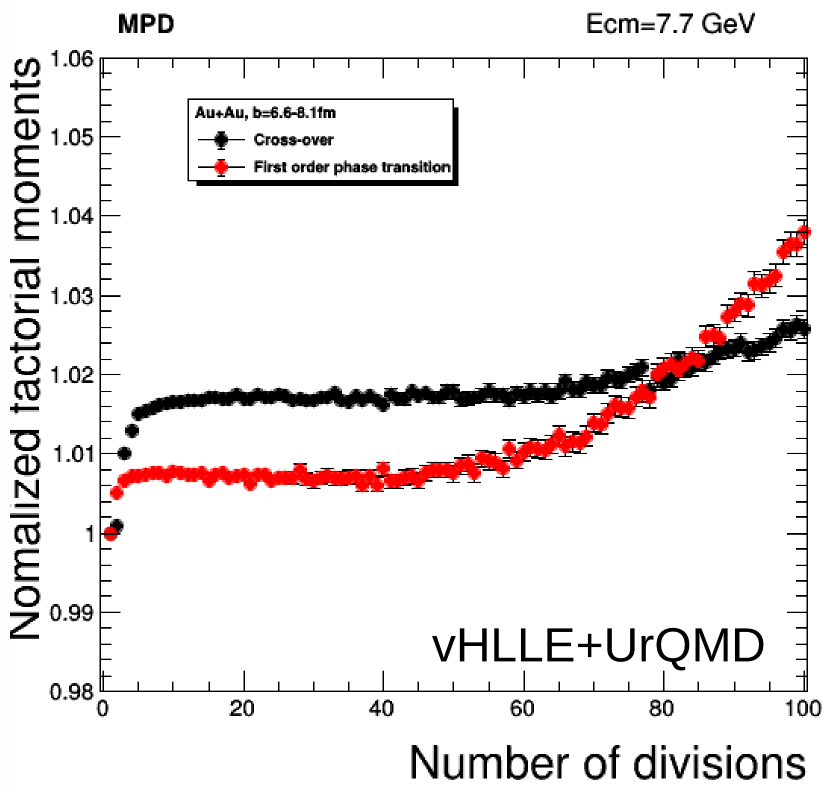
## Method:

- Divide the central rapidity range [-1, 1] into N bins, where N is from 1 to M
- Calculate the normalized factorial moments:

$$F_i = M^{i-1} \times \left\langle \frac{\sum_m k_m \times (k_m - 1) \times \ldots \times (k_m - i + 1)}{N \times (N-1) \times \ldots \times (N - i + 1)} \right\rangle$$

- Plot as a functions of the number of divisions (M)

Bialas, A. and Peschanski, R.B. (1986) Nuclear Physics B, 273, 703.




F2 as a function of the number of divisions of the rapidity interval [-1,1] do the samples with cross-over and the first-order phase transition

## Plan:

- construct higher order moments
- compare different event generations at generator and reconstruction levels
- investigate factorial moments with events mixing technique
- test other methods with moments of the multiplicity distributions

# Package for Femtoscopic Analyses and Other Software

**Femtoscopy:**

- ✔ Inherited from STAR (StHbtMaker) and ALICE (AliFemto)
- ✔ Keeps the same hierarchy as in ALICE (PckgName/, PckgNameUser/, macros/)
- ✔ Works with ROOT 5 and 6
- ✔ Lighter than ancestors:
  - ✔ Most of STAR-developed classes replaced with ROOT ones
  - ✔ Better compression, smaller sizes
- ✔ Implemented running options (INDEPENDENT on experiment-dependent software):
  - ✔ Standalone mode – compile with g++ (clang) and run on your "laptop"
  - ✔ Maker; Tasks will be also implemented

**Factorial moments:**

Factorial moments analysis code inherited from Mirabel experiment

**Data formats (DST):**

- ✔ General-purpose data format for Monte Carlo generators - McDst ( https://github.com/nigmatkulov/McDst )
  - ✔ Similar to UniGen (developed at GSI)
  - ✔ Lighter, faster, easy expandable, works with ROOT 5 and 6, g++ (clang)
  - ✔ Possibility to add converters from other generators: Terminator, EPOS, AMPT, etc...
- ✔ Group has positive experience on the data format developments:
  - ✔ (St)PicoDst format in STAR (standard data format for physics analysis)

# Questions & Suggestions

Information flow should be improved. For instance, non-intuitive step from http://mpd.jinr.ru/ to http://mpd.jinr.ru/experiment/. Why BM@N is in MPD?

- Computer resources:
  - What is the plan for computer resources? Common at JINR? Distributed?
  - How to get computer (lxpub, govorun, etc) accounts? Procedures should be simplified: easy to get, clear and quick. Current time line ~ <months>
  - Access to the protected information (internal): what is the procedure?

- Mailing lists:
  - Common page with all mailing lists
  - Simple subscription to the list via checkbox

- Coordination, cooperation and communication:
  - Running same MC generators at different places – waste of resources (both disk and CPU). The common strategy should be developed (including reco and later steps)
  - Track reconstruction: should be documented and a few versions (if exist) should be available
  - Information should be easily accessible: e-mails, mailing lists, groups, group leaders (conveners, coordinators, representatives, PIs, etc…)
  - Public meetings: physics, hardware, software
  - It should be clear who is responsible for what

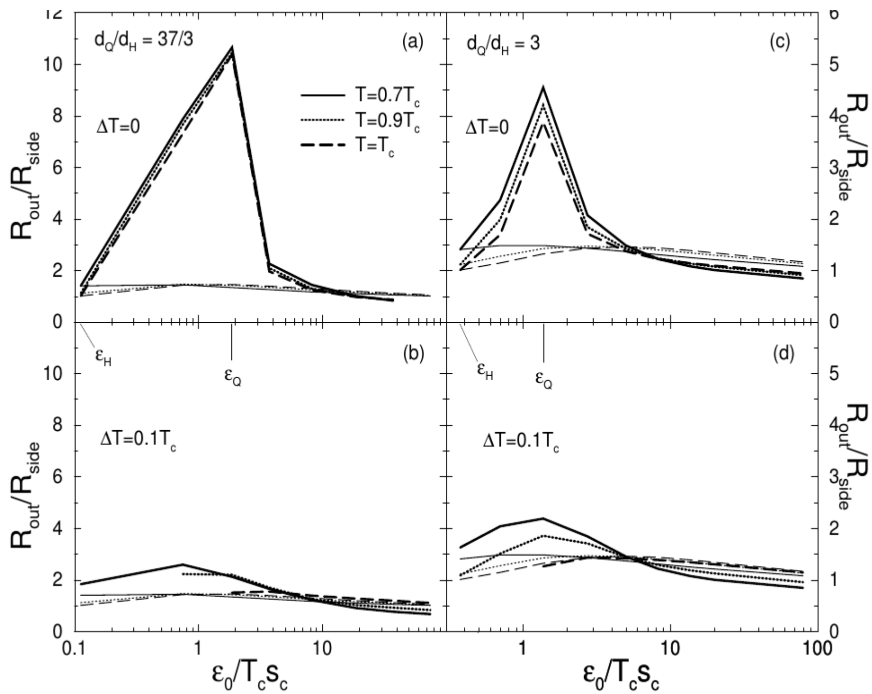
- Data formats:
  - Should be common, established, and maintained
  - Should be as small as possible and INDEPENDENT on the experiment-specific environment

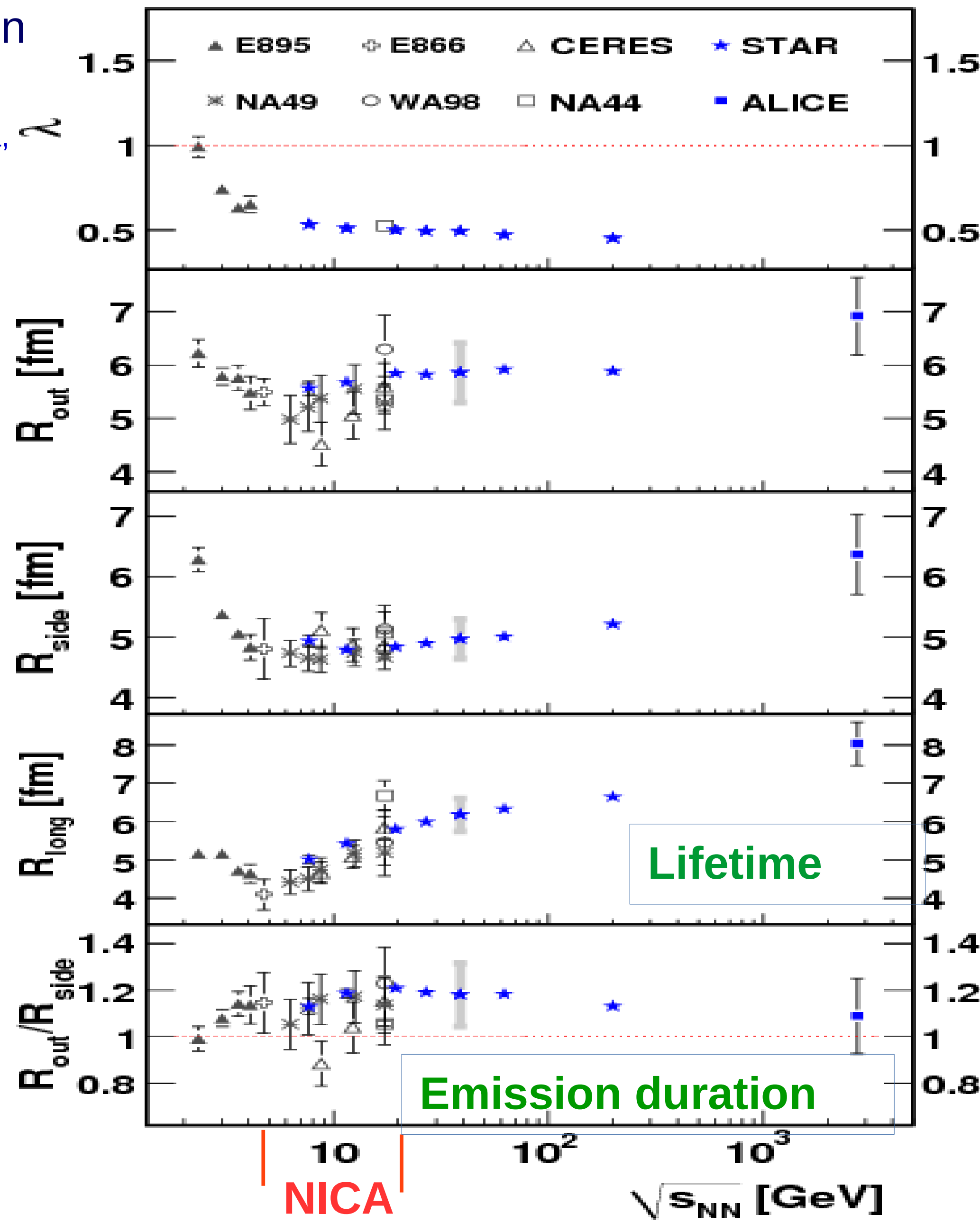
# Additional slides

# Expected features of 1st order PT

- It was predicted that for 1st order phase transition $R_{out}/R_{side} > 1$ & large $R_{long}$ due to emission stalling during phase transition
( S. Pratt, Phys. Rev. D 33 (1986) 1314.G. Bertsch, M. Gong, M. Tohyama, Phys. Rev. C 37 (1988) 1896)
**D. H. Rischke and M. Gyulassy, Nucl. Phys. A608, 479 (1996)**

STAR, Phys.Rev. C92 (2015) 1, 014904



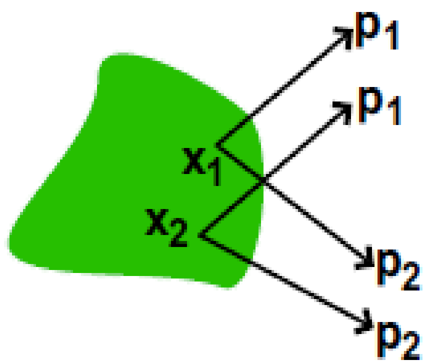




- But r-t correlations in expanding source reduce the observed $R_{out}$ -> $R_{out}/R_{side}$

- What do the modern hydrodynamic (hybrid) models expect ?

# Introduction

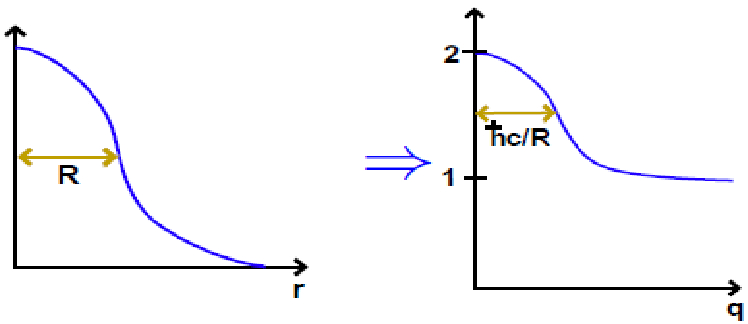
Correlation femtoscopy : measurement of space-time characteristics R, cτ ~fm of particle production using particle correlations due to the effects of quantum statistics ( QS ) and final state interactions ( FSI )




- Two particle Correlation Function (CF):

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

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




$S(q)$ – pairs from same event

$B(q)$ – pairs from different event

- Parametrization:

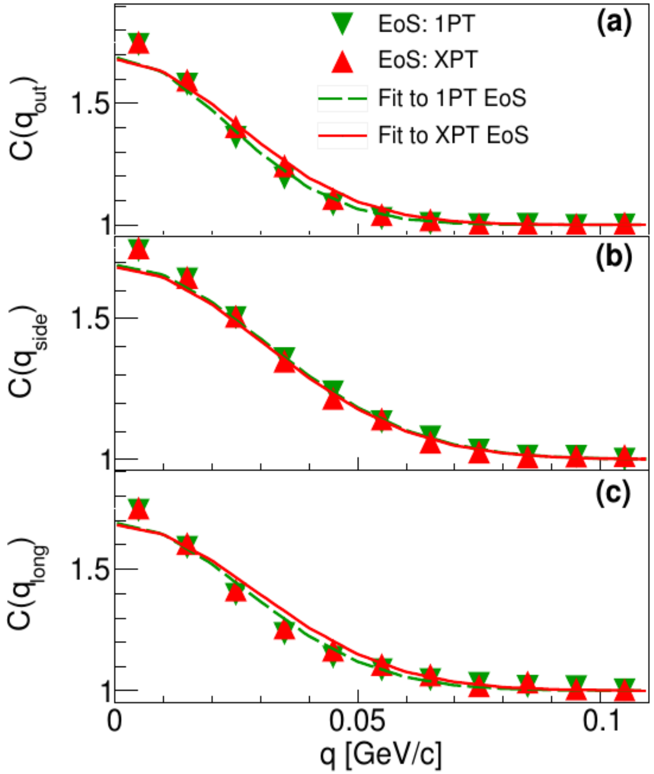
1D: $C(q_{inv}) = 1 + \lambda \exp(-R^2 q_{inv}^2)$ ***R*** Gaussian radius in Pair Rest Frame (**PRF**), ***λ*** correlation strength parameter

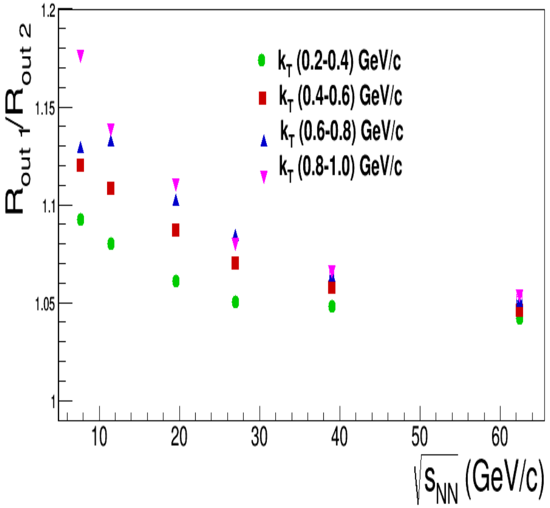
3D: $$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)$$

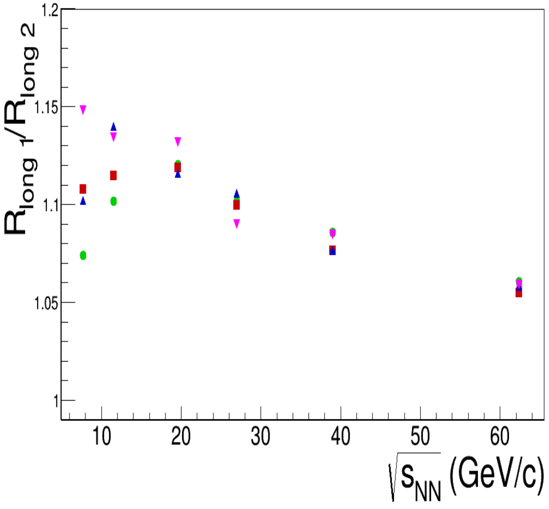
where both ***R*** and ***q*** are in Longitudinally Co-Moving Frame (**LCMS**)
long || beam; out || transverse pair velocity $\boldsymbol{v}_T$; side normal to out,long

# Comparison of pion CF for 1PT and XPT vers. sqrt($s_{NN}$)

Pion correlation functions calculated with vHLLE+UrQMD sqrt(sNN)=7.7 GeV



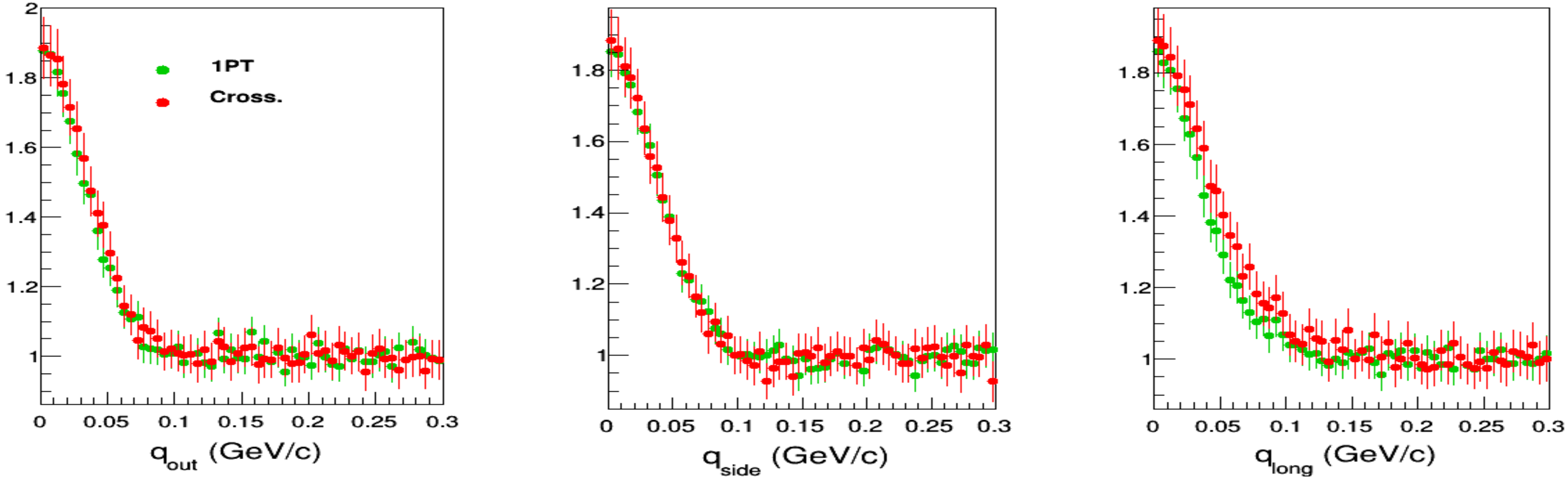

- $R_{side}$ radii in the 1PT EoS and XPT EoS scenarios practically coincide;
- $R_{out}$ ($R_{long}$) for 1PT EoS > XPT EoS, strong dependence on kT interval **difference ~ 10-20%**
- The difference comes from weaker transverse flow developed in the fluid phase with 1PT EoS as compared to XPT EoS & longer lifetime of the fluid phase in 1PT EoS

The difference between pion CF for 1st order PT and XPT is small, but can be seen in the ratios of extracted radii

**For K/p it is expected to be larger**

# Comparison of kaon CF for 1PT and XPT vers. sqrt($s_{NN}$)

Kaon correlation functions calculated with vHLLE+UrQMD sqrt(sNN)=7.7 GeV



# vHLLE+UrQMD model

Pre-thermal phase → hydrodynamic phase → hadronic cascade

UrQMD | vHLLE (3+1)-D viscous hydrodynamics | UrQMD

We already started simulations with vHLLE+UrQMD with different Equation of States (EoS): first order phase transition (1PT), Crossover (XPT):

1 mln events for sqr(sNN)=7.7 and 11.5 GeV/c, 0-5% are generated for comparison with STAR BES femtoscopic correlation radii for pions (more detailed study) and kaons ;