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

within the RFBR Mega Grant # 18-02-40044

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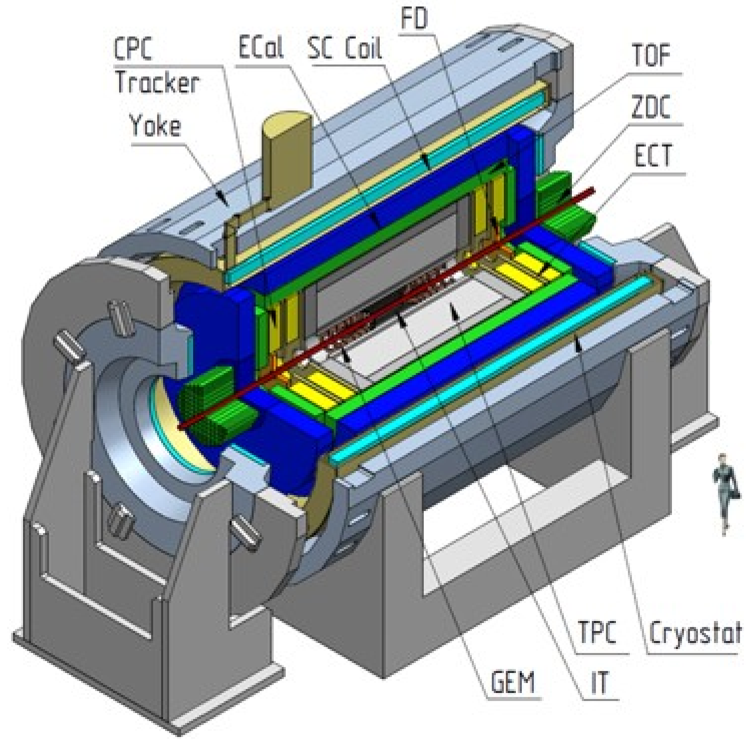
– Anna Romanova (student, MSU)



Outline

- Femtoscopy & Factorial moments group activities
- Femtoscopy & Motivation
- Hybrid vHLLE+UrQMD model
- Comparison with STAR BES pions for vHLLE
- Comparison of Pions and Kaons for vHLEE and UrQMD
- First tests with reconstructed data
- Factorial Moments
- Conclusion

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:

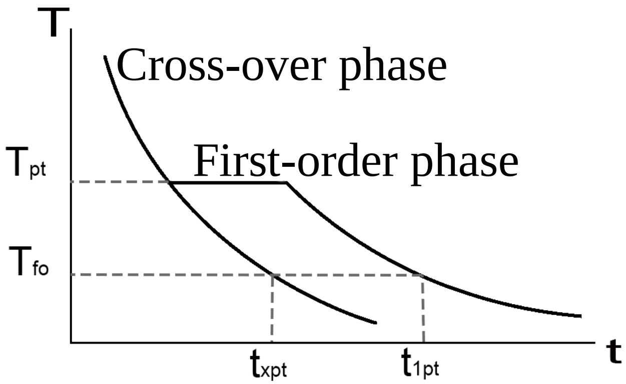
- Development of the data analysis methods and software that will be integrated in the Multi-Purpose Detector (MPD) software environment
- Analysis of the data simulated with different event generators (in particular, UrQMD and vHLLE) Au+Au collisions at NICA energies
- Study the dependence of femtoscopic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

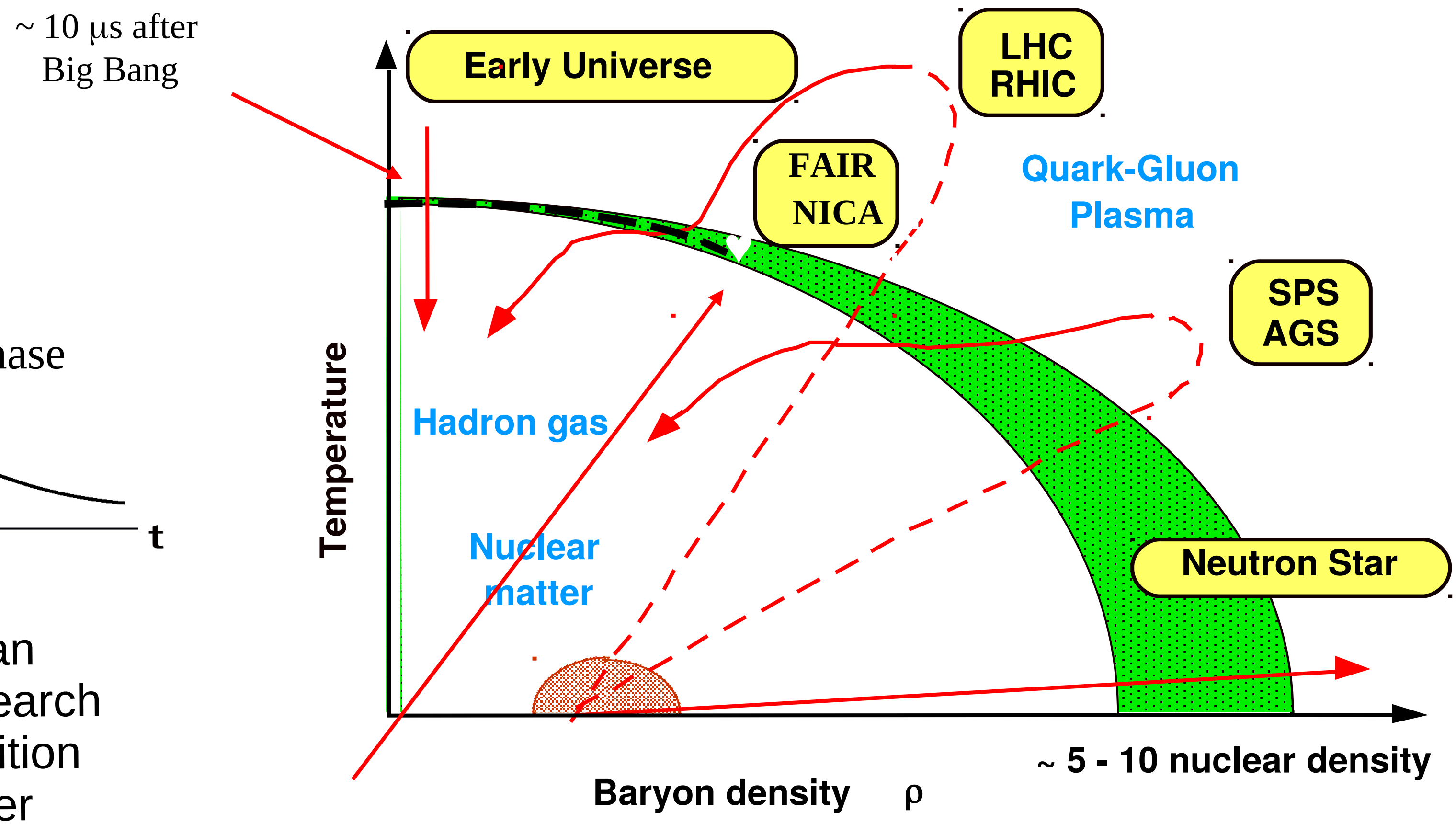
Activites in 2019-2020

- 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
  - other activities
- Femtoscopic analysis (at one collision energy) and extraction of source parameters 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

Motivation: Phase diagram QCD

- Crossover transition to QGP occurs at RHIC & LHC
- 1st order phase transition to QGP occurs at lower energies (?)



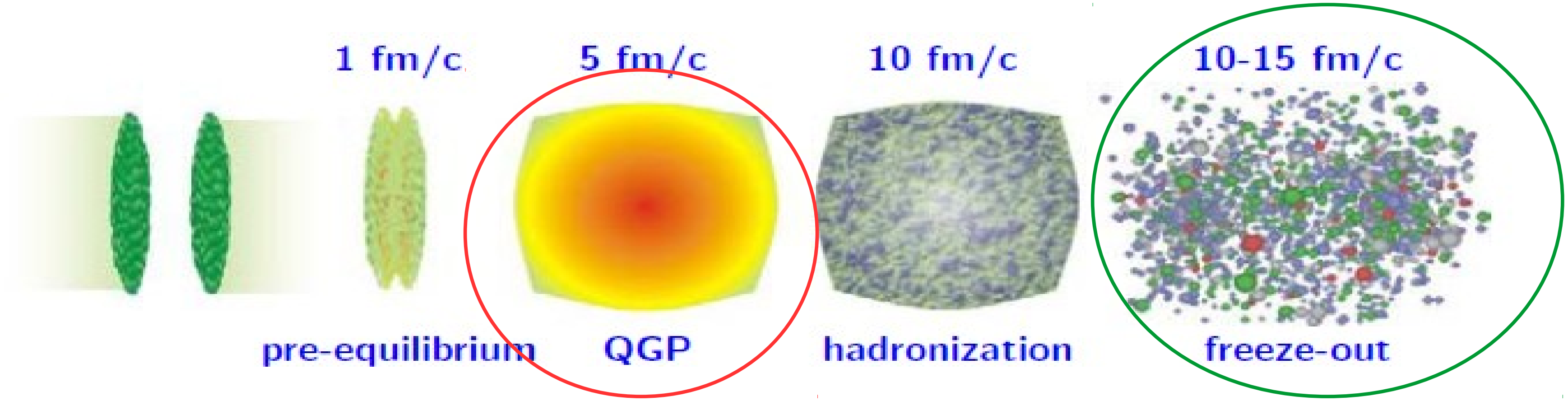


$\varepsilon_c \sim 1\ \text{GeV/fm}^3$

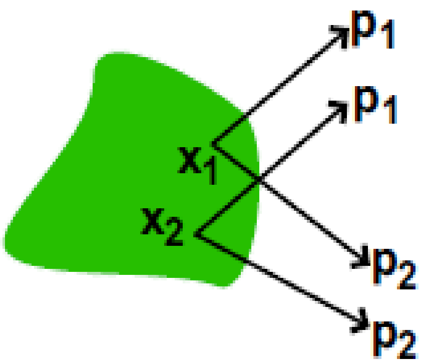
- Beam Energy Scan (BES) program: search for location of transition point from Crossover (XPT) to 1st order (1PT) phase transitions

- BES RHIC (√s=3-60 ГэВ) и NA61@SPS (E_{lab}=10-158 GeV);
- projects: CBM@FAIR (GSI) и **MPD@NICA (JINR)**

Correlation Femtoscopy



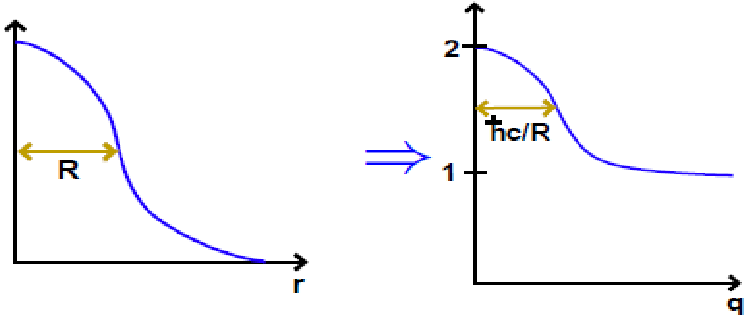
Correlation femtoscopy : measurement of space-time characteristics R, cτ ~fm of particle production using particle correlations due to the effects of quantum statistics (QS) and final state interactions (FSI)



- 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

Femtoscopy: frequently used parametrizations

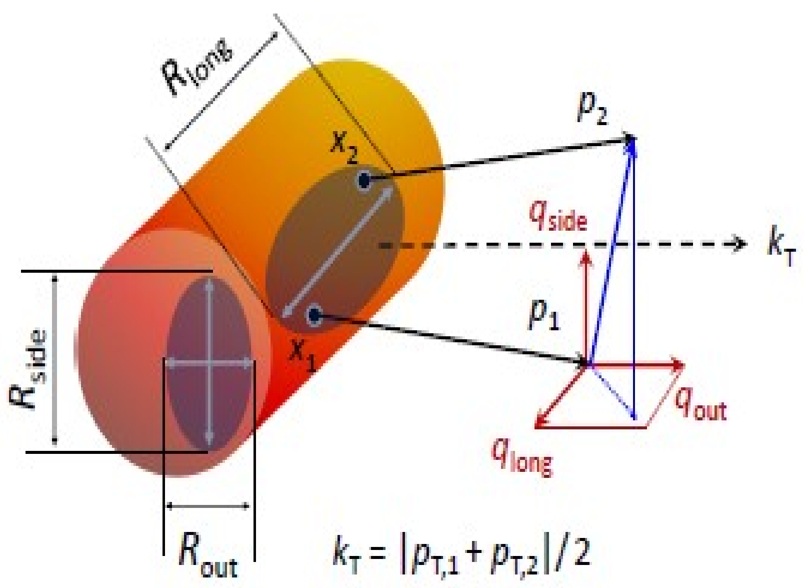
$$C(q) = 1+\lambda\exp(-R_{inv}^2 q_{inv}^2),$$ λ- correlation strength,

R_{inv}, Gaussian radius in Pair Rest Frame (**PRF**)

1d- analysis is only sensitive to the system size averaged over all directions ;

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

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



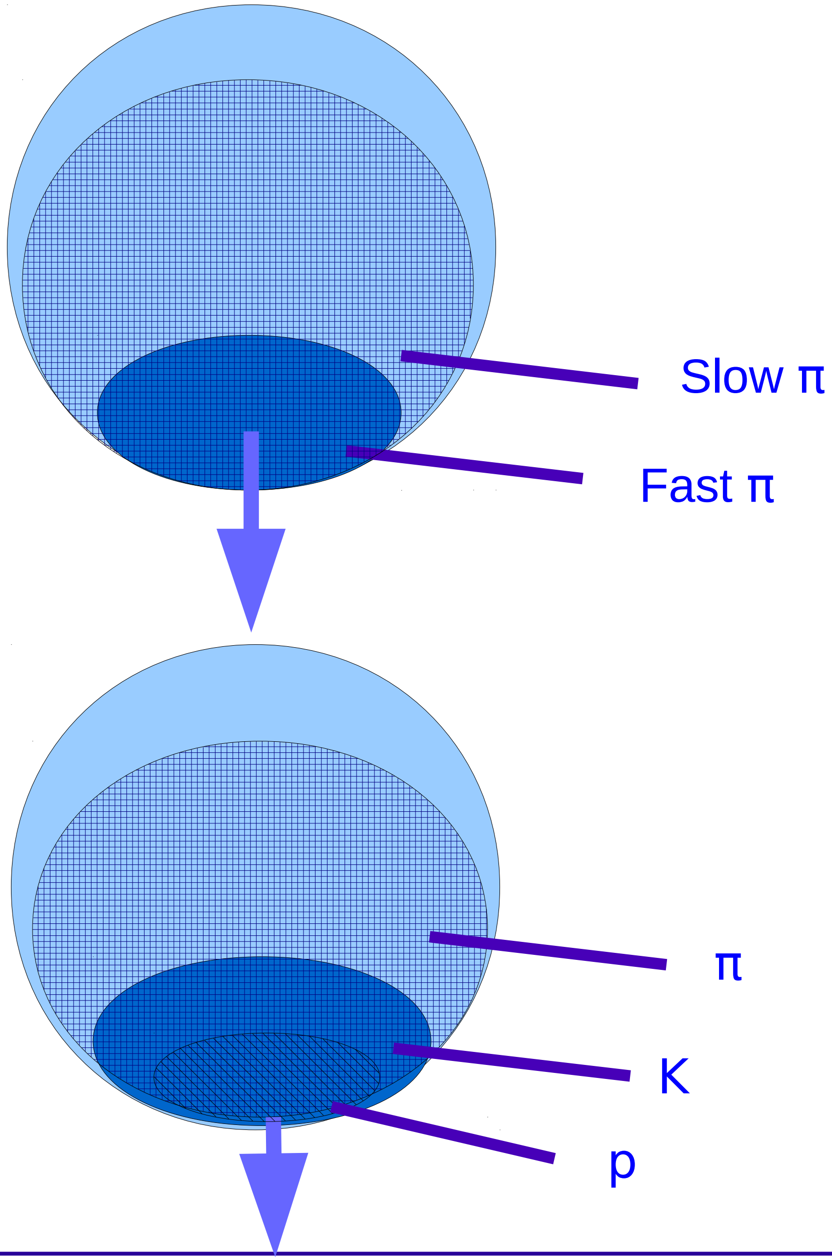
long || beam;
out || transverse pair velocity $\mathbf{v}_T$
side normal to out,long

3D- analysis

R_{side} sensitive to geometrical transverse size.
R_{long} sensitive to time of freeze-out.
R_{out} / R_{side} ~ sensitive to emission duration.

Motivation

expanding source: x:p correlations



- Femtoscopy
  - Measure the spatial & temporal characteristics of the particle emitting regions
  - Study collective dynamics, radial flow
  - Put constraints on system evolution models, e.g. timescales & scattering parameters

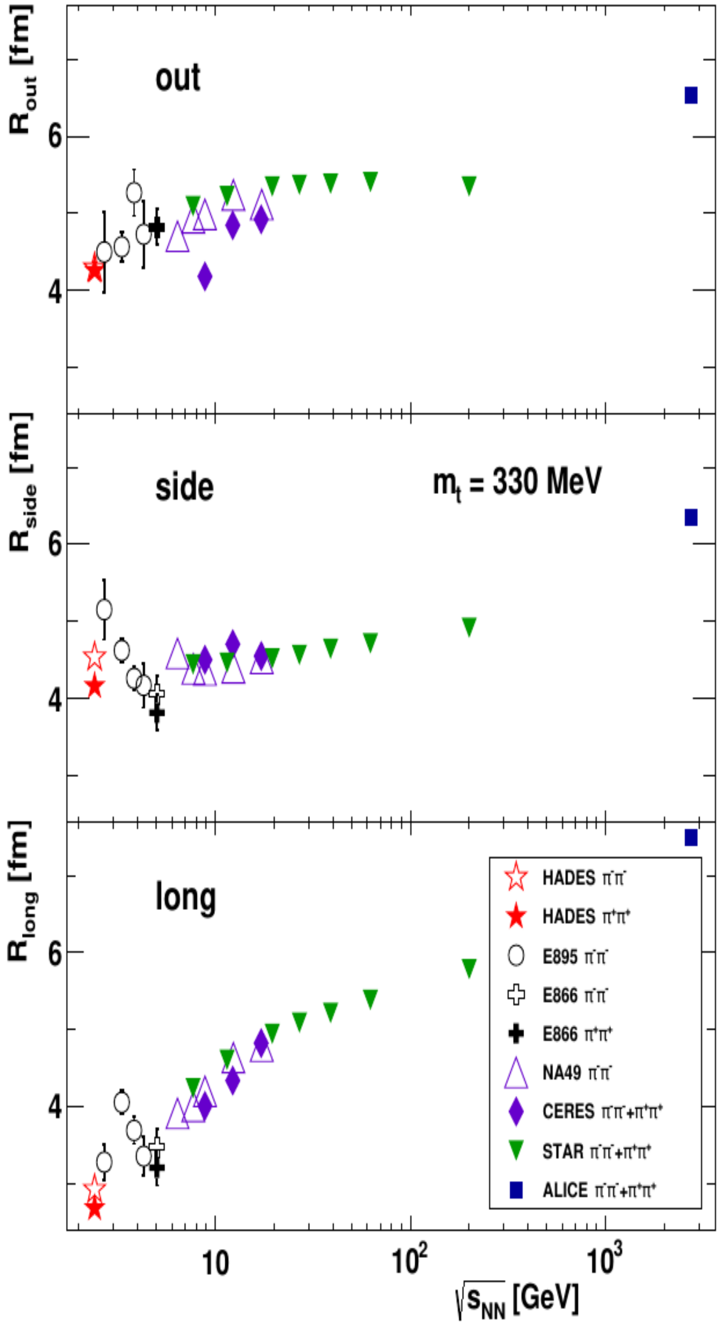
- Femtoscopy of heavier particles - complement to ππ
  - Strong constraints for hydrodynamic models predictions: they should work for heavier mesons and baryons.
  - Check for m_T dependence -> determine freeze-out conditions
  - Possibility to distinguish between different model scenario

Motivation: Correlation femtoscopy.

- **<u>Femtoscopy allows one:</u>**
  - 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
  - first collider measurements below 7.7 GeV
    - including K and heavier



Our software developments:

Package for Femtoscopy analyses:

- ✔ 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 is written

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)

Mini DST format:

Output data format derived from STAR has been incorporated to MpdRoot.

VHLLE interface software:

Allows to perform simulations with vHLLE+UrQMD model by simple and understandable way (vHLLE_package/README.md)

Femtoscopy with vHLLE

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

Pre-thermal phase → Hydrodynamic phase → Hadronic cascade

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

The transition to hydrodynamics occurs at a hyper-surface of constant longitudinal proper time τ_0
Minimal value of the starting time τ0 is taken to be equal to the average time for the two colliding nuclei to completely pass through each other:

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

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

EoS to be used in the model

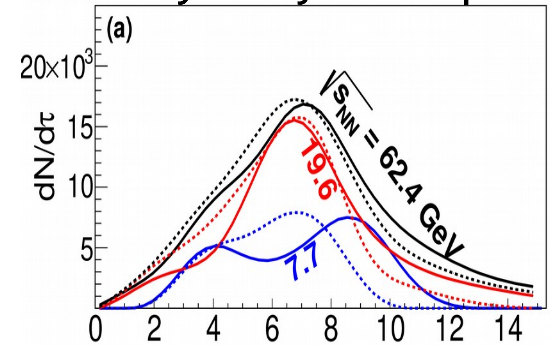
- Chiral EoS — crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model
  1st-order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

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

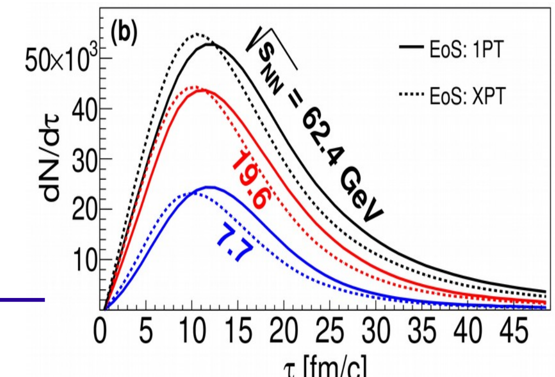
Fluid to particle transition at energy density = 0.5 GeV/fm^3

Pion emission time

after hydrodynamic phase



after cascade

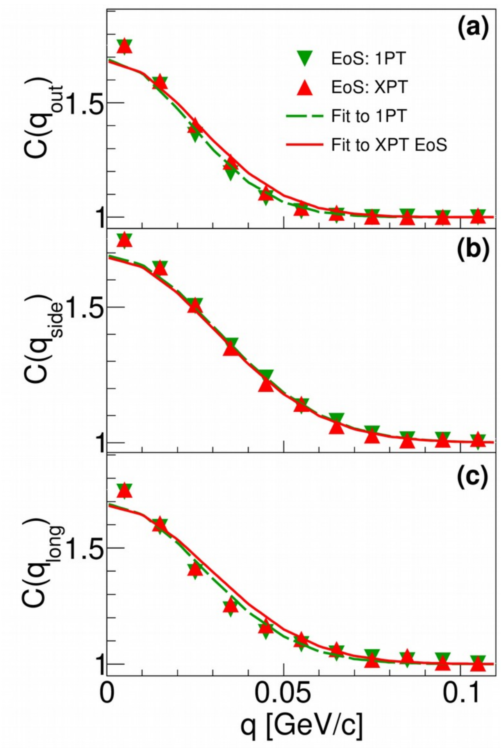


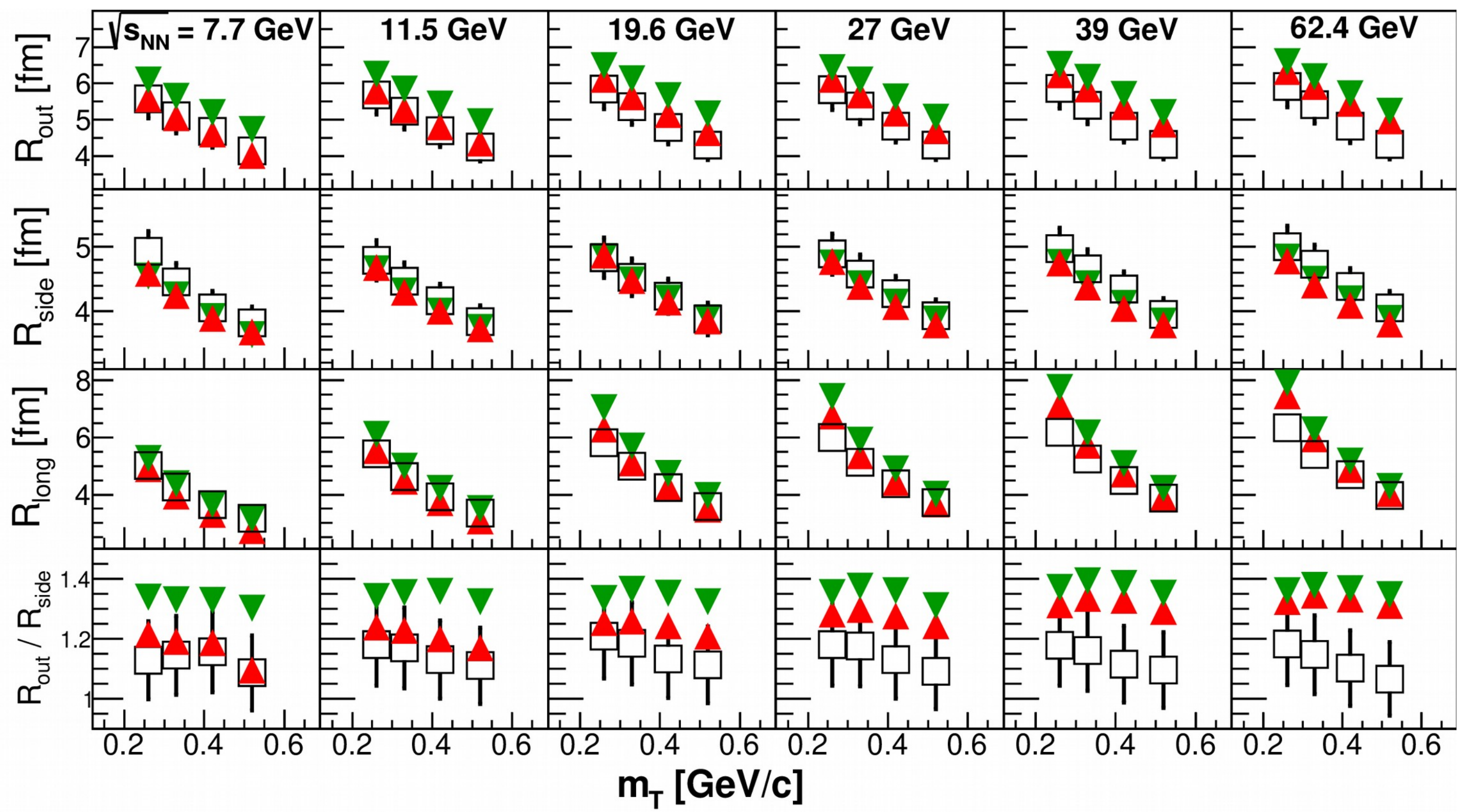
Can we probe this difference with femtoscopy ?

3D Pion radii with vHLLE model

Phys.Rev. C96 (2017) no.2, 024911

Projections of 3D Model CF





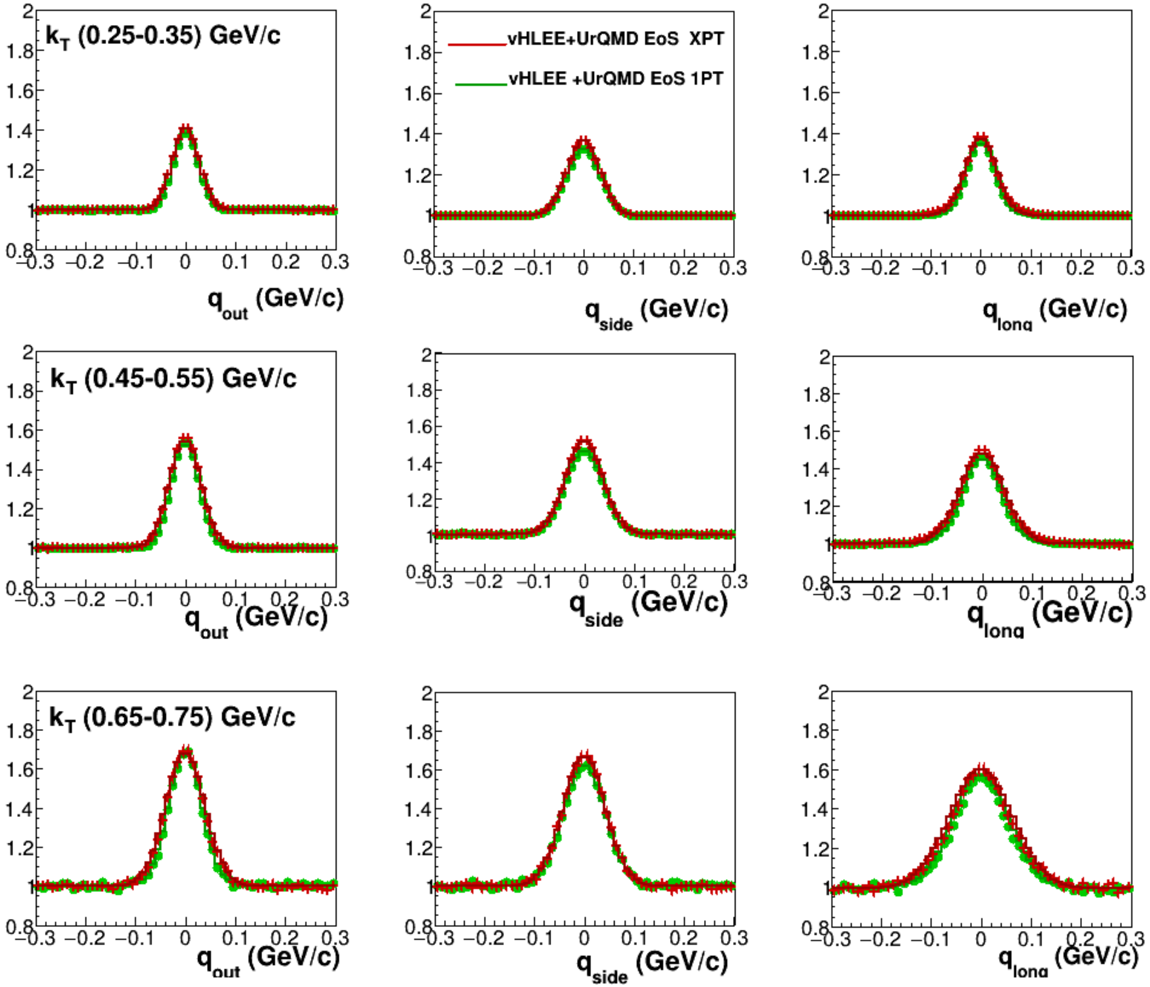
- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS describes better R(mT) dependencies
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT) by value of ~1-2 fm.**
- R_{out} /R_{side} (XPT) agrees with STAR data points at 7.7 and 11.5 GeV, but then increases with increasing collision energy while ratio in data is independent with collision energy; R_{out}/R_{side} for 1PT systematically overestimate data and is independent on collision energy.

3D Pion Correlation Functions with vHLLE model

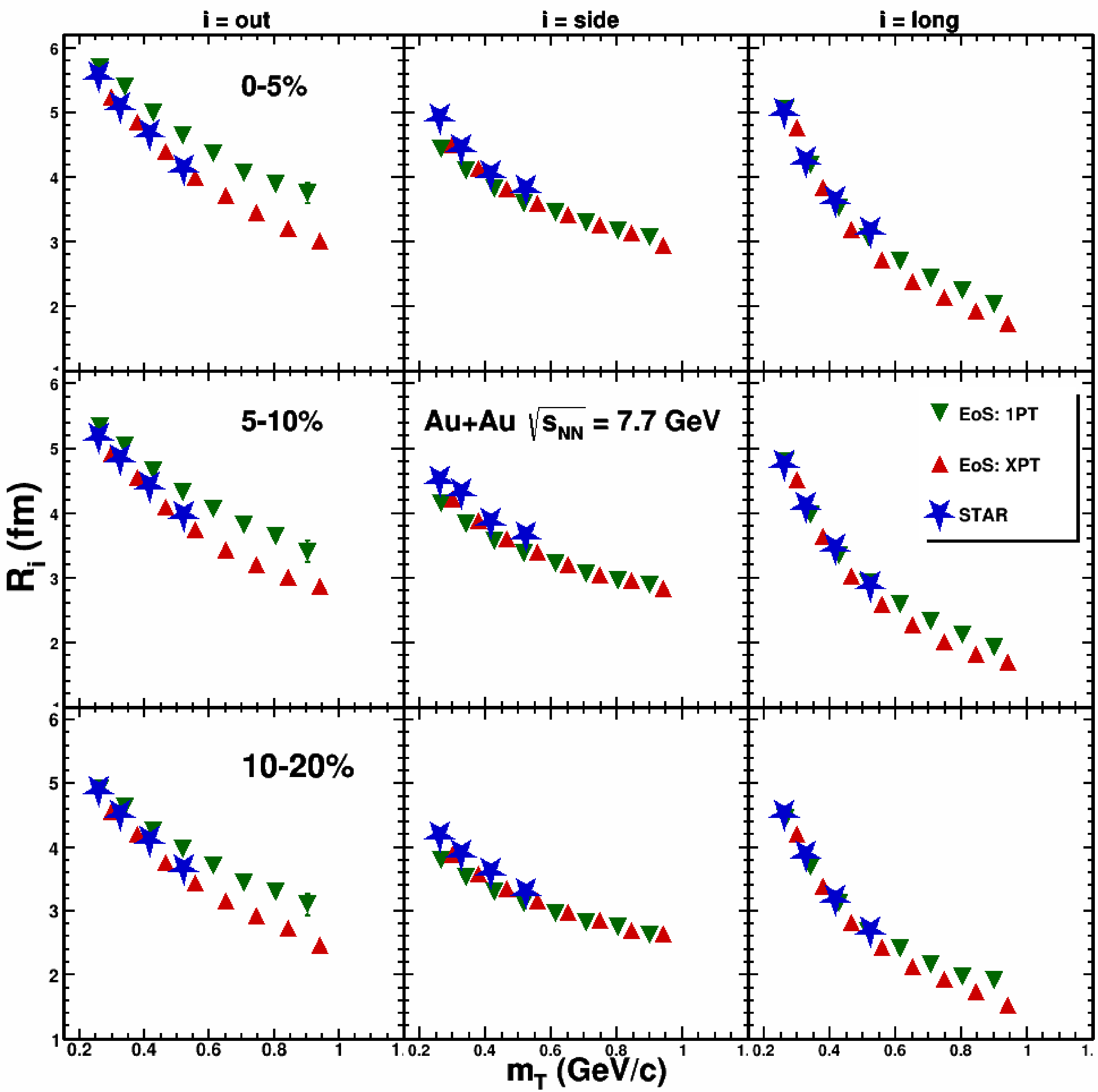
Analysis

- MDP femto package (see Grigory Nigmatkulov's talk)
- We performed analysis of pion and kaon correlations for vHLEE and UrQMD for different centrality ranges
- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV central events vHLLE
- Standard 3D Gaussian fit used
- Projections of 3D pion correlation functions on out-side-long
- XPT CF projections on long direction are wider than 1PT especially
- CF become wider with increasing k_T

1PT -green dots; XPT – red dots

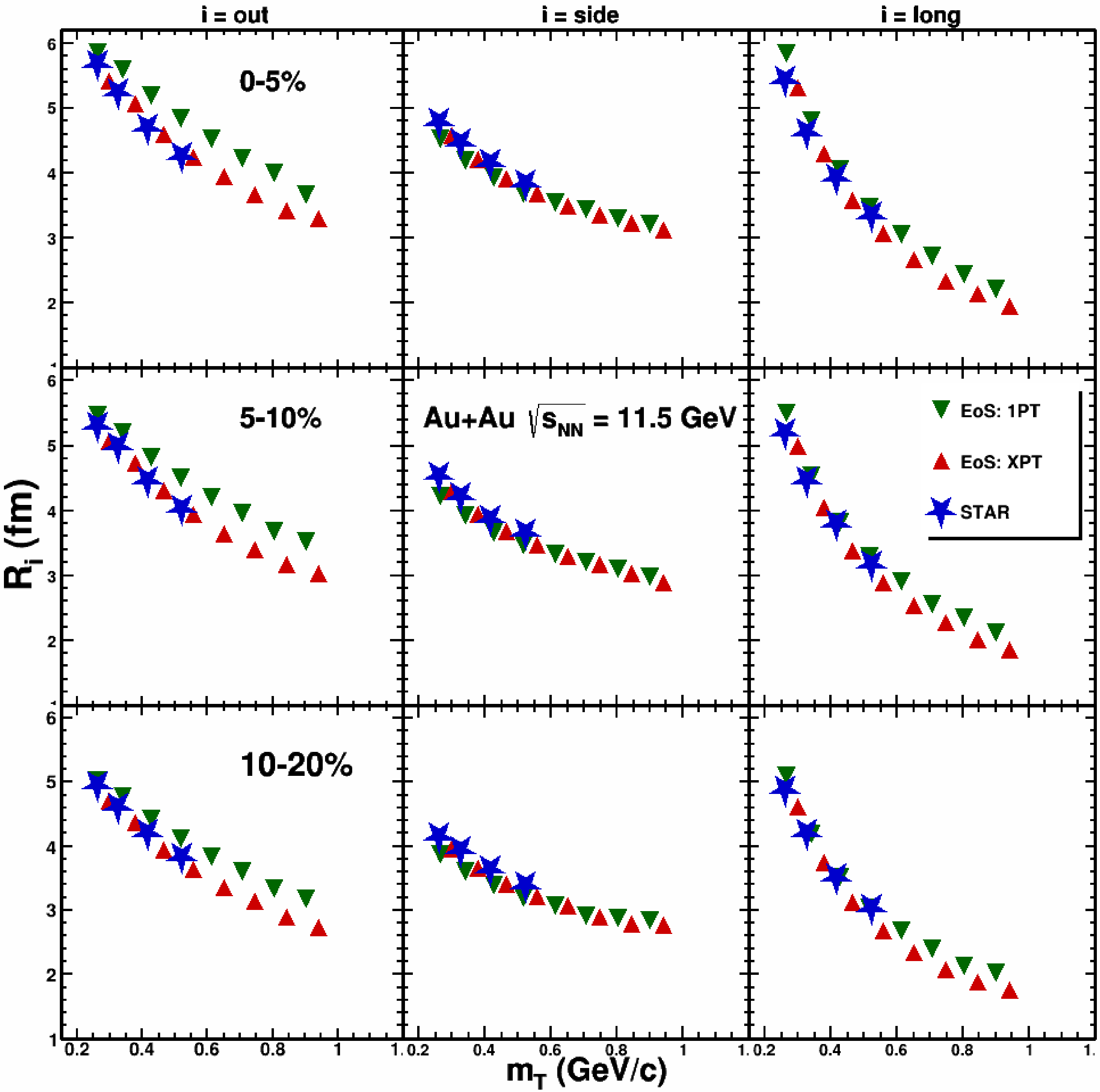


Pion radii with vHLEE for different centralities.



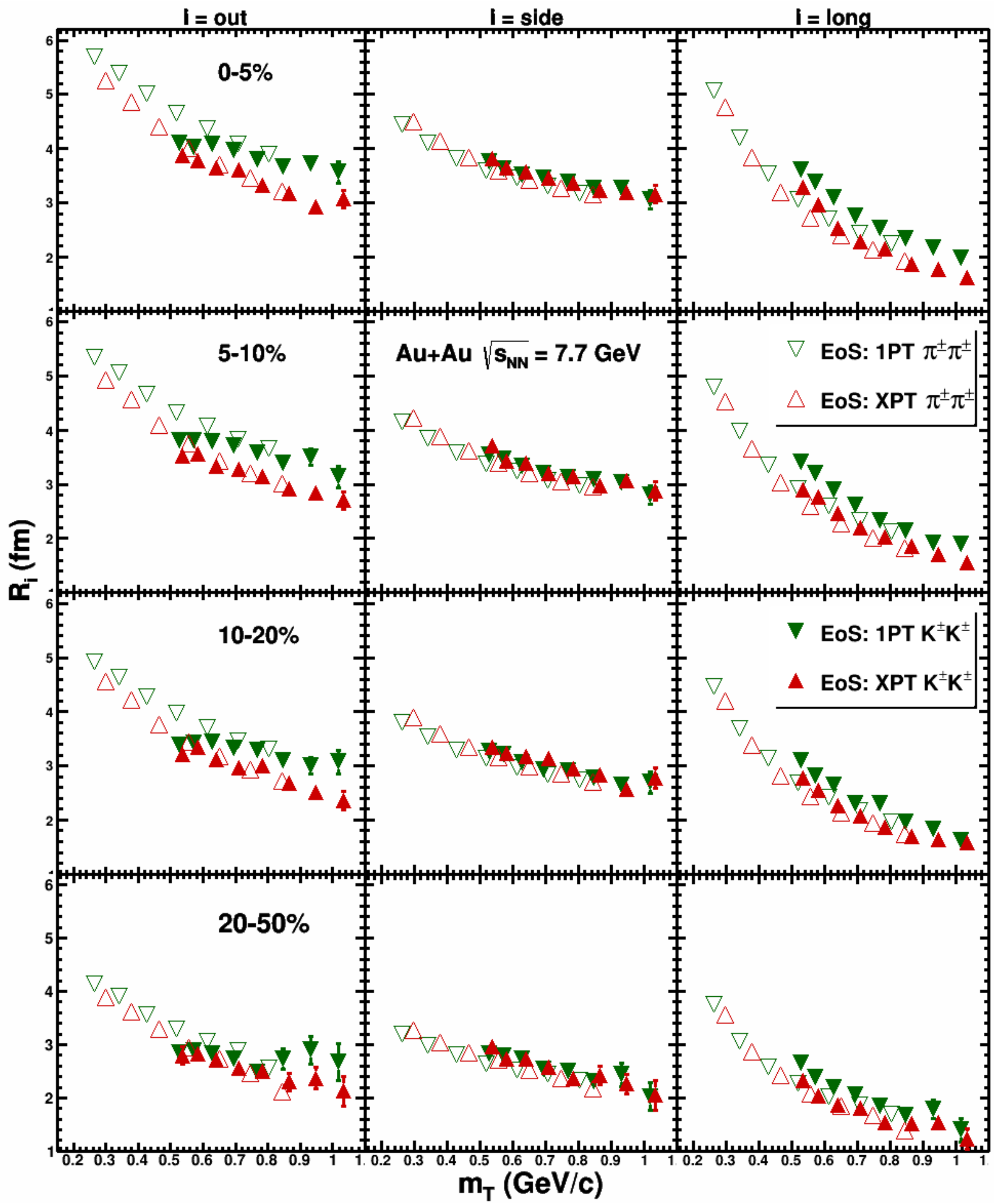
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- It is important to study k_T (m_T) dependence in larger interval than STAR
- Radii decrease with m_T → radial flow
- Increase size with increasing centrality → simple geometric picture of the collisions.
- Crossover EoS describes better R(m_T) dependencies
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT)**

Pion radii with vHLEE for different centralities.



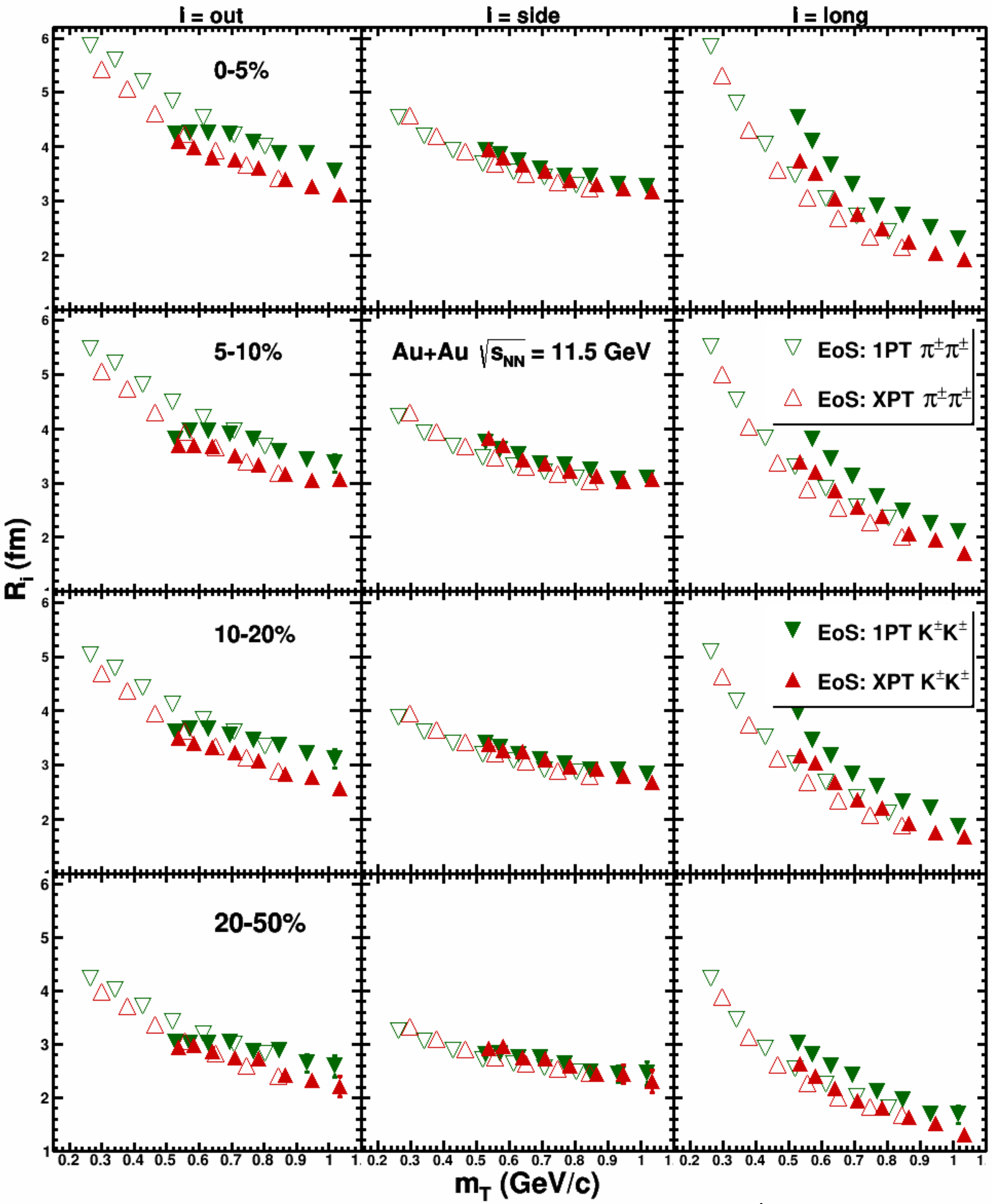
- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- Similar to $\sqrt{s_{NN}}$ = 7.7 GeV

Pion and kaon radii with vHLEE model



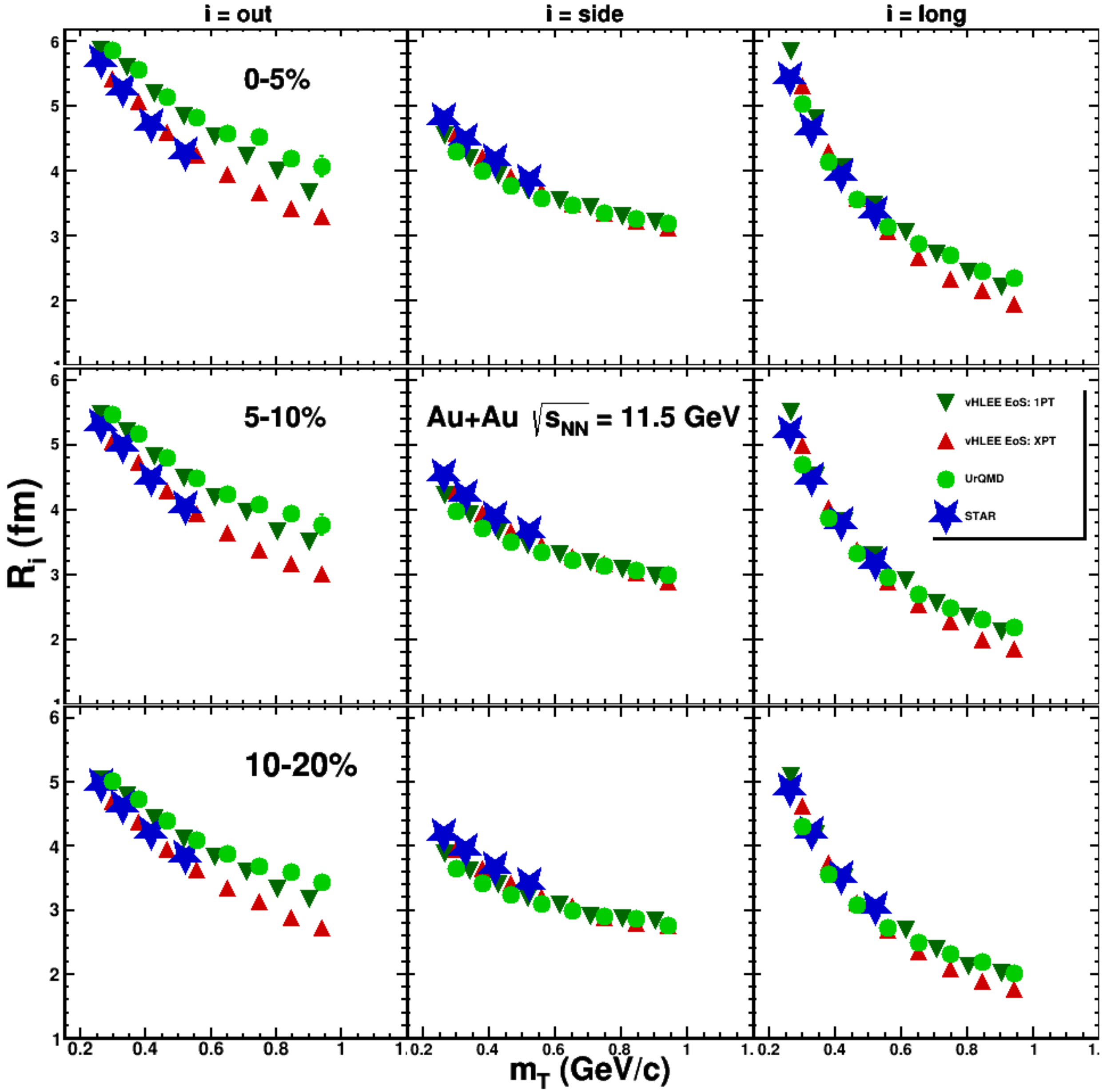
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- Approximate m_T scaling is observed for R_{side}
- Similarly to pions : kaon radii decrease with m_T → radial flow ;
  for 1PT EoS almost flat dependence R_{out} (m_T) is observed → weaker flow
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT)**
- R_{long} kaon radii for XPT > R_{long} pion similarly to experiment (LHC & RHIC)
  → indication on importance of hadronic cascade
- Very different predictions of vHLLE model for different EoS → importance to study heavier than pions
  particles → kaons

Pion and kaon radii with vHLEE model



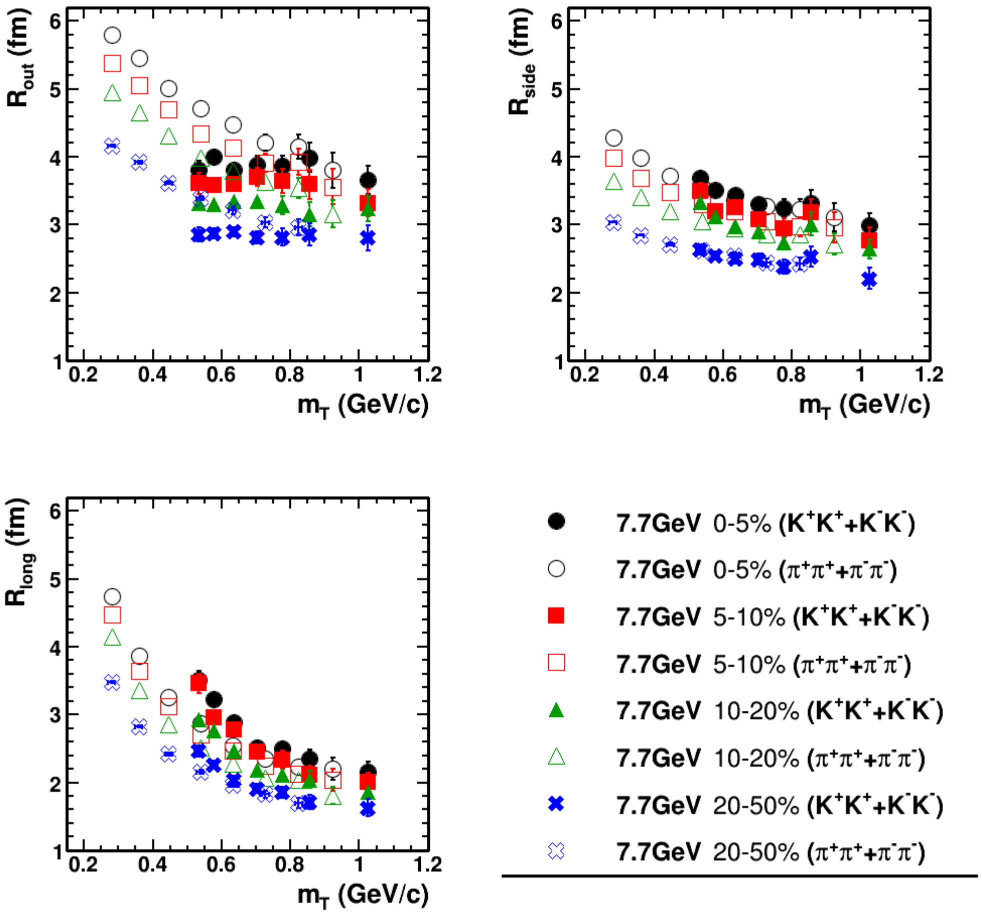
- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- Similar to $\sqrt{s_{NN}}$ = 7.7 GeV

Comparison of pion radii for UrQMD and vHLEE



- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- UrQMD overestimates R_{out} and is close to vHLEE+UrQMD with 1st order EoS
- Crossover EoS describes better $R(m_T)$ dependencies
- Approximately the same results are obtained for other centrality and for Au+Au $\sqrt{s_{NN}}$ = 7.7 GeV

Comparison of pion and kaon radii for UrQMD



- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV

  Will be redone like slide 15-16

- kaon radii demonstrate almost flat behavior
  similarly to vHLEE with the 1st order EoS
  → weak flow

- R_{long} kaon radii are larger than pion ones similarly to experiment (LHC & RHIC)

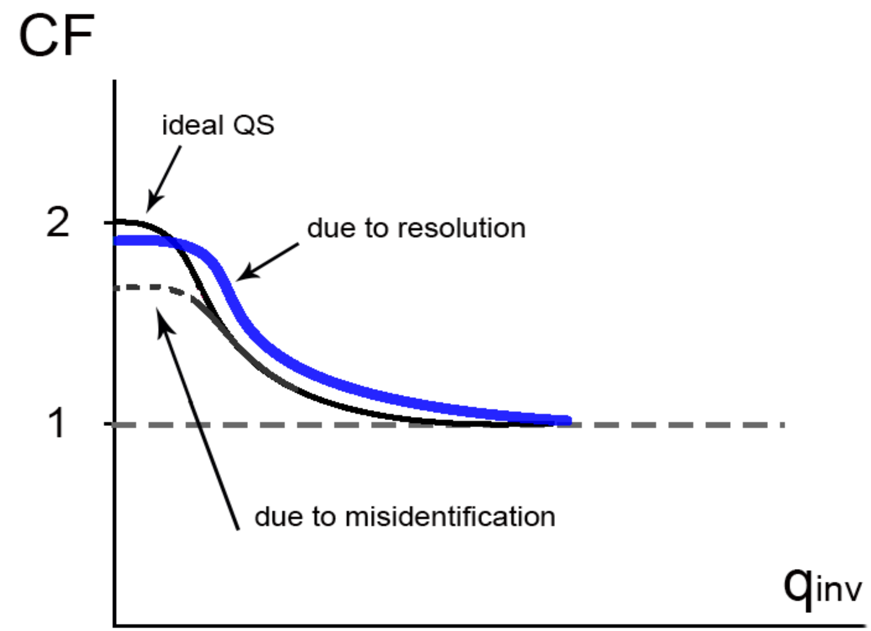
- **Does vHLLE with XPT EoS describe better the collision dynamics ?**

Detector reconstruction influence on CF

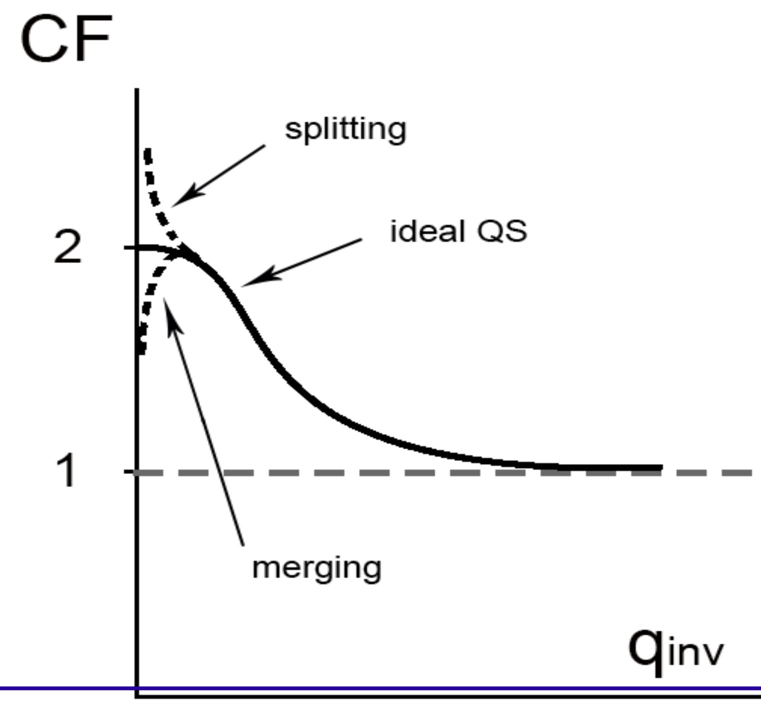
Detector reconstruction influences the shape of CF:

- Single track effects:
  - the momentum resolution effects smear CF, making it wider and extracted radii smaller
  - CFs should be corrected by resolution

  - the particle misidentification influences only λ-parameter of CF, radii do not change.
  - CF should be corrected by pair purity.
  Pair purity is obtained from particle purity



- Two track effects:
  - track splitting (one track is reconstructed as two)
  - track merging (two tracks are reconstructed as one)
  These effects are studied and the special pair cuts are used in the analysis.



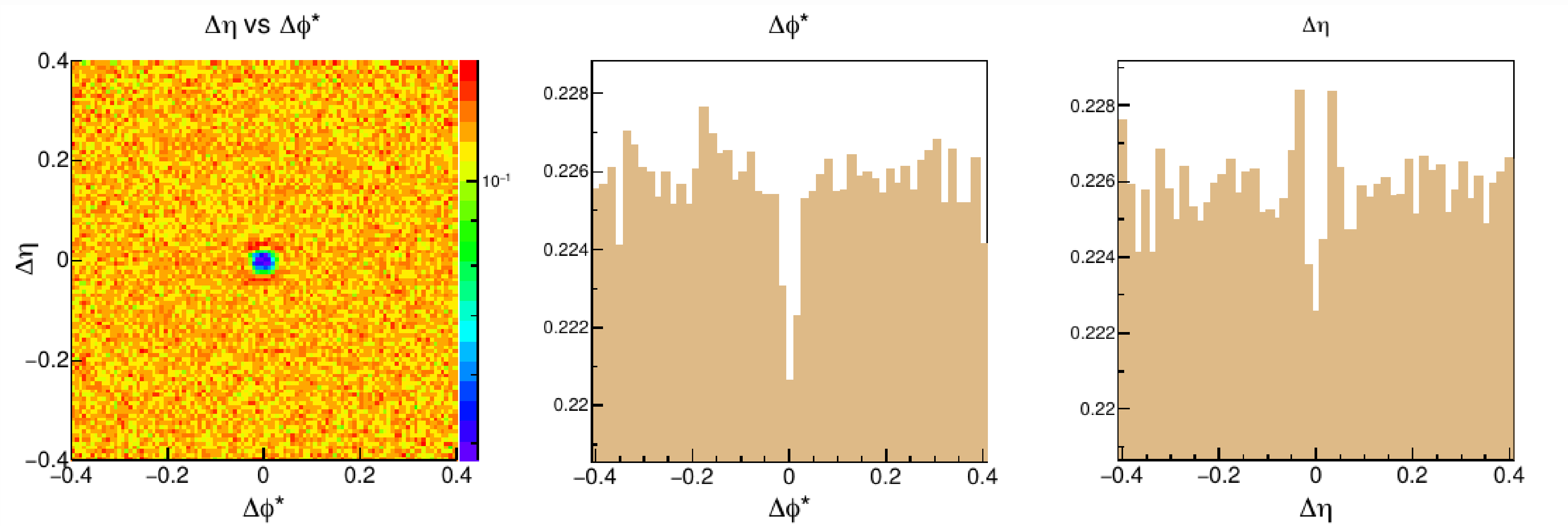
First tests with reconstructed data : two-tracks effects

$\Delta\eta$-$\Delta\varphi_*$ with MPD reconstructed tracks

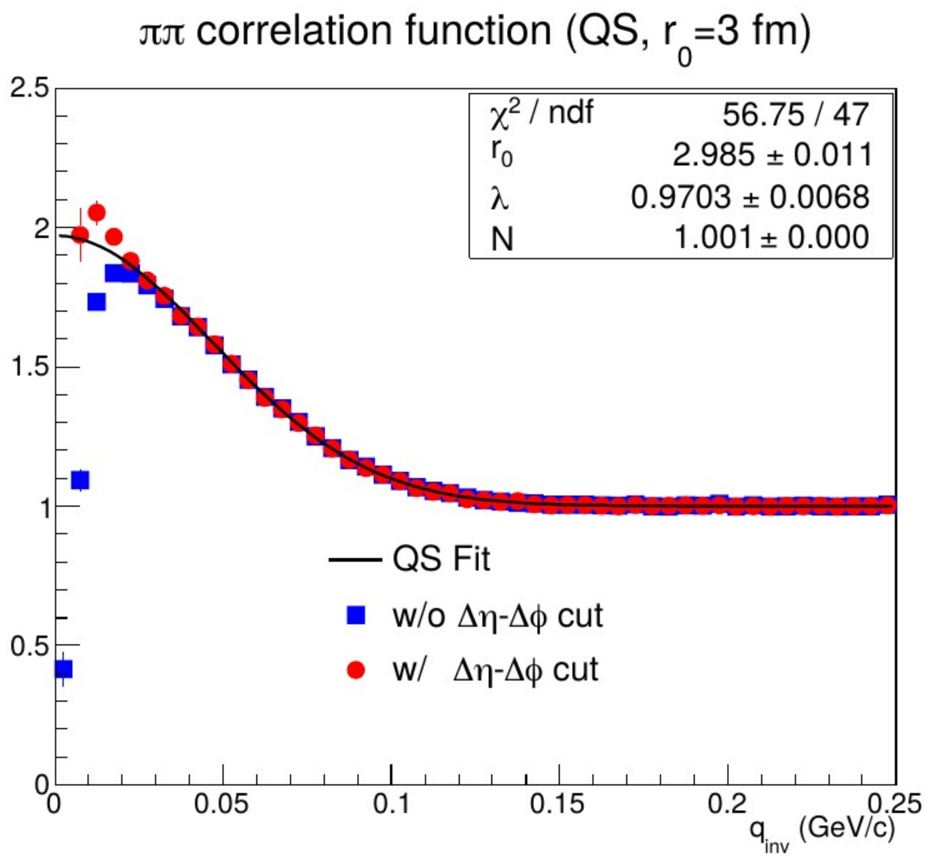
$$\Delta\phi^* = \phi_1 - \phi_2 + \arcsin\left(\frac{z \cdot e \cdot B_z \cdot R}{2p_{T1}}\right) - \arcsin\left(\frac{z \cdot e \cdot B_z \cdot R}{2p_{T2}}\right)$$

R is a given cylindrical radius

$\Phi_{1,2}$ are azimuthal angles of track at reconstructed vertex



First tests with reconstructed data : two-tracks effects



cut $\Delta\eta<0.04$ and $\Delta\varphi^*<0.02$

- Pion femtoscopic CF can be correctly reconstructed if two-tracks cuts are applied
- But good knowledge of tracking procedure is necessary

Introduction: Factorial Moments (intermittency)

Factorial Moments
(see Olga Kodolova's talk)

It was proposed by A. Bialas and R. Peschanski (Nucl. Phys. B 273 (1986) 703) to study the dependence of the normalized factorial moments

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

Note: there is a set of definitions of moments and cumulants.

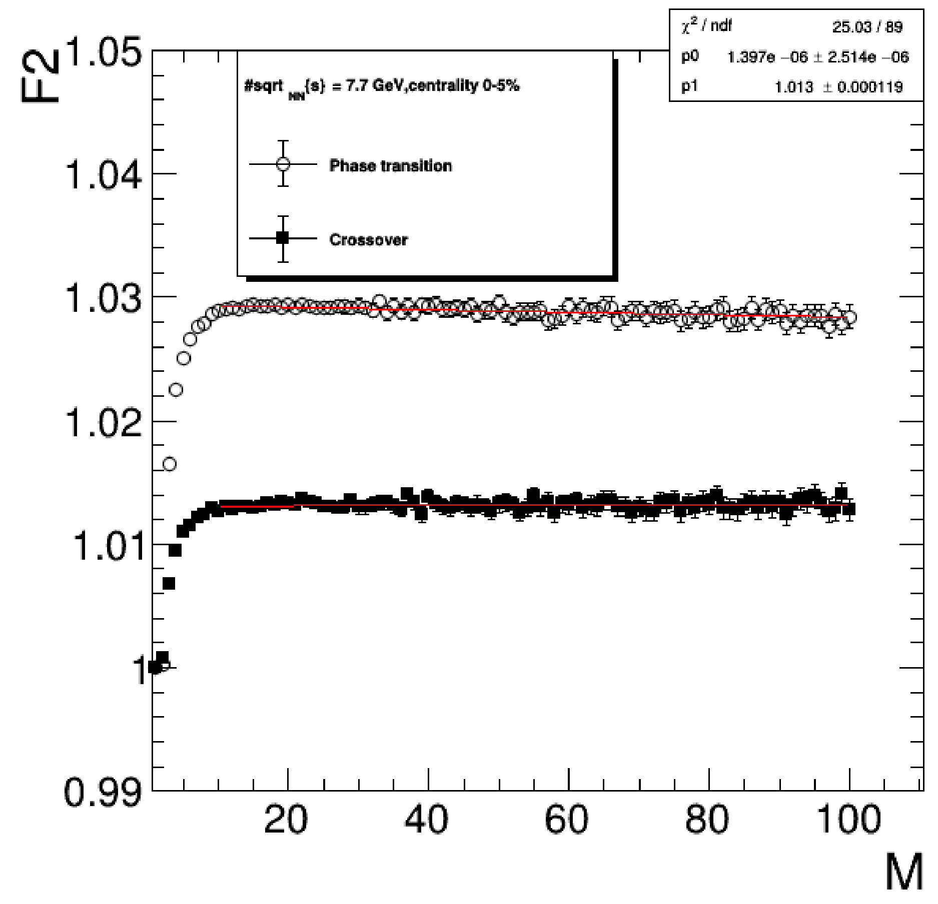
of the rapidity distribution on the size δy (Δy/M, M is the number of bins, Δy is the size of the mid rapidity window):

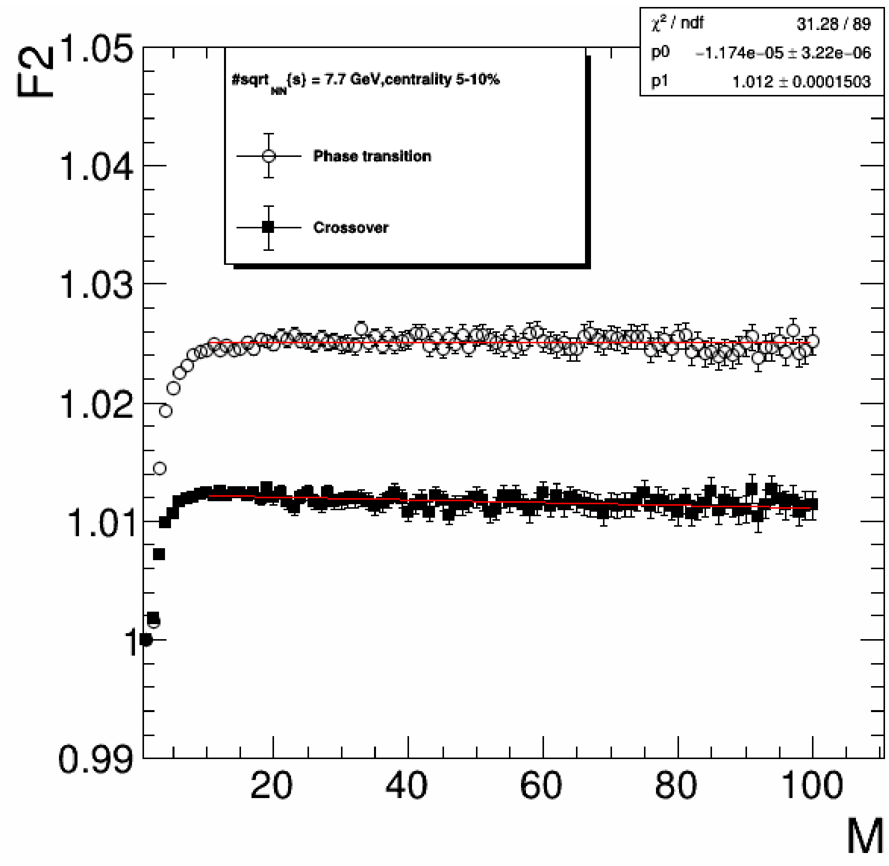
1. if fluctuations are purely statistical no variation of moments as a function of δy is expected

2. Observation of variations indicates the presence of physics origin fluctuations

Intermittency (fluctuations of various different sizes in 1D, 2D and 3D phase space) have been studied at LEP, Tevatron, Protvino in ee, hh, hA, AA interactions at the various energies.

Factorial Moments with vHLLE+UrQMD (7.7GeV)

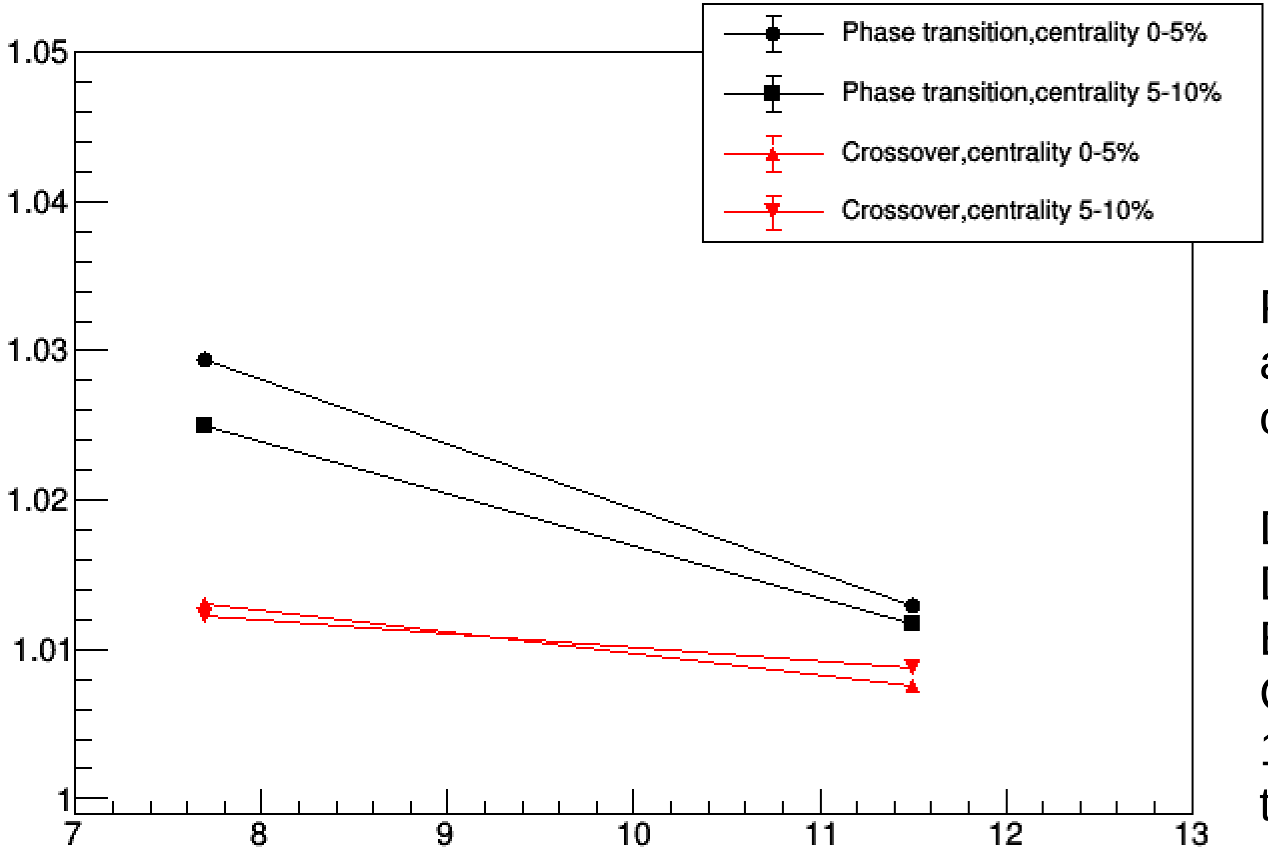




Fit the level of maximum with polinom of the first order: a+b x M
b is of the order of 10^{-6}

Energy dependence

F2 maximum



E, GeV

Plot the F2 max as a function of energy.

Different energy Dependence is Expected for Crossover and the 1st order phase transition

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

- Our studies were presented in the MPD Physics Seminars on and in internatinal conferences WPCF2019 and QFTHEP 2019

Activities within RFBR grant 18-02-40044

- Three Master and 1 PhD student in Femto group

- PWG3 Meetings: 8 events(2019) and 4events(2020) → https://indico.jinr.ru/category/346/

- MPD Physics Seminars:

L.Malinina. «Correlation femtoscopy at NICA» 21-11-2019
G.Nigmatkulov. «Looking at Data Stored in MpdDst» 21-11-2019
K. Mikhaylov «The first tests of MC data obtained using vHLLE model» 19-09-2019

- Conferences:

P. Batyuk. «Femtoscopy with identified particles for NICA/MPD». XIV WPCF, Dubna, 2019
K. Mikhaylov. «Correlation femtoscopy at NICA energies». XXIV QFTHEP, Sochi, 2019
P. Batyuk. "Correlation femtoscopy and factorial moments at theNICA energies". NICA-days 2019, Warsaw, 2019

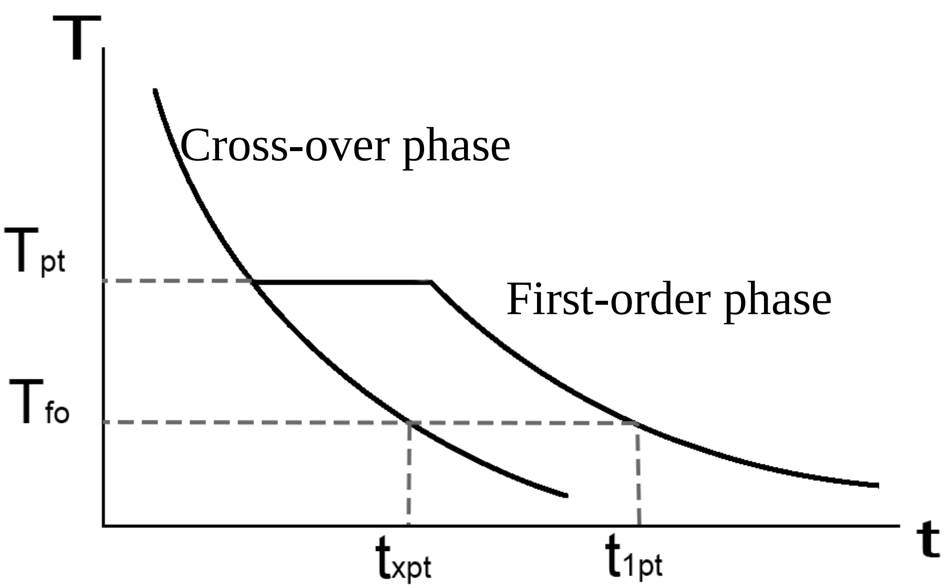
- Publications:

K.Mikhaylov, P.Batyuk, O.Kodolova, L.Malinina, G.Nigmatkulov and G.Romanenko,
«Correlation femtoscopy at NICA energies», EPJ Web Conf. Volume 222, 2019, 02004
P. N. Batyuk, L. V. Malinina, K. R. Mikhaylov, and G. A. Nigmatkulov,
«Femtoscopy with Identified Charged Particles for the NICA Energy Range», Physics of Particles and Nuclei, 2020, Vol. 51, No. 3, pp. 252–257

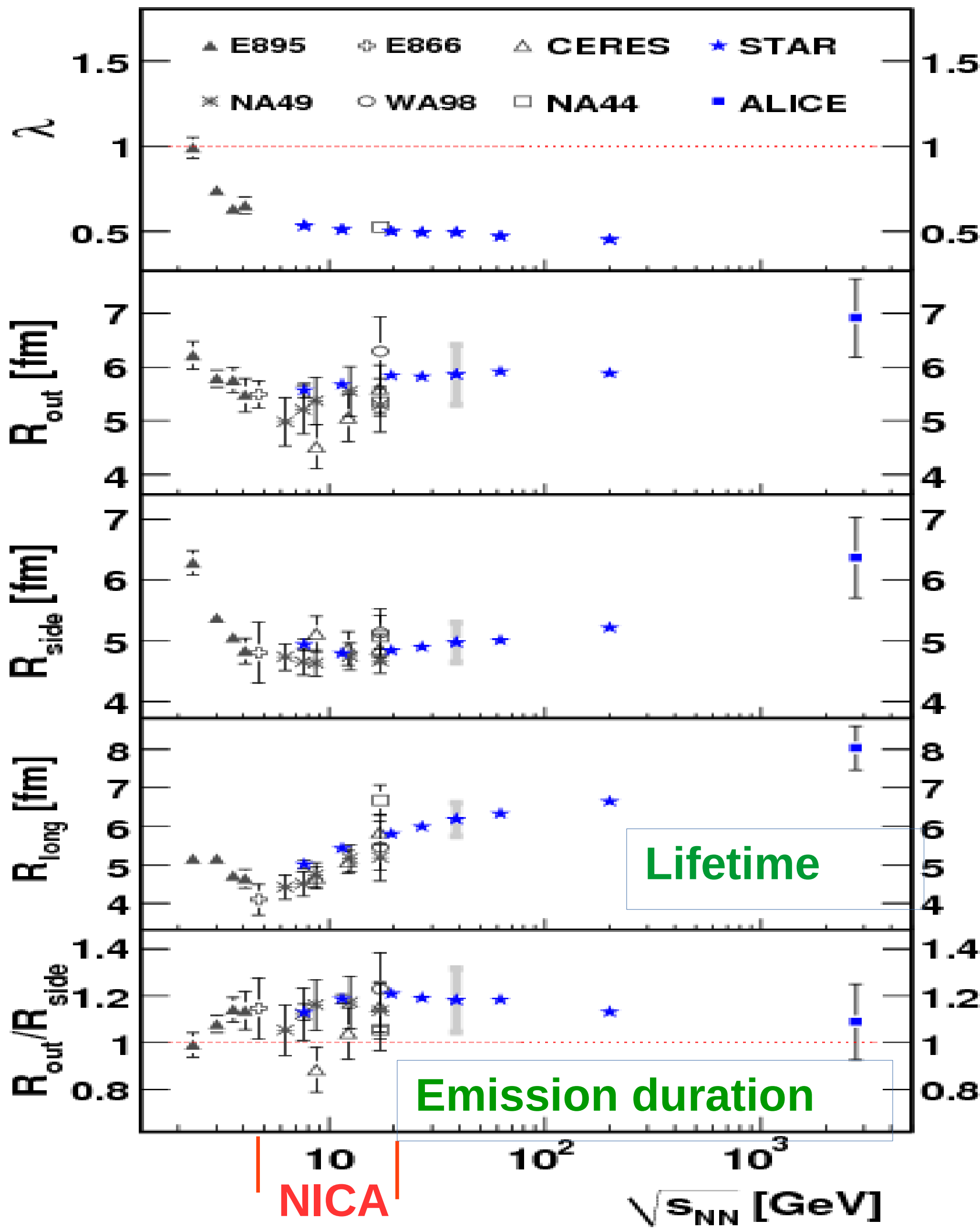
Additional slides

Motivation: Correlation femtoscopy.

- 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



- RHIC Beam Energy Scan program (BES-I): √sNN = 7.7, 11.5, 19.6, 27, 39 GeV pion and kaon femtoscopic radii were measured
- New fix target results with sqrt(sNN)=4.5 GeV
Flow and interferometry results from Au+Au collisions at sqrt(sNN) = 4.5 GeV STAR, 2007.14005

Hybrid (hydro+hadron gas) vHLLE+UrQMD model

Pre-thermal phase → hydrodynamic phase → hadronic cascade

UrQMD | vHLLE | UrQMD

(3+1)-D viscous hydrodynamics

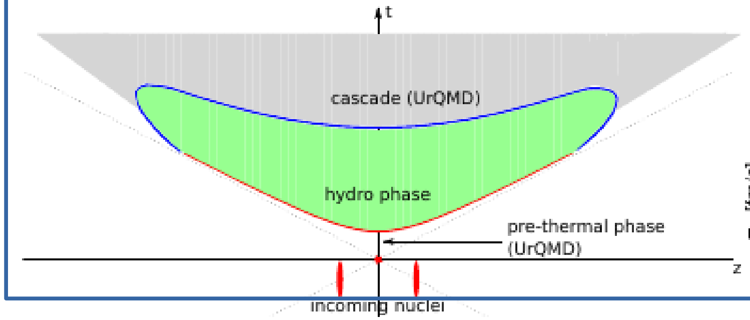
Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978,1509.3751 , talk QM2015

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

The transition to hydrodynamical description occurs at a hyper-surface of constant longitudinal proper time τ_0
The minimal value of the starting time τ0 is taken to be equal to the average time for the two colliding nuclei to completely pass through each other:

$$\tau_0 = 2R/\sqrt{(\sqrt{s_{\rm NN}}/2m_N)^2 - 1},$$

At τ = τ0 energy, momentum and baryon/electric charges of hadrons are distributed to fluid cells ijk around each hadron's position according to Gaussian

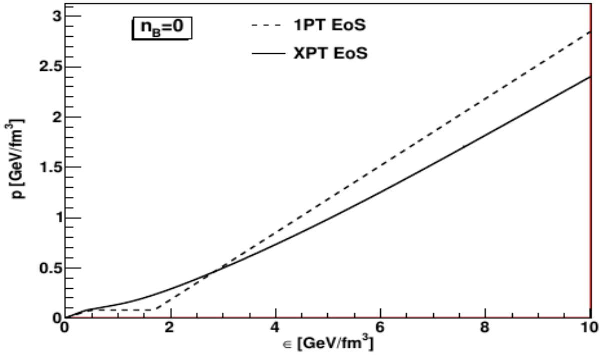


VHLLE (3+1)-D viscous hydrodynamics

HadronGas + Bag Model → 1st order PT (1PT) P.F. Kolb, et al, PR C 62, 054909 (2000)

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

Thermodynamic pressure as a function of energy density, evaluated at zero baryon density from the equations of state used in the hydrodynamic stage XPT & 1PT



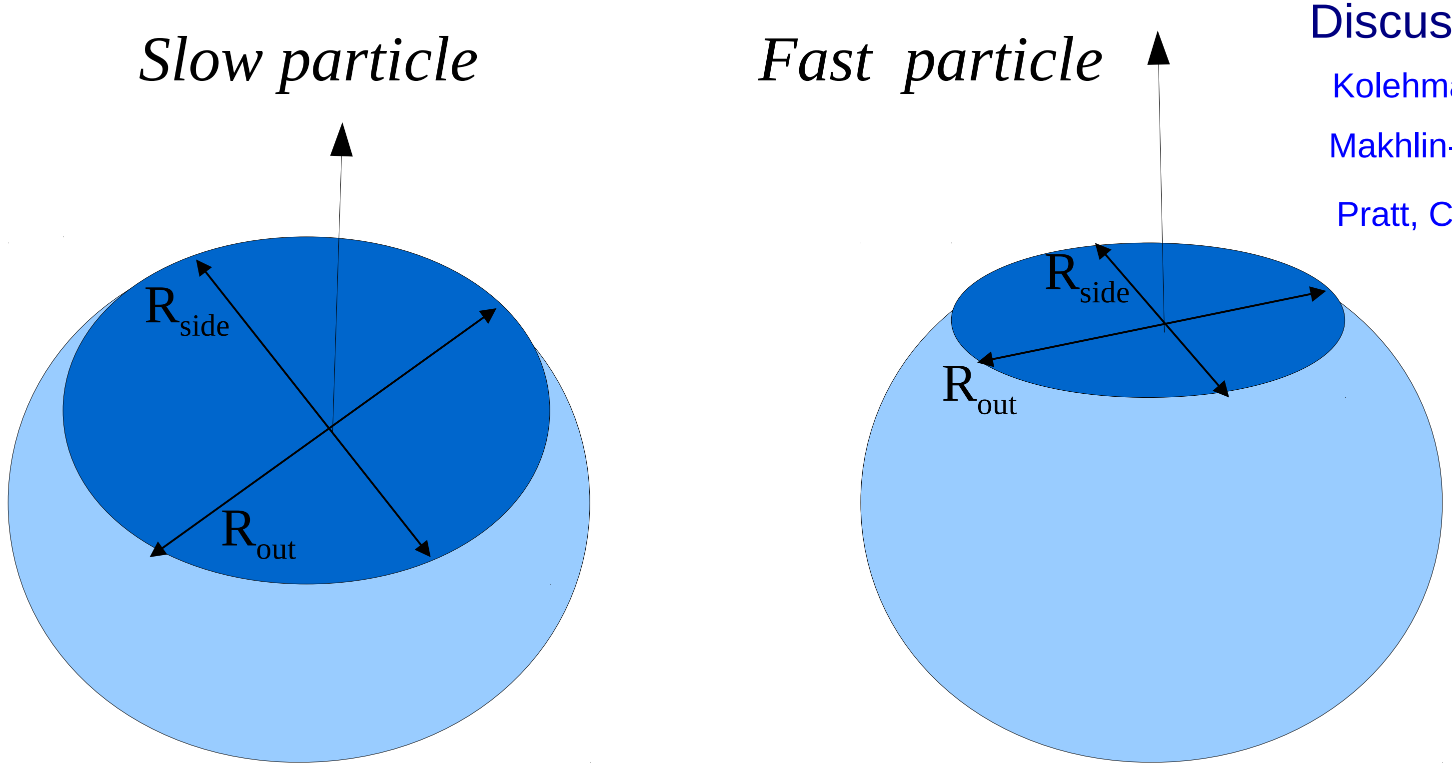
Fluid to particle transition, or particlization, is set to happen at a hypersurface of constant (hydrodynamic) energy density sw = 0.5 GeV/fm3 ,

The particlization hypersurface is reconstructed with the CORNELIUS subroutine.

At this hypersurface, individual hadrons are sampled using the Cooper-Frye formula including shear viscous corrections to the distribution functions. The hadronic rescatterings and decays are treated with the UrQMD cascade.

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

$R_{long} = \tau\,(T/m_T)^{1/2}$ assuming a longitudinal boost invariant expansion

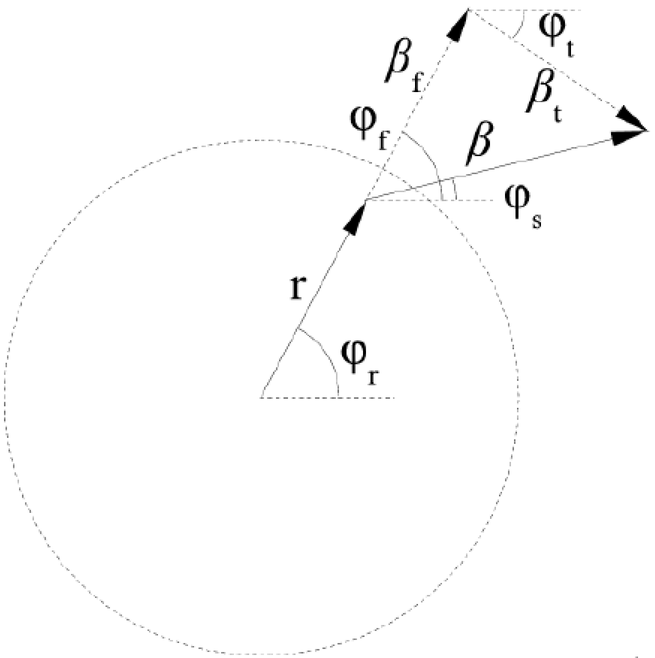
$R^2_{out} \sim R^2_{side} + 1/2(T/m_T)^2\beta_T^{\,2}\tau^2$

Femtoscopy with expanding source

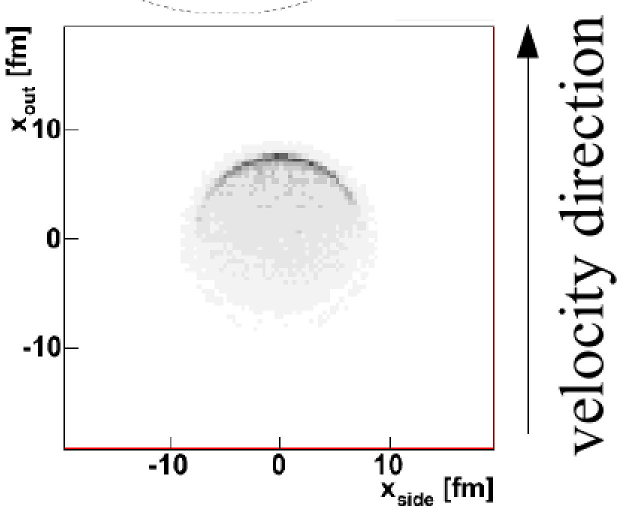
Interference probes only parts of the source at close momenta – **homogeneity regions.**

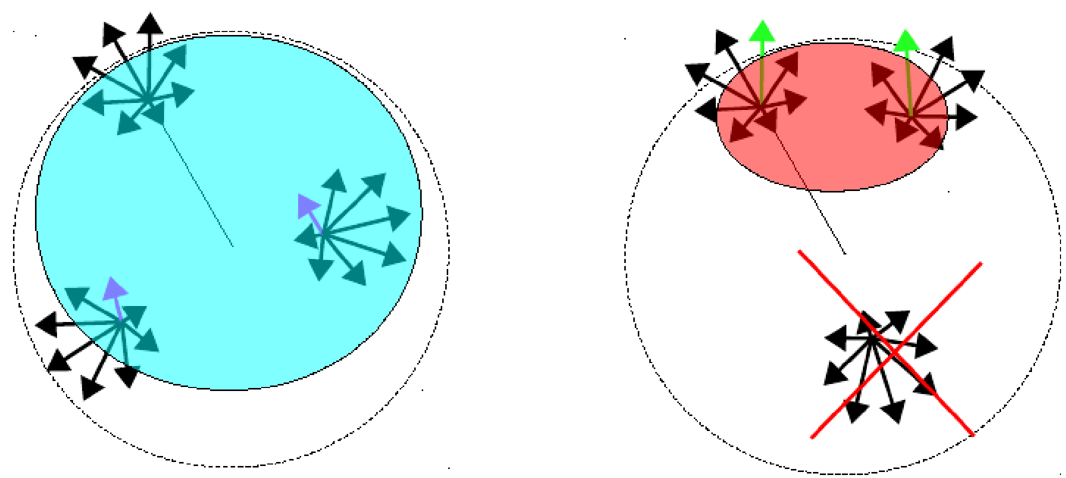
[Yu.M. Sinyukov, Nucl. Phys. A 566, 589 (1994);]

Figures and consideration from A. Kisiel Phys.Rev. C81 (2010) 064906

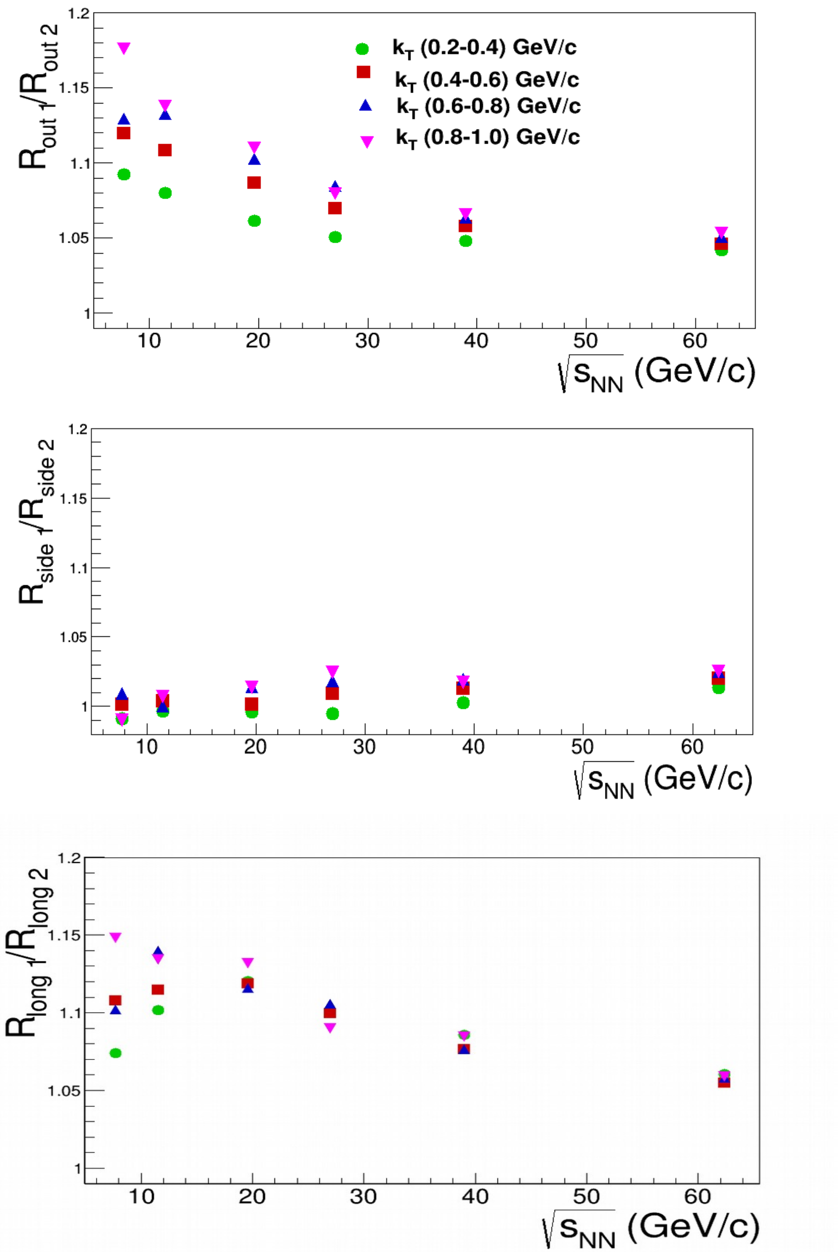


- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source





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

Factorial Moments with vHLLE+UrQMD (11.5 GeV)