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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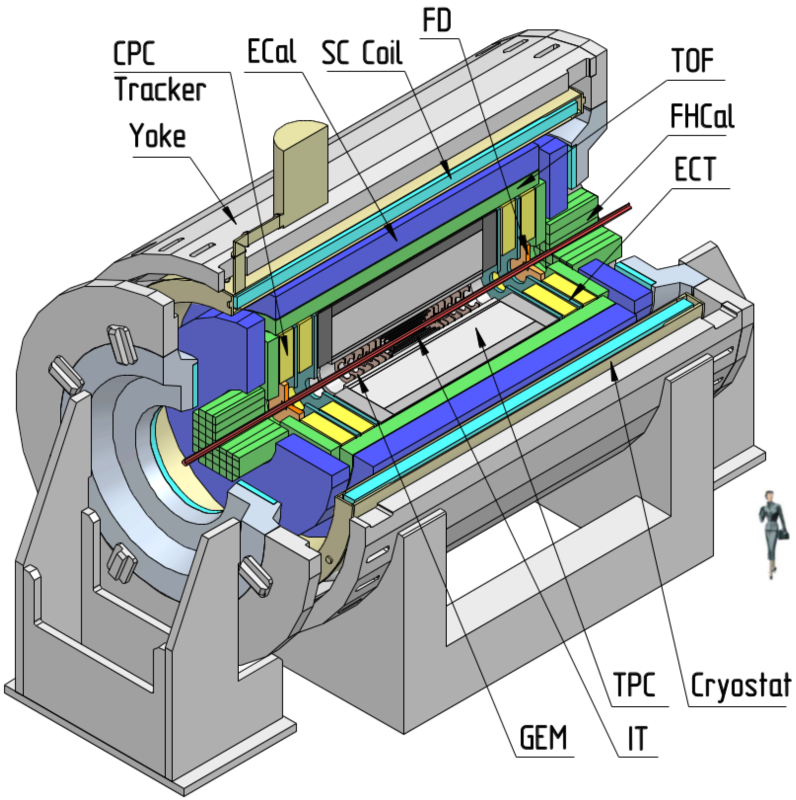
Outline

- Activities
- Femtoscopy & Motivation
- Hybrid vHLLE+UrQMD model
- Comparison with STAR BES
- First tests with reconstructed data
- Factorial Moments
- Other activities
- Plans for 2020
- Conclusion



Activities within RFBR grant 18-02-40044

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 and factorial moments (on going)

Activities within RFBR grant 18-02-40044

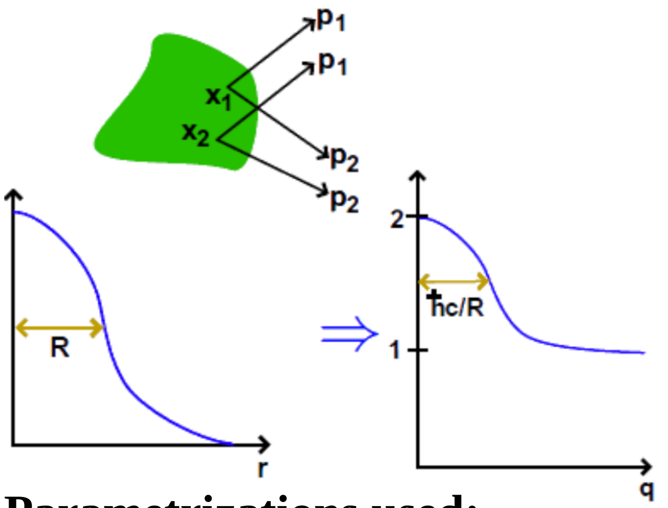
PWG3 Meetings: 8 events(2019) and 4events(2020) → https://indico.jinr.ru/category/346/

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 HEPQFT, Sochi, 2019
P. Batyuk. "Correlation femtoscopy and factorial moments at theNICA energies". NICA-days 2019, Warsaw, 2019

Publication:
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

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

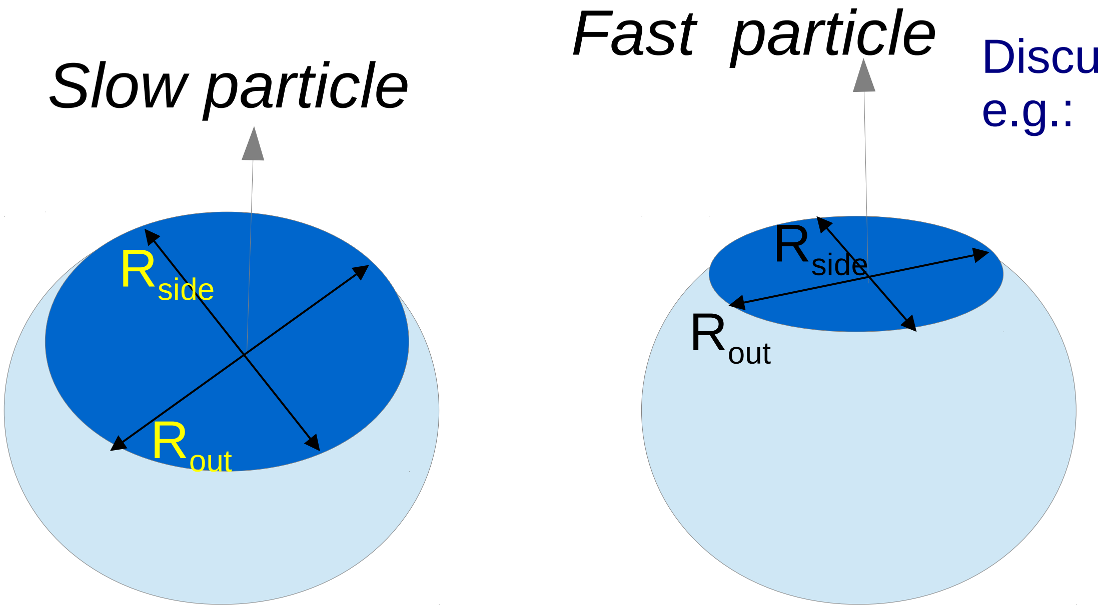
Parametrizations used:

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

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

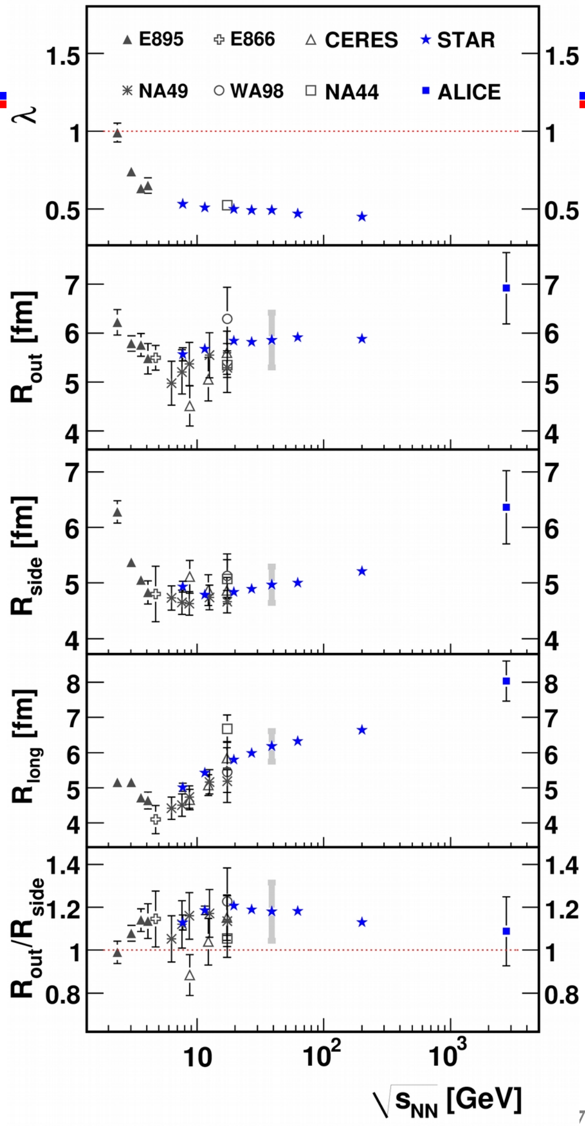
$R^2_{out} \sim R^2_{side} + 1/2(T/m_T)^2\beta_T^{\,2}\tau^2$

Motivation

- **<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 GeV



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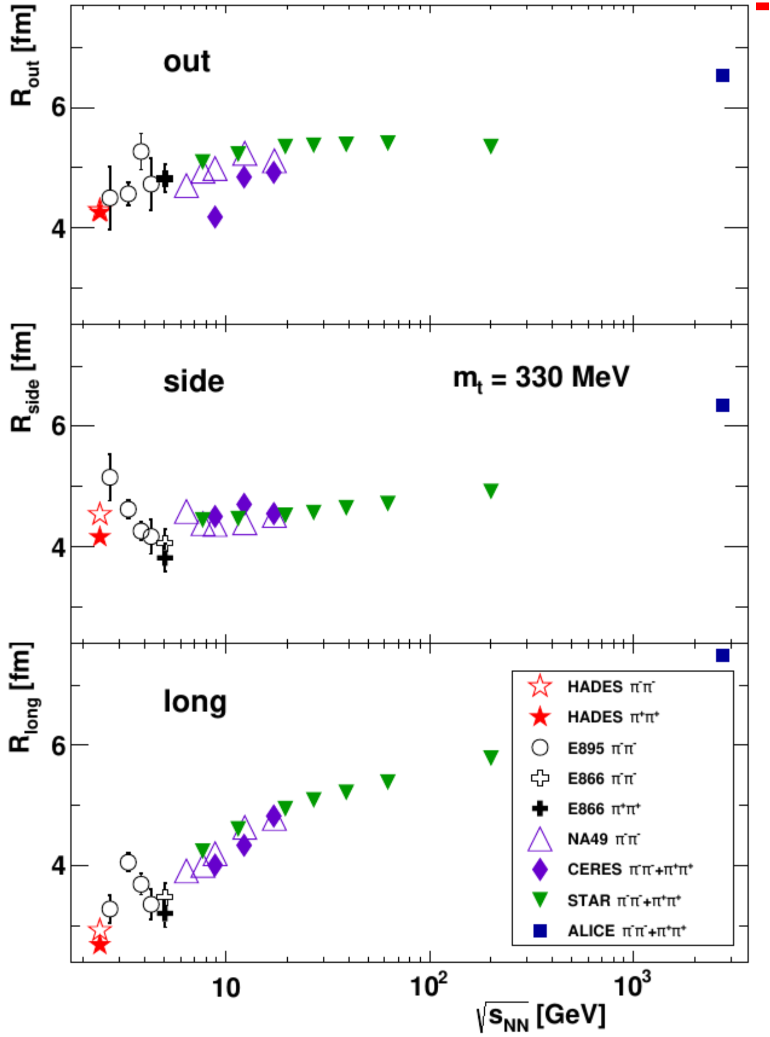


Femtoscopy with vHLLE+UrQMD

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

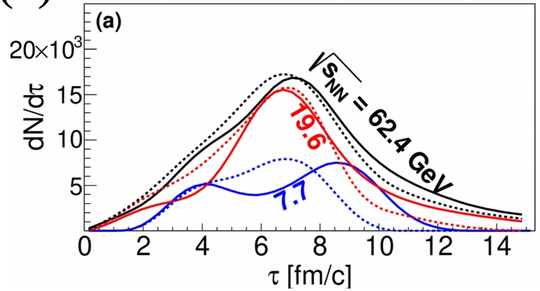
- Chiral EoS — crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model 1st-order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

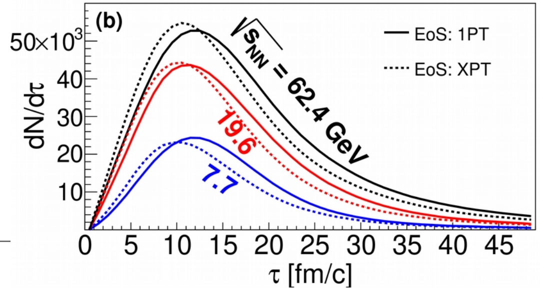
Hydrodynamic phase lasts longer with 1PT, especially at lower energies but cascade smears this difference.

Pion emission time

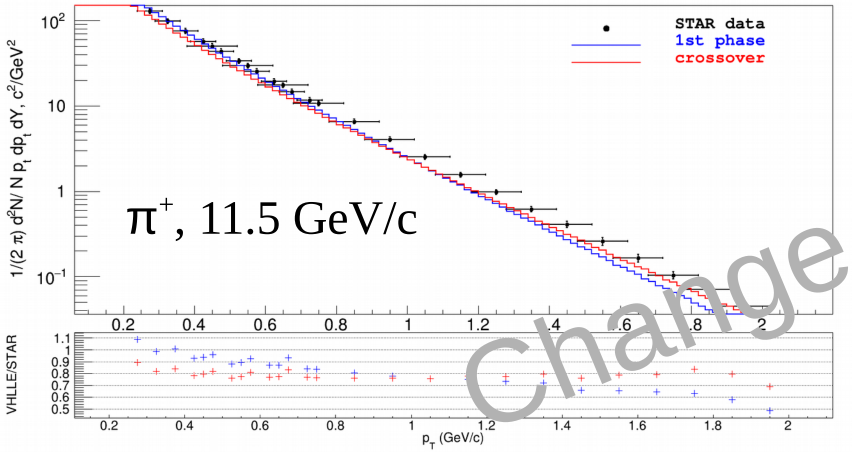
(a) - after hydrodynamic phase

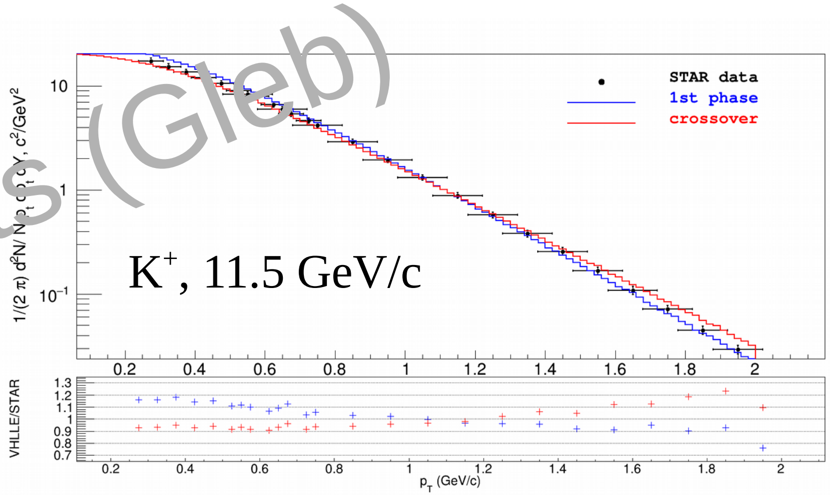
(b) - after cascade





p_T- spectra of π and K with vHLLE+UrQMD

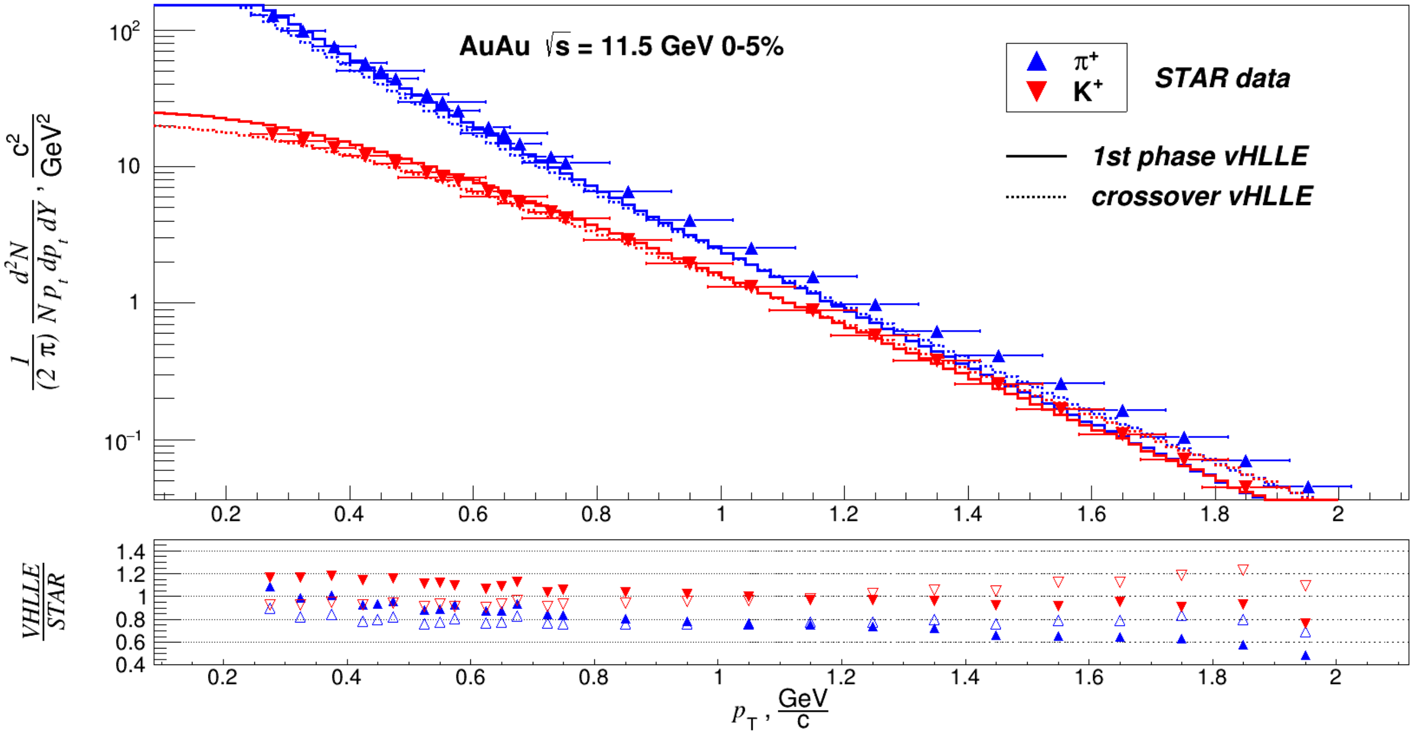




- STAR data: PHYSICAL REVIEW C 96, 044904 (2017)
- EoS: 1st order phase transition and crossover phase transition
- vHLEE+UrQMD model with both EoS describe reasonably soft part of p_T-spectra of pions and kaons

p_T- spectra of π and K with vHLLE+UrQMD

STAR data: PHYSICAL REVIEW C 96, 044904 (2017)

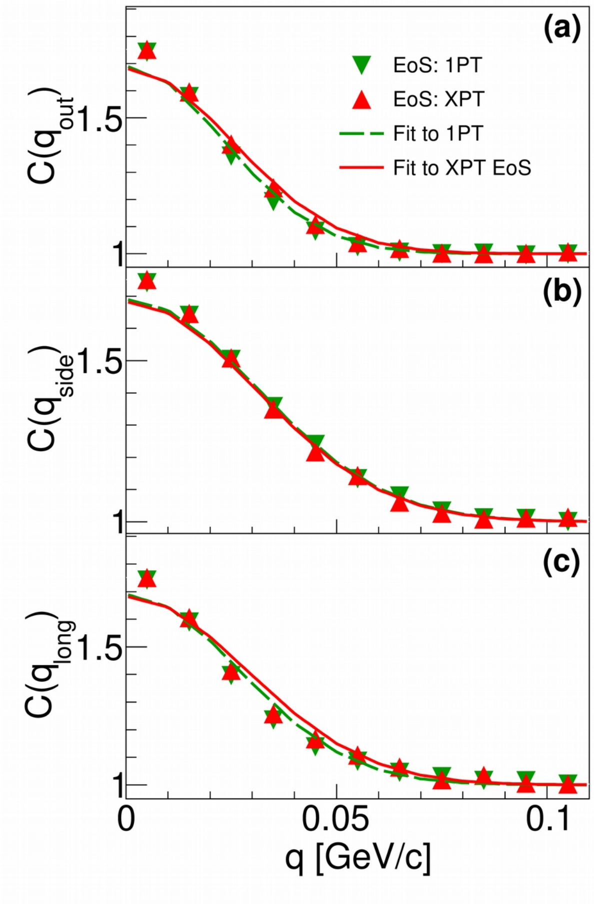


- vHLLE+UrQMD simulation with different EoS
- AuAu 11.5 GeV
- Pion pT spectra
- Kaon pT spectra

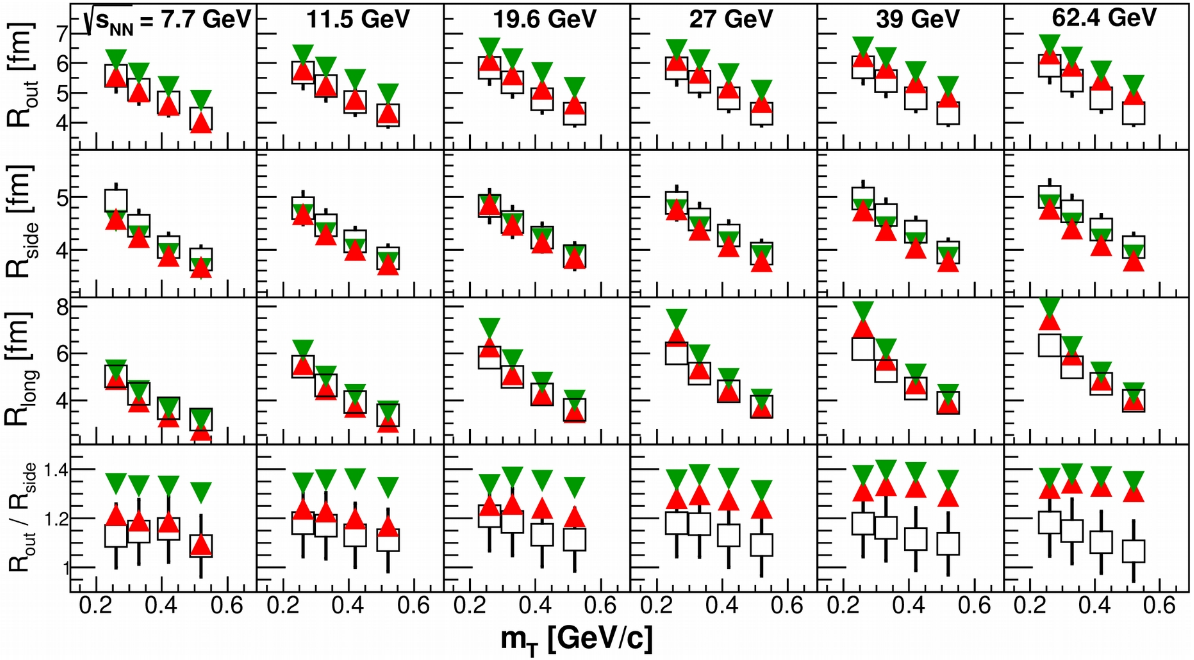
- vHLEE+UrQMD model with both EoS describe reasonably soft part of p_T-spectra of pions and kaons

3D Pion radii versus m_T with vHLLE+UrQMD

Model CF



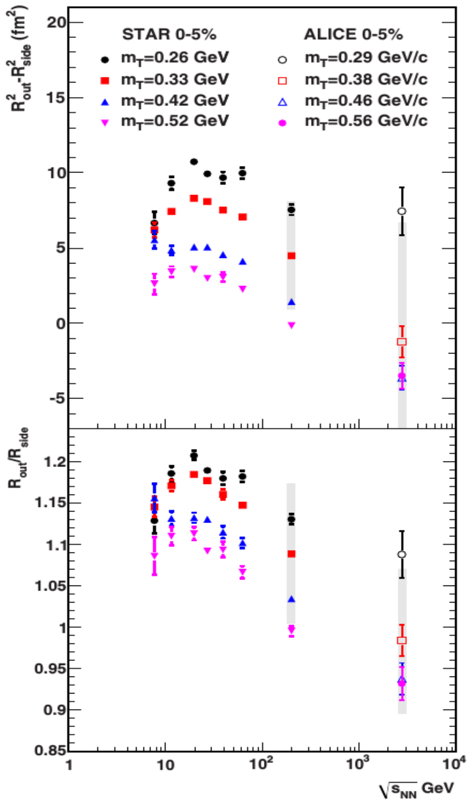
Comparison of extracted radii with the STAR data[PRC 96, 024911(2017)]

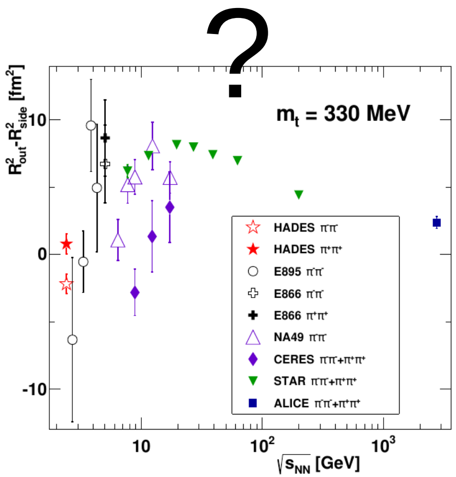


- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS does better job at lowest collision energies.
- R_{out} (XPT) at high energies and R_{out} (1PT) at all energies are slightly overestimated
- $R_{out,long}$ (1PT) > $R_{out,long}$ (XPT) by value of ∼1-2 fm.

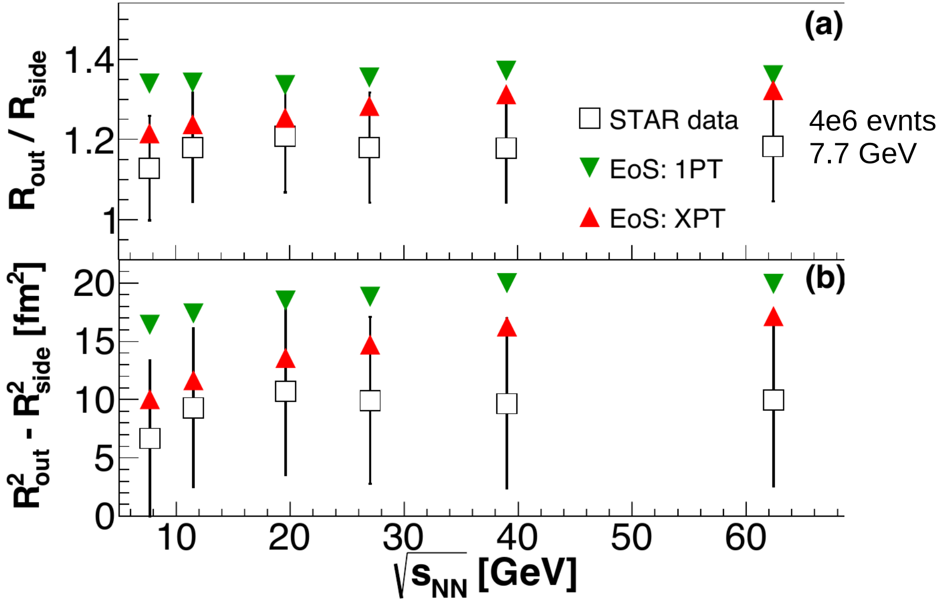
R_{out}/R_{side} with vHLLE + UrQMD model

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



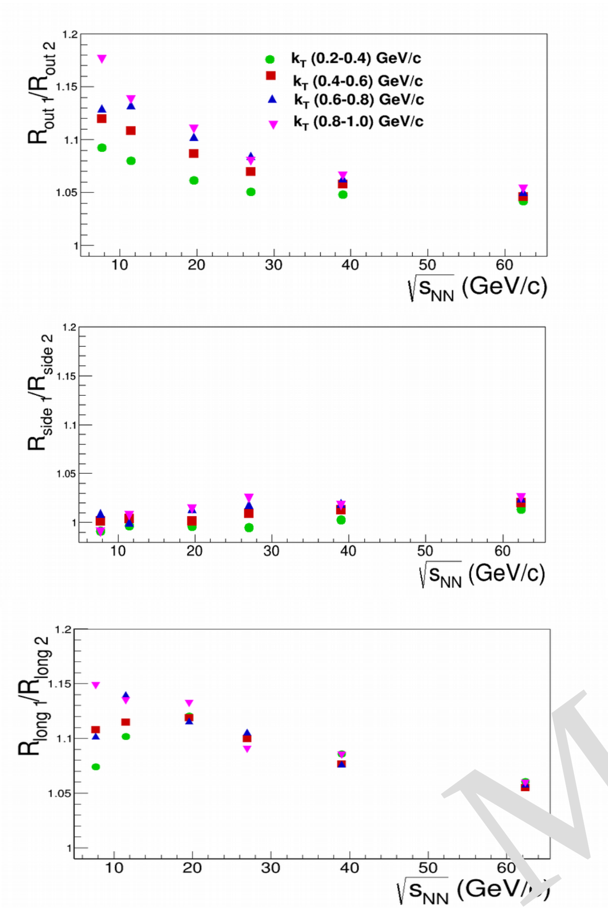


Present vHLLE+UrQMD calculations:



- 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!)

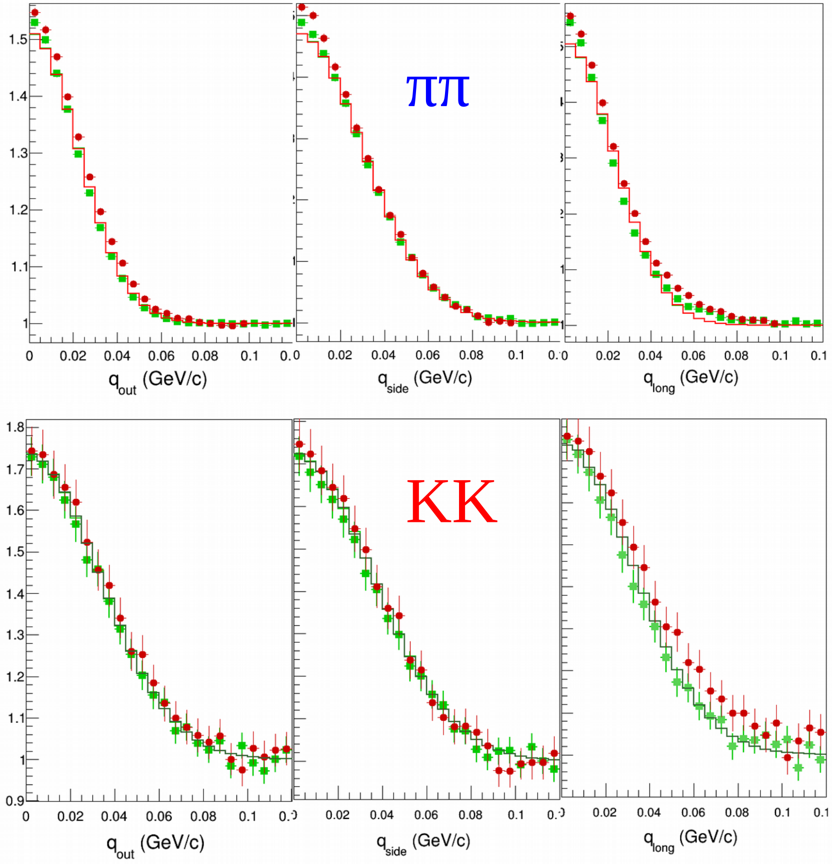
Analysis:

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

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

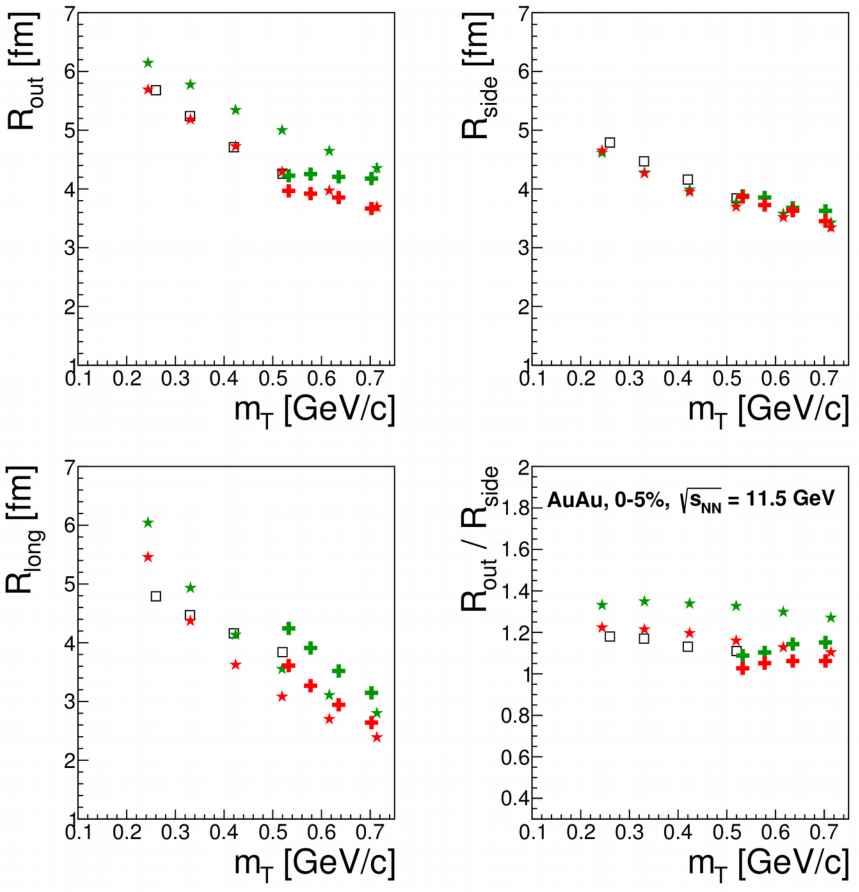
- XPT CF projections on long direction are visibly wider than 1PT especially for kaons → measurable with MPD

1PT -green dots; XPT – red dots



Radii π and K vs. mT with vHLLE+UrQMD

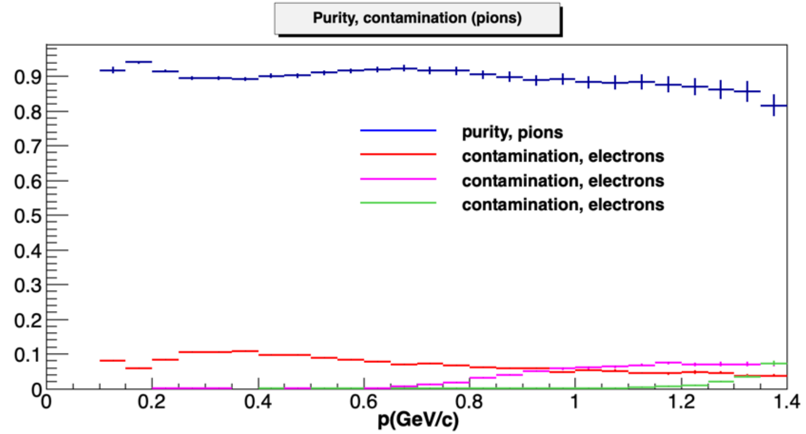
1PT -green dots; XPT – red dots

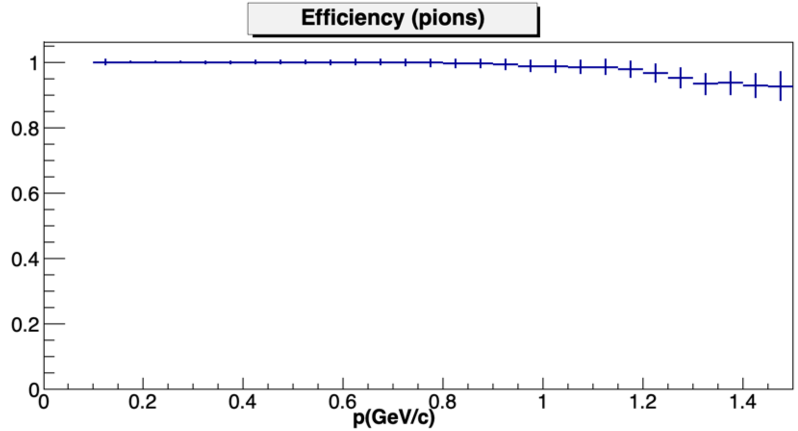


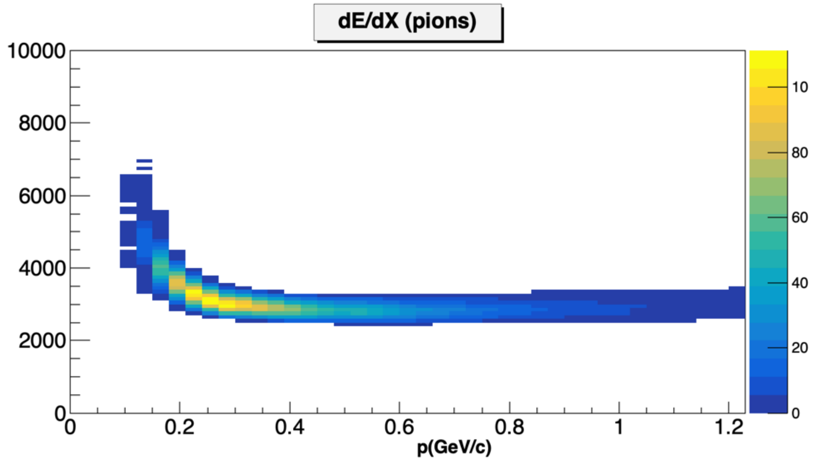
- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- As well as for π, kaon out and long radii greater for 1PT than for XPT
- Approximate m_T-scaling for pions and kaons observed only for "side" radii
- R_{out} almost flat for 1PT
- R_{long}(KK) is greater than R_{long}(ππ) kaons on average emitted later than pions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

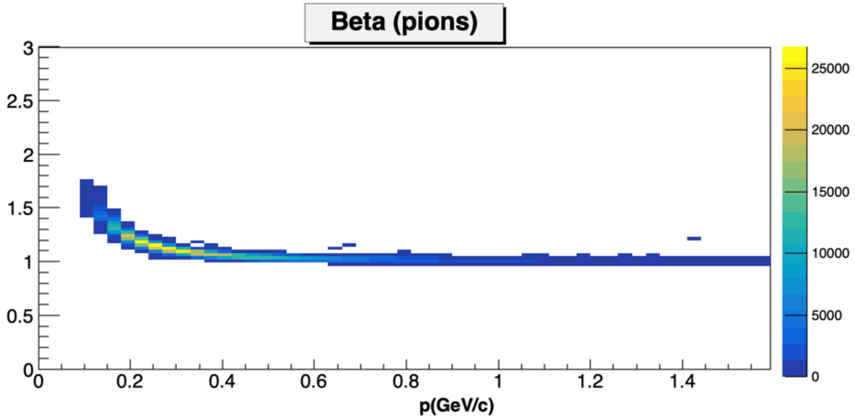
- It is important to measure both kaons and pions

MPD response for femtoscopy

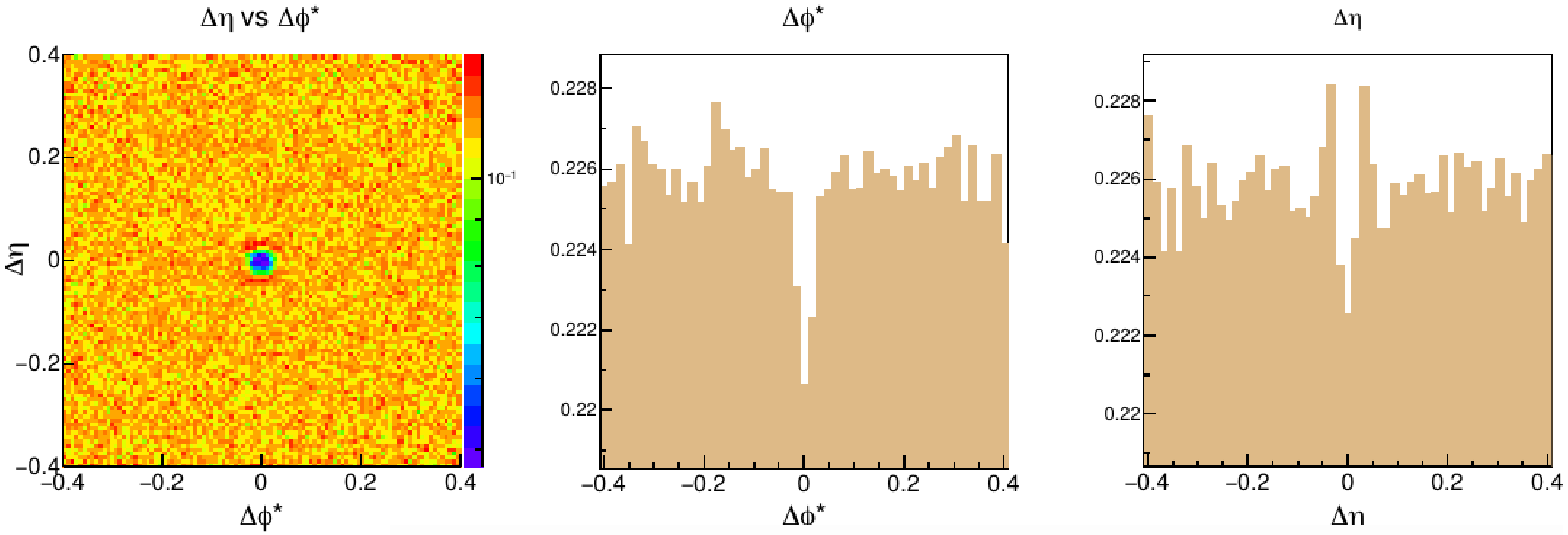








Two track effects (merging/splitting)

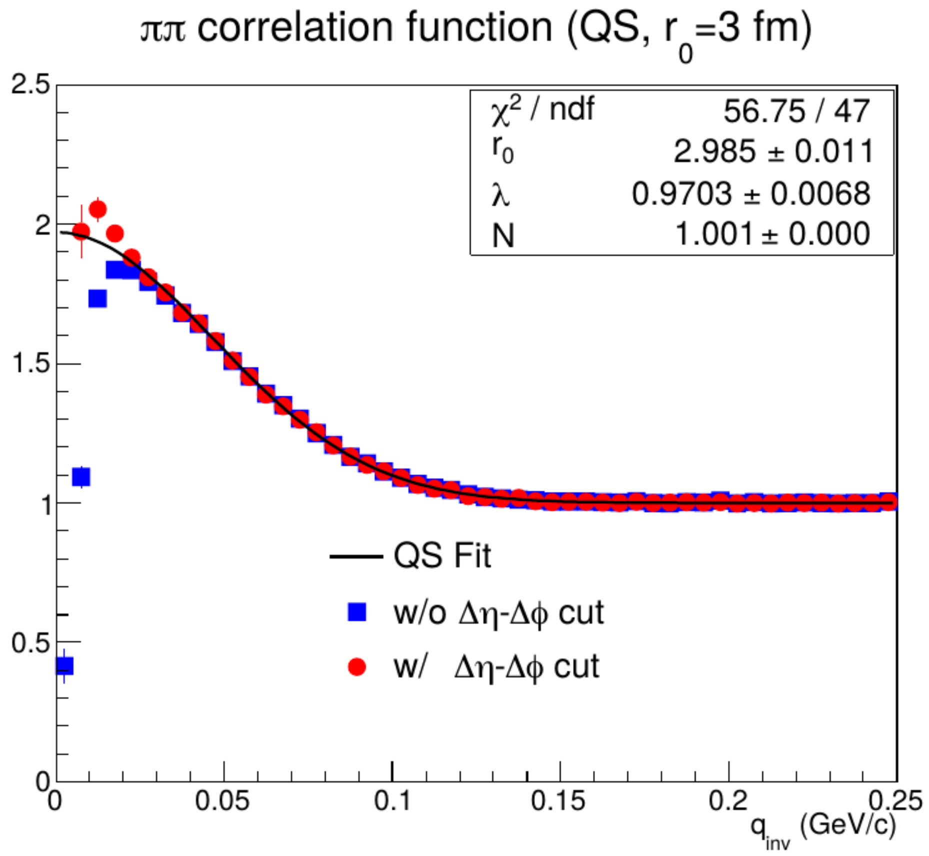


Δη-Δϕ* cut:

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

R is a given cylindrical radius, $\phi_{1,2}$ are azimuthal angles of track at reconstructed vertex

Reconstructed correlation function



- UrQMD AuAu 11 GeV reconstructed evnts
- With cut $\Delta\eta<0.04$ and $\Delta\phi^*<0.02$
- Without cut on $\Delta\eta$ and $\Delta\phi^*$
- Pion femtoscopic CF can be correctly reconstructed if two-tracks cuts are applied
- Good knowledge of tracking procedure is necessary

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.

See Olga's talk

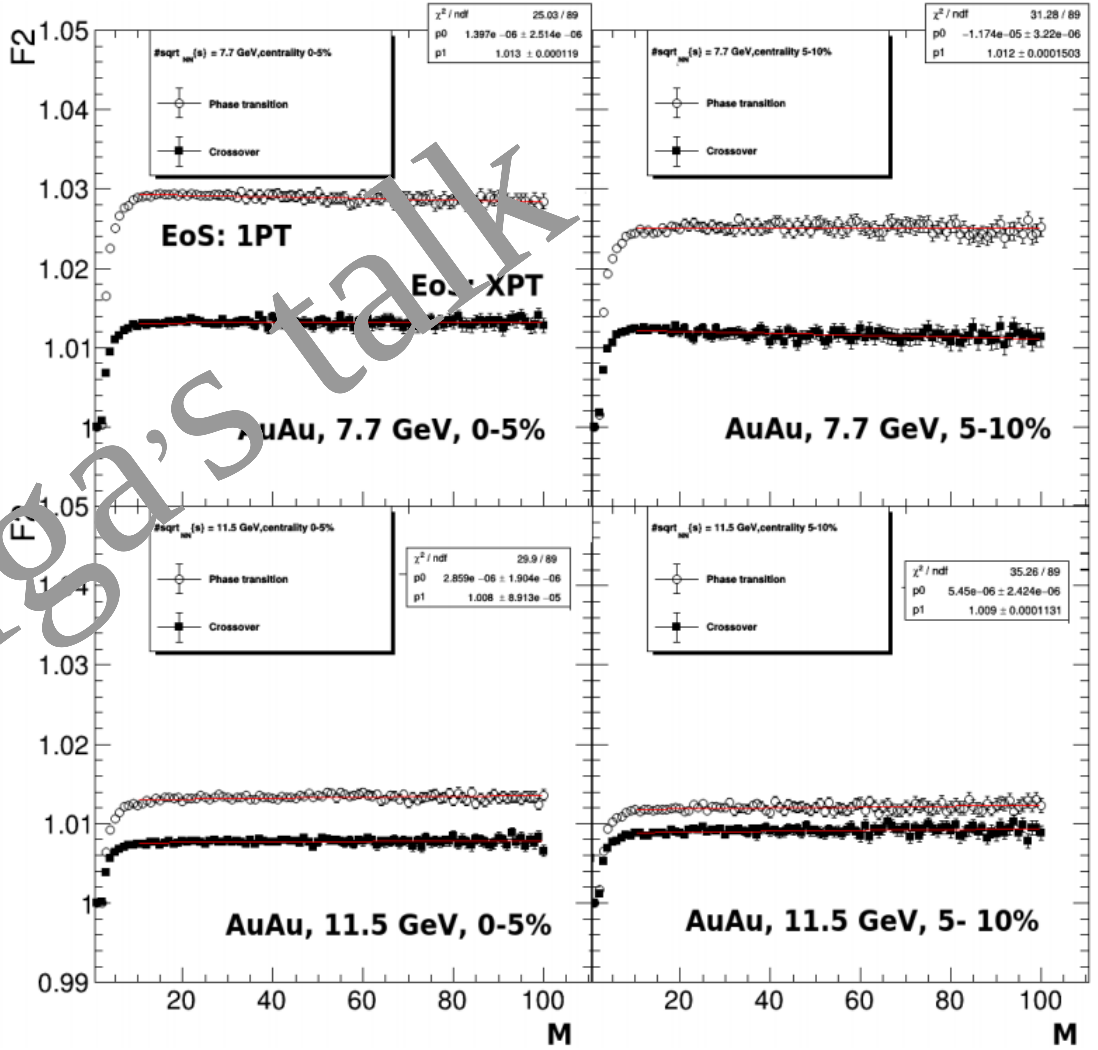
Olga: we need references →
This method have been used at NA61, LEP, Tevatron, Protvino in ee, hh, hA, AA interactions at the various energies.

Factorial moments with vHLLE+UrQMD

- F2 as a function M for |y|<1
- 5e5 generated events (vHLLE)

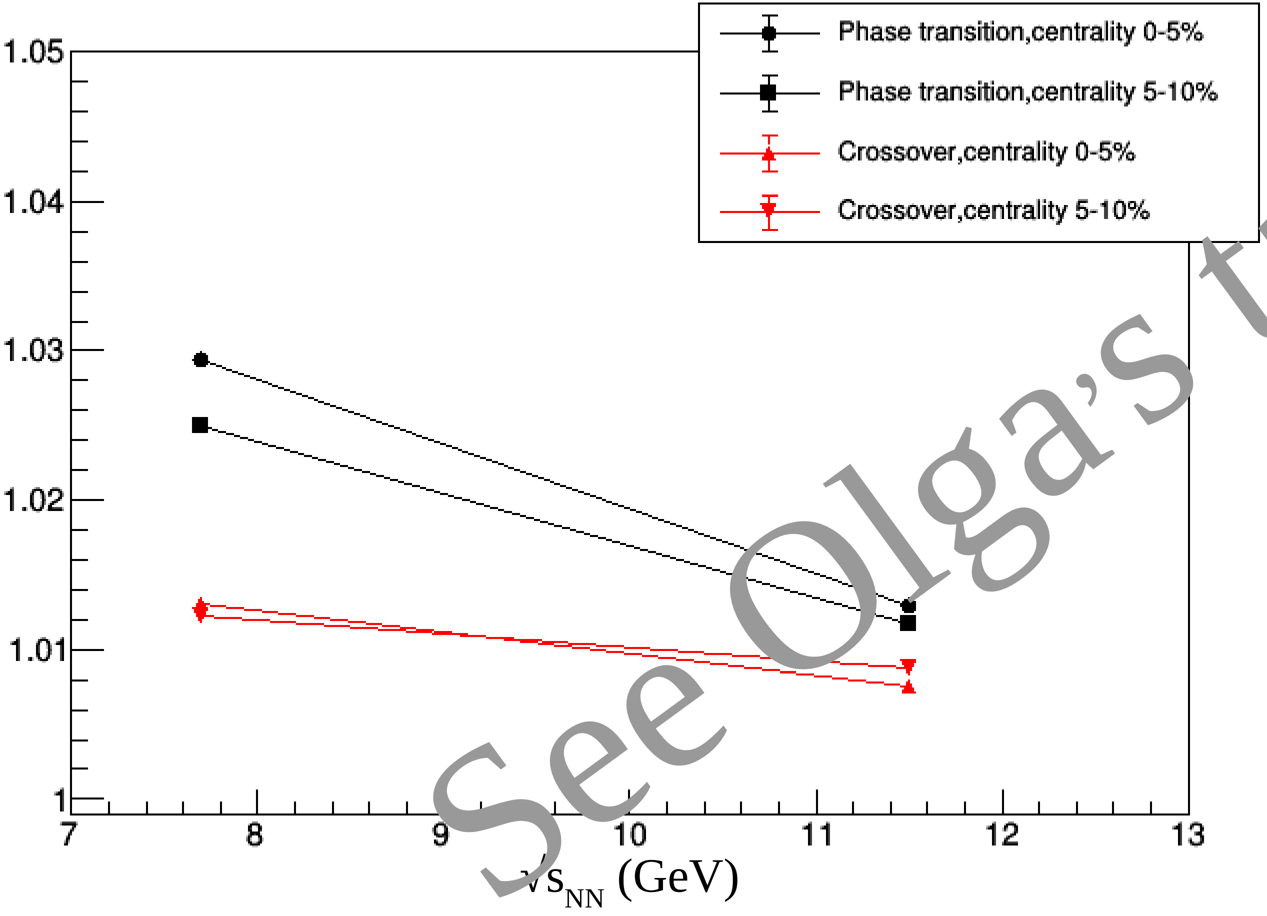
- Fit F2 by the first order polynomial: a+bM
  F2 is almost flat (b is about 10^{-6})

- F2 maximum is determined from fit



See Olga's talk

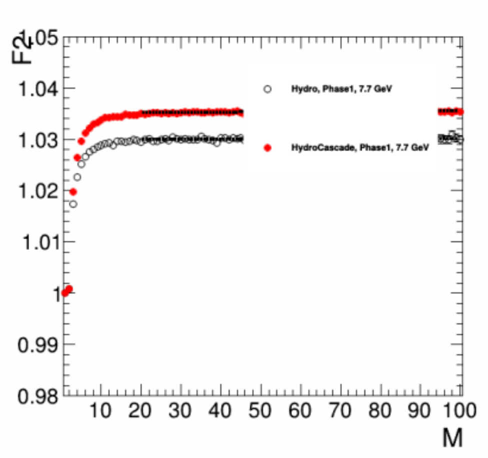
Energy dependence of F2 maximum

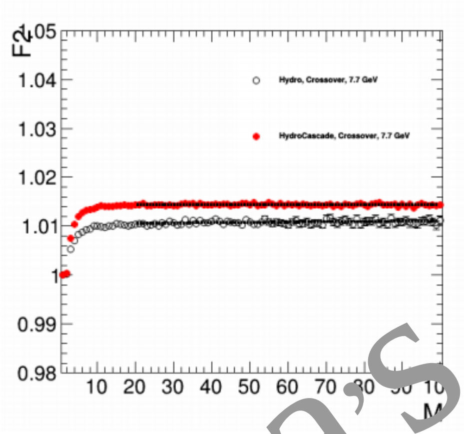


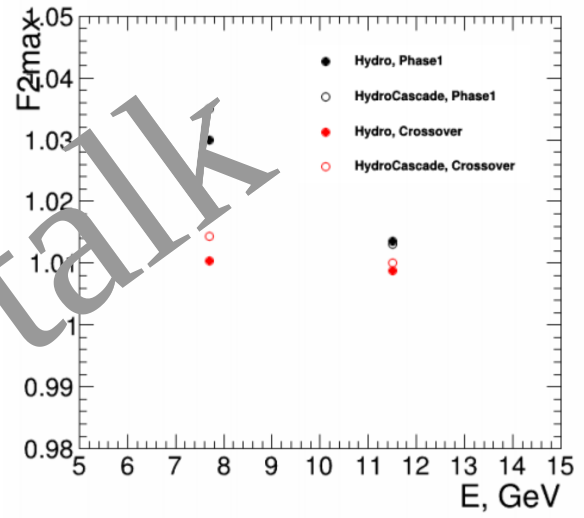
See Olga's talk

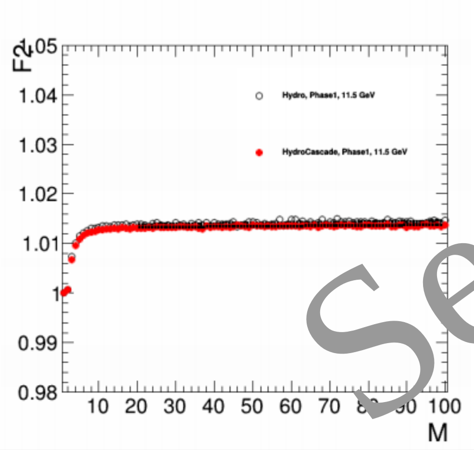
- Plot the F2 max as a function of energy
- F2 energy dependence is expected for Crossover and 1^{st} order phase transition
- Experiment: slop is expected in 1PT

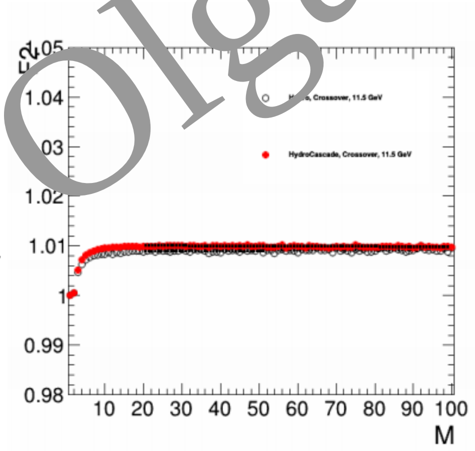
Hydro and HydroCascade separately











See Olga's talk

There is a small increase of the F2 maximum for HydroCascade. w.r.t Hydro only.
However the different trend in the F2 behaviour for the Phase 1 transition and crossover is visible

Activities in software

<u>Package for Femtoscopy analyses:</u>

- ✔ 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

<u>Factorial moments:</u>

Factorial moments analysis code inherited from Mirabel experiment is written

<u>Data formats (DST):</u>

- ✔ 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)

<u>Mini DST format:</u>

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

<u>VHLLE interface software:</u>

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

First physics

Bi+Bi 10^5 minimum bias events
pi-pi one dimension correlation function
mT-dependence
mT inclusive 3d CF ?
???

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 ππ 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!

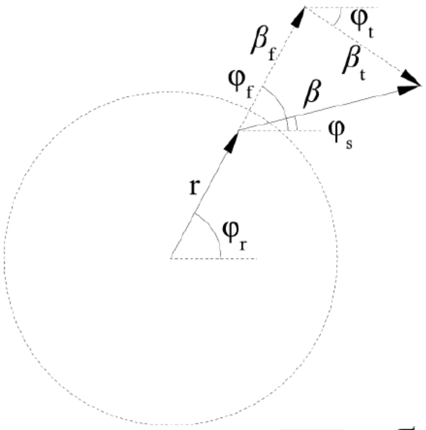
Title

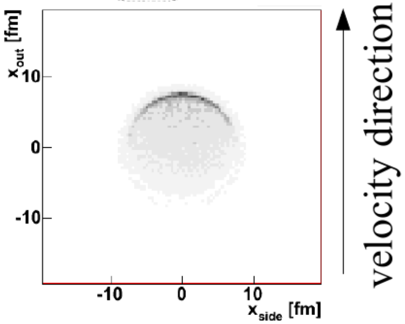
Title

Femtoscopy with expanding source

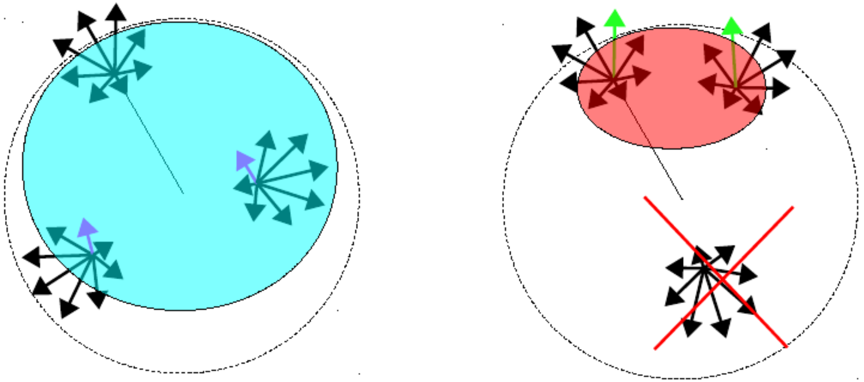
Interference probes only parts of the source at close momenta – **homogeneity regions.**

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



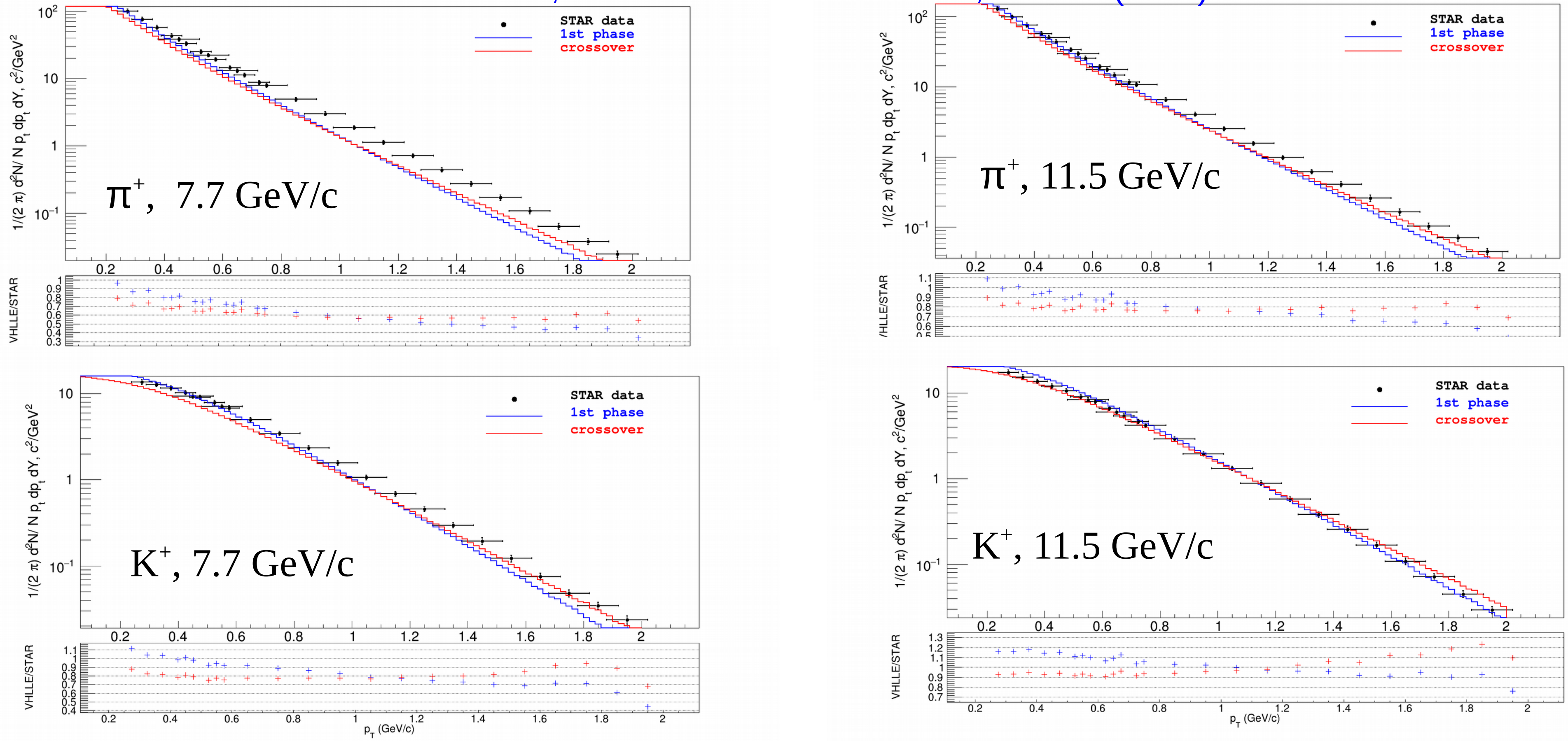


- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source



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 soft part of p_T-spectra of pions and kaons