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

Femtoscopy correlations with MPD at NICA

on behalf of PWG3 (Correlations and Fluctuations)

Supported by the RFBR grant 18-02-40044

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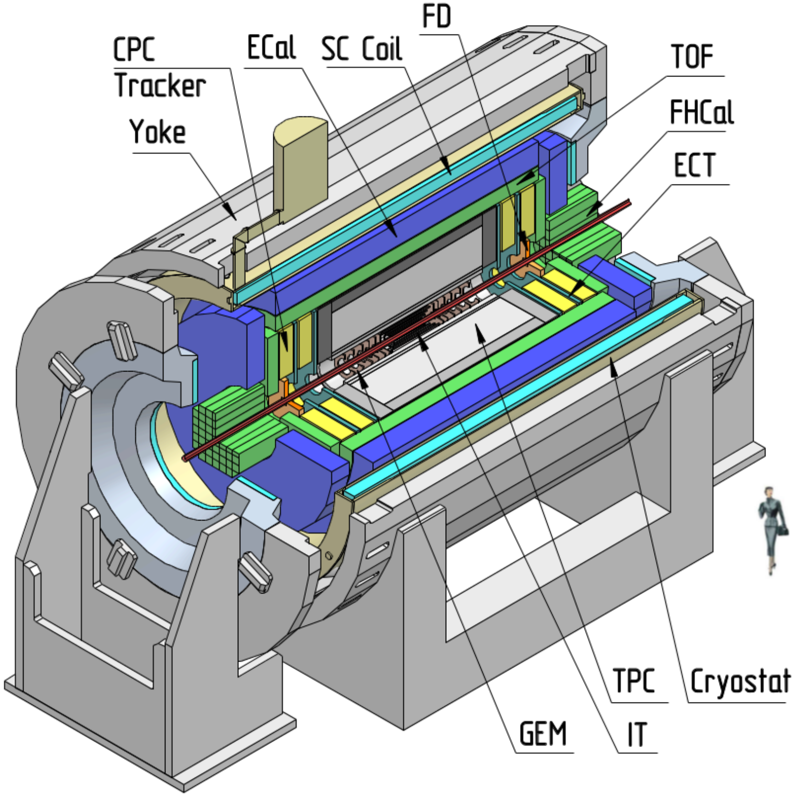
Outline

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



Activities within RFBR grant 18-02-40044

- Three students 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 HEPQFT, 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

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

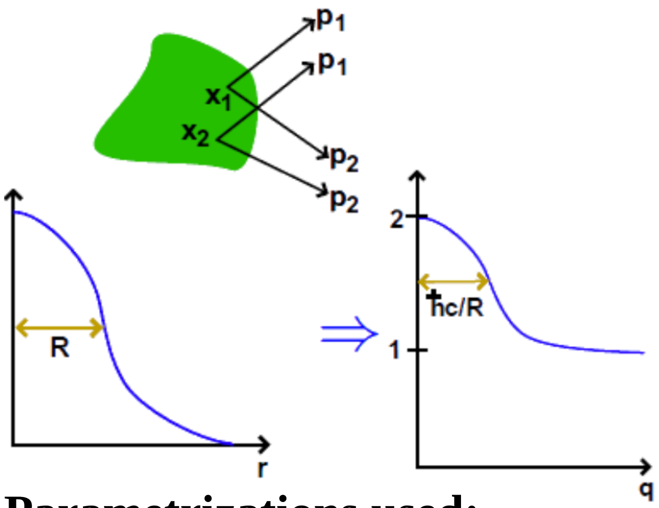
Goals:

- 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)

Femtoscopy



Correlation femtoscopy :

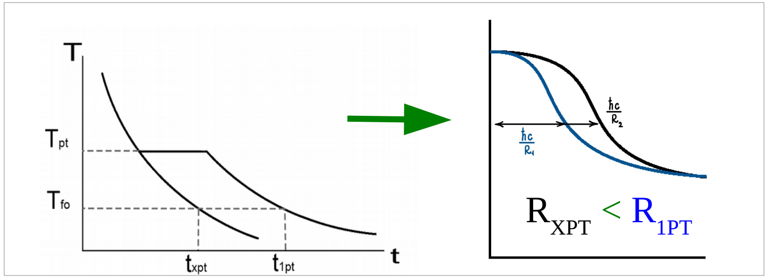
Measurement of space-time characteristics **R**, **cτ** of particle production using particle correlations due to the effects of quantum statistics (QS) and final state interactions (FSI)

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

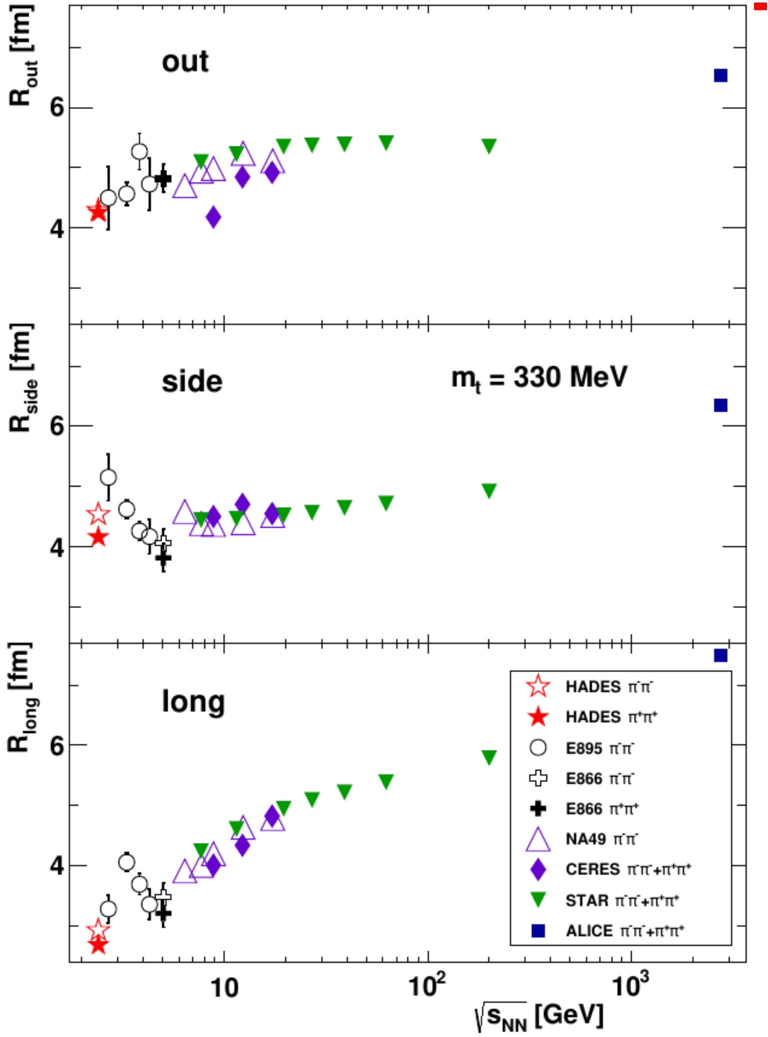
R and *q* are in Longitudinally Co-Moving Frame (**LCMS**)
long || beam; out || transverse pair velocity $\boldsymbol{v}_T$; side normal to out,long

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 7.7 GeV
    - including K and heavier



Femtoscopy with vHLLE+UrQMD

Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher,

Pre-thermal phase → Hydrodynamic phase → Hadronic cascade

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

vHLLE

(3+1)-D viscous hydrodynamics

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)

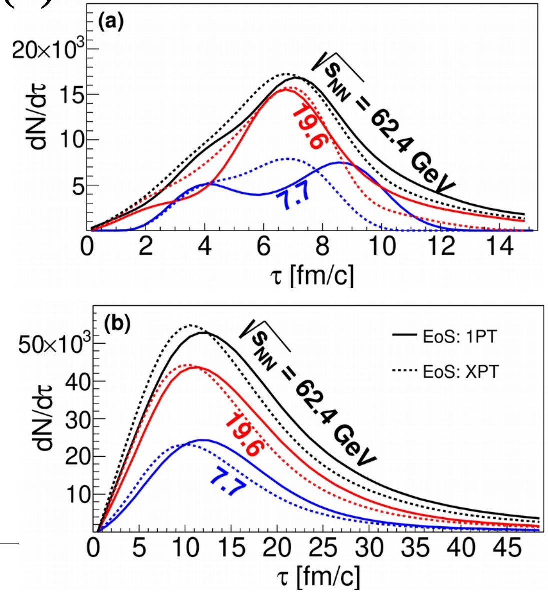
Hydrodynamic phase lasts longer with 1PT, especially at lower energies but cascade smears this difference.

UrQMD

Pion emission time

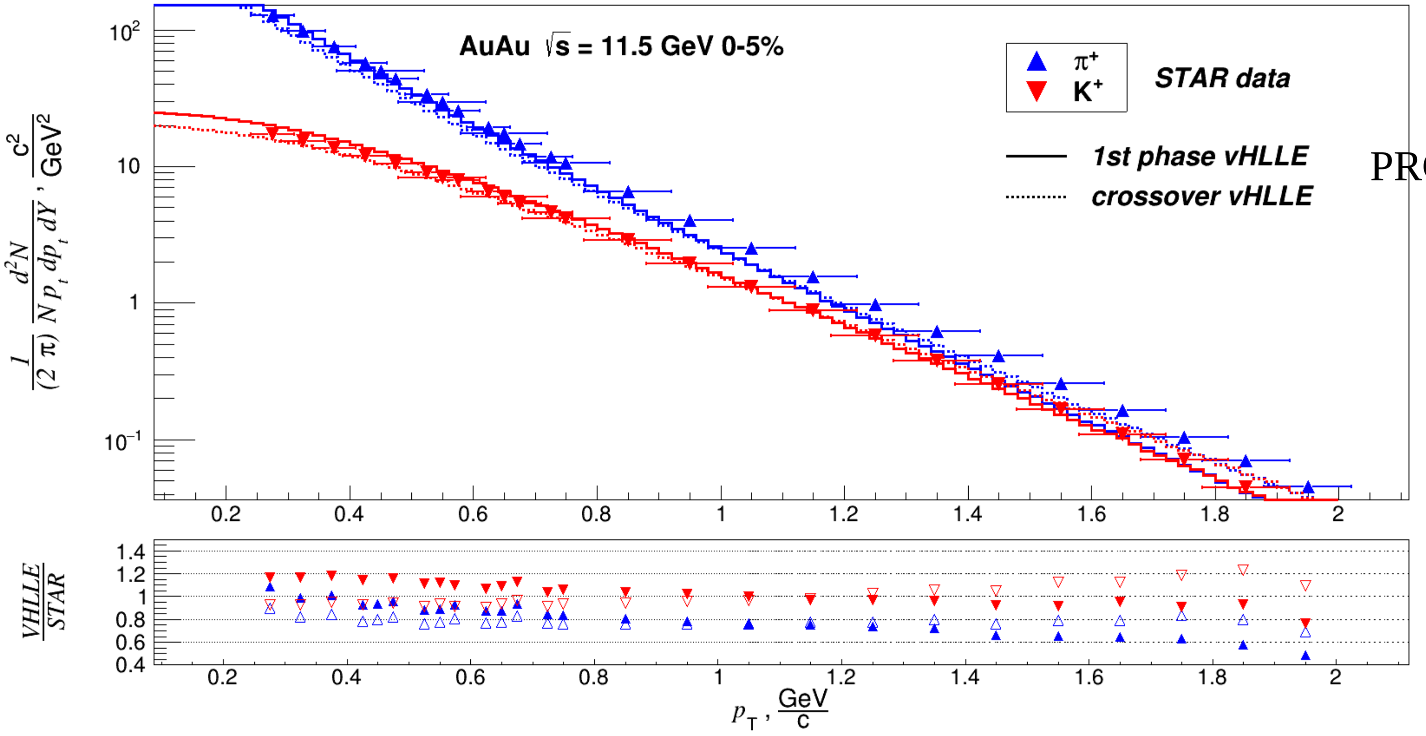
(a) - after hydrodynamic phase

(b) - after cascade



p_T- spectra of π and K with vHLLE+UrQMD

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



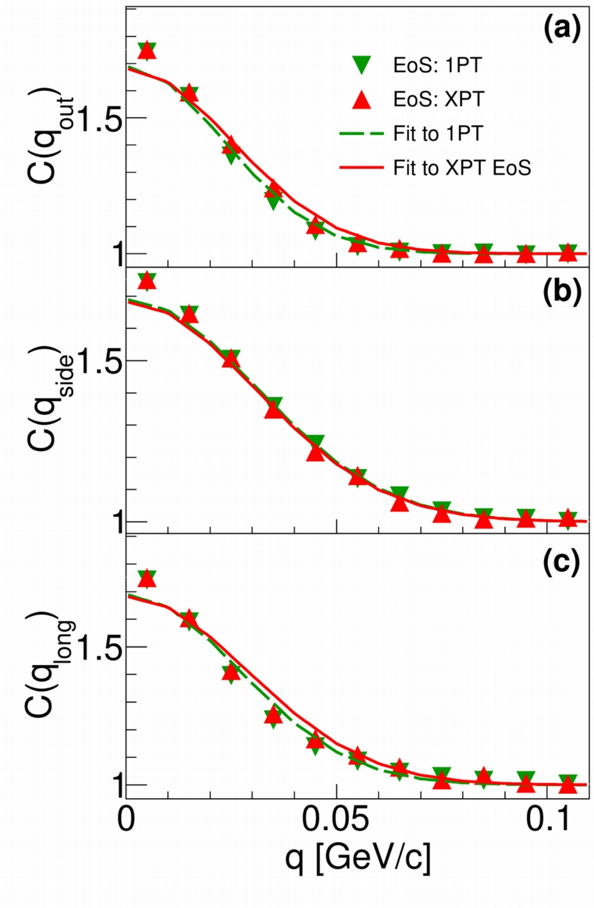
PRC 91, 064901 (2015)

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

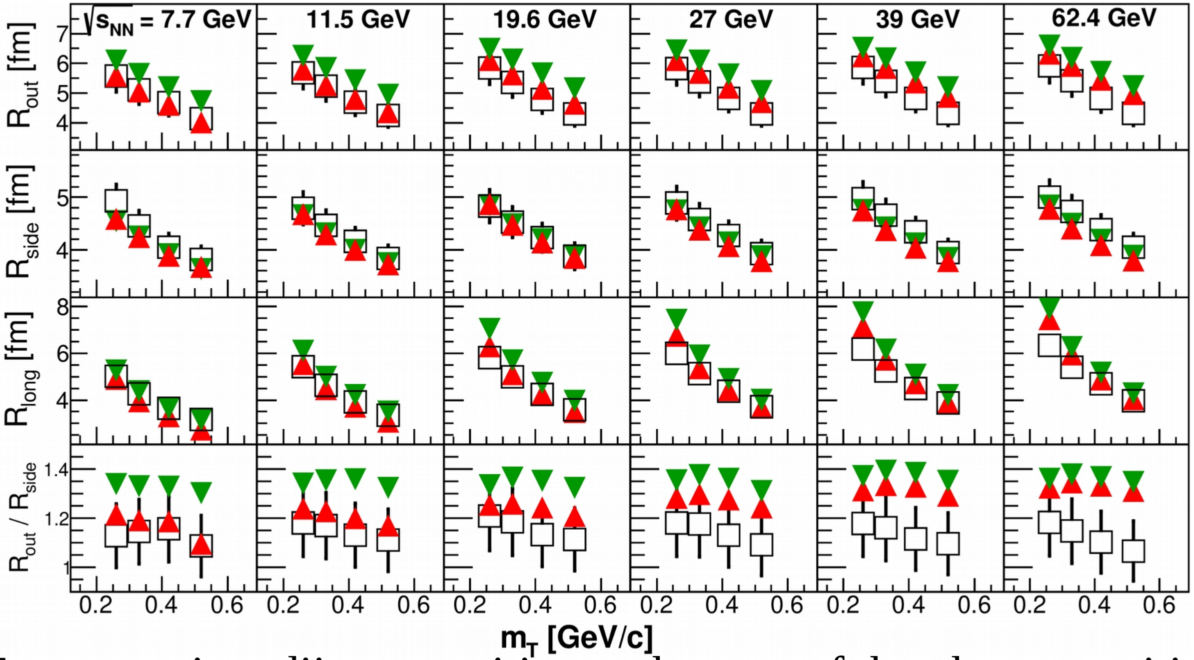
- vHLEE+UrQMD model with both EoS describe reasonably soft part of p_T-spectra of pions and kaons

3D Pion radii versus m_T with vHLLE+UrQMD

Model CF



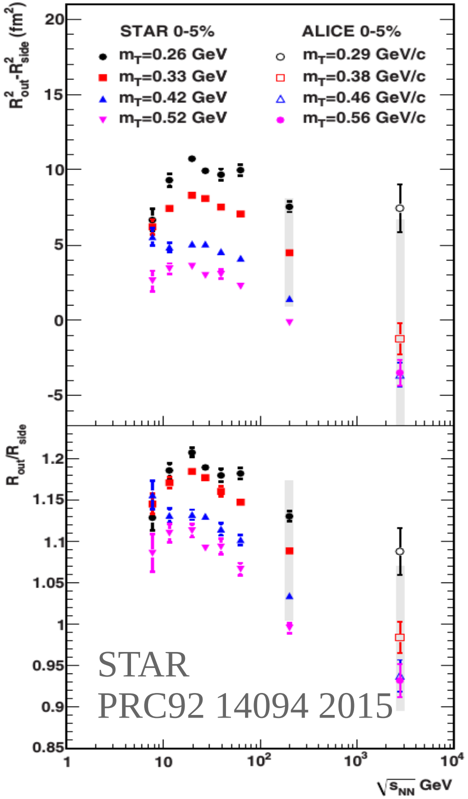
Comparison of extracted radii with the STAR data [PRC 96, 024911(2017)]



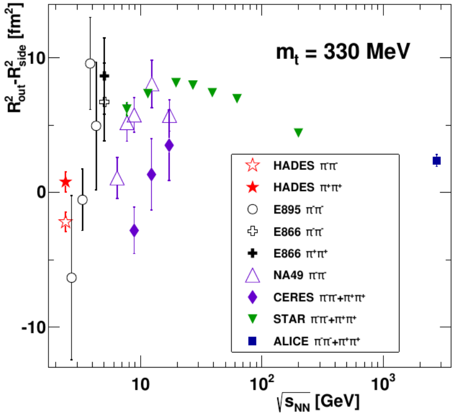
- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS does better job at lowest collision energies.
- R_{out} (XPT) at high energies and R_{out} (1PT) at all energies are slightly overestimated
- $R_{out,long}$ (1PT) > $R_{out,long}$ (XPT) by value of ~1-2 fm.

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

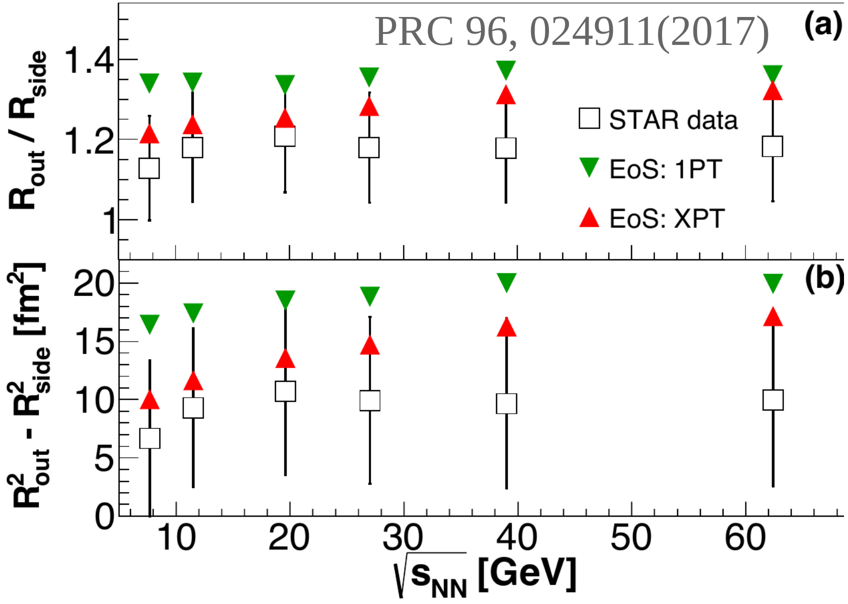
Exp. data: R_{out} /R_{side} and R^2_{out} - R^2_{side} as a function of $\sqrt{s_{NN}}$ at a fixed m_T demonstrate a wide maximum near $\sqrt{s_{NN}} \approx 20$ GeV



HADES arXiv:1910.07885



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

Kaon correlation functions with vHLLE+UrQMD (NEW!)

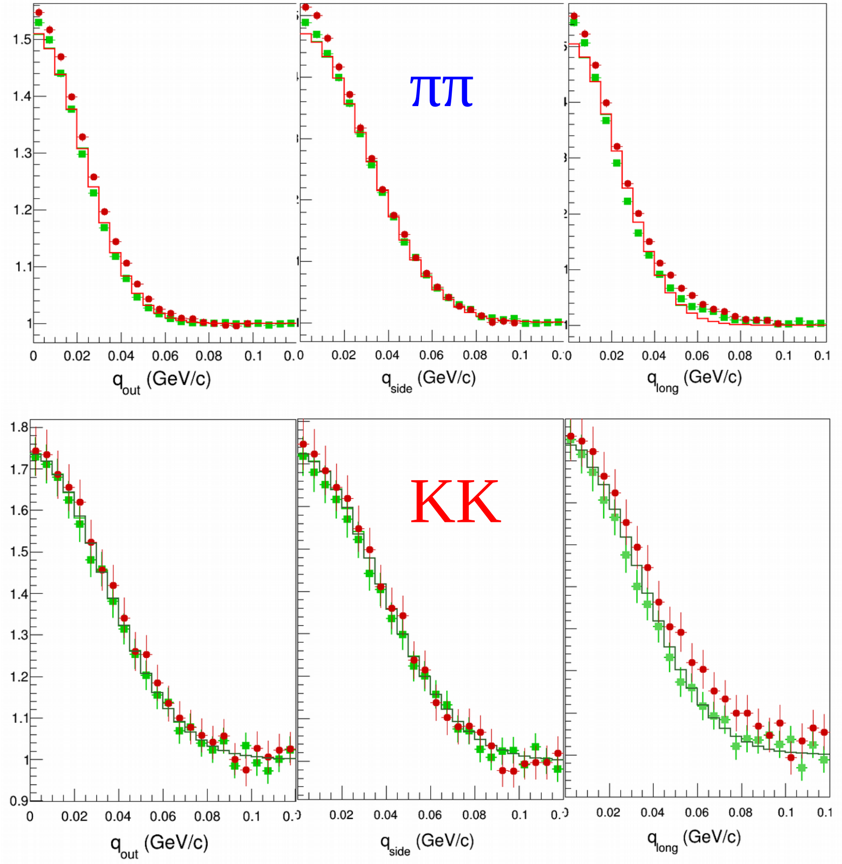
Analysis:

- MDP femto package (see Grigory talk)
- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- $N_{events} \approx 4 \cdot 10^5$ 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

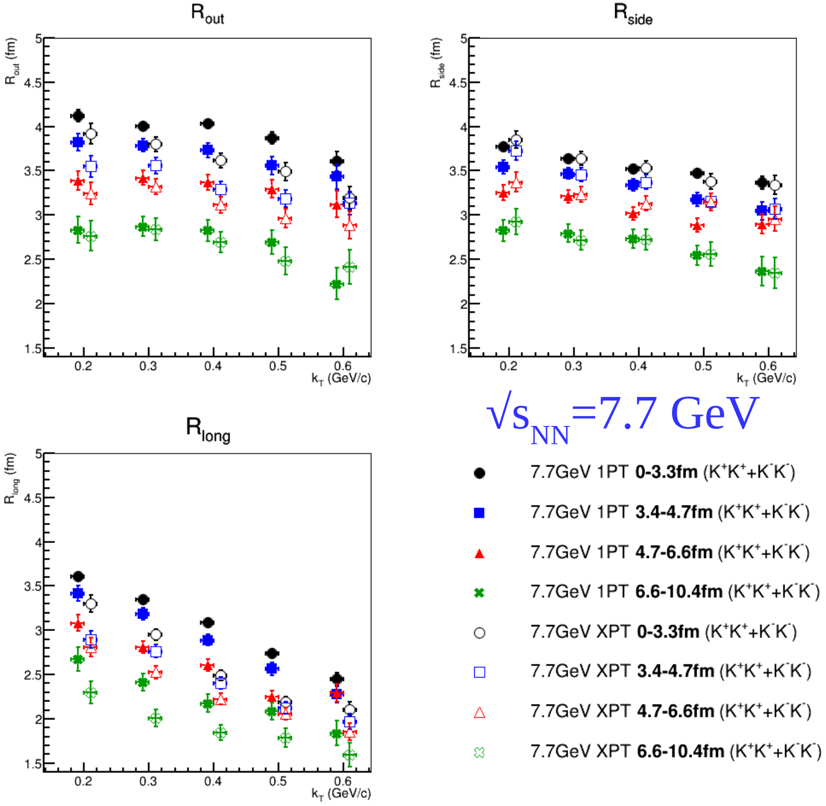
- XPT CF projections on long direction are visibly wider than 1PT especially for kaons → measurable with MPD

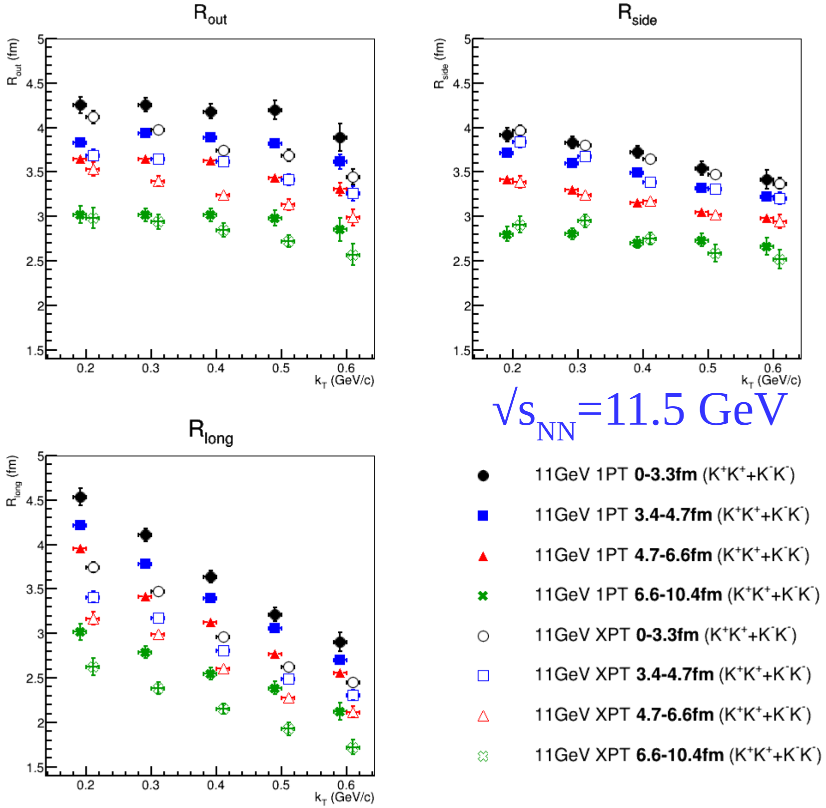
1PT -green dots; XPT – red dots



R vs. k_T with vHLLE $\sqrt{s_{NN}}$=7.7 and 11.5 GeV (preliminary)

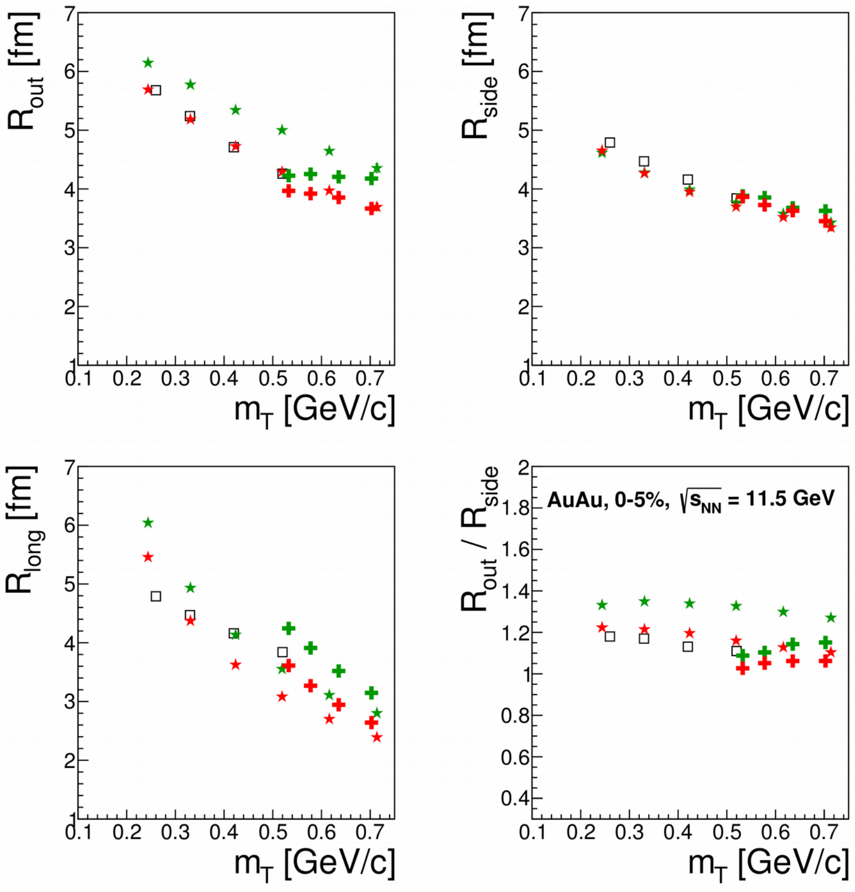
- Radii for 0-5, 5-10, 10-20 and 20-50% centrality and 1PT, XPT EoS are shown
- R decreases with kT and centrality
- Significant difference between XPT and 1PT in R out and long ($R_{XPT} < R_{1PT}$)





Radii π and K vs. mT with vHLLE+UrQMD

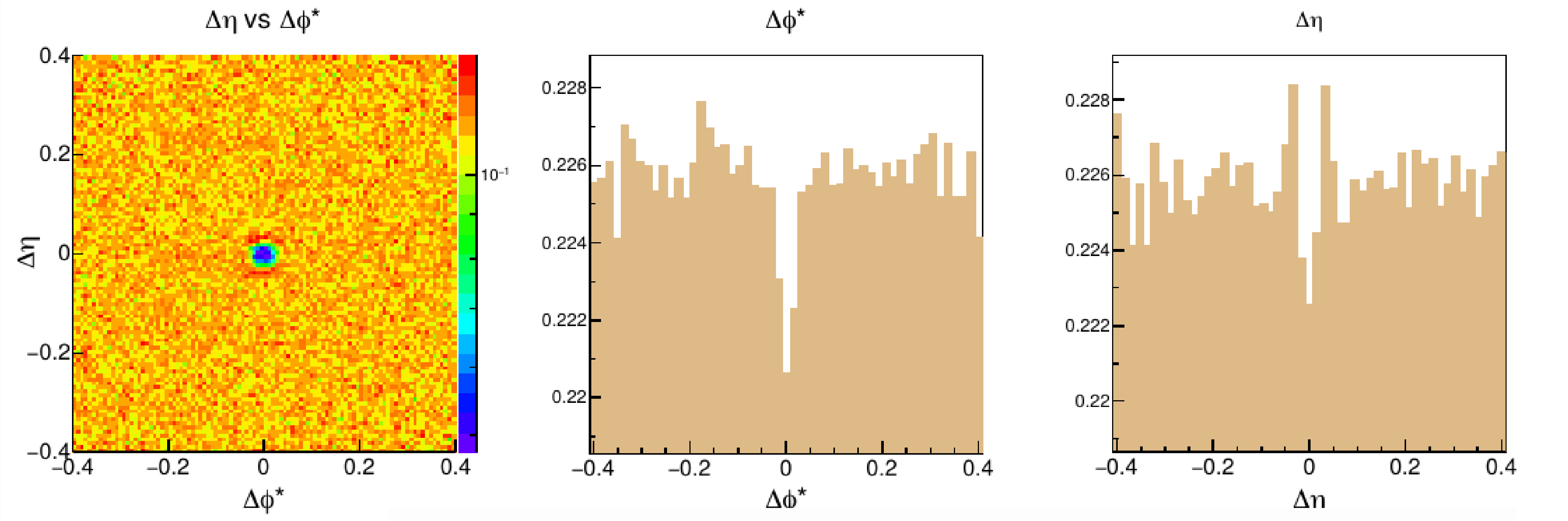
1PT -green dots; XPT – red dots



- Au+Au (0-5%), $\sqrt{s_{NN}}$ = 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

Two track effects (merging/splitting)

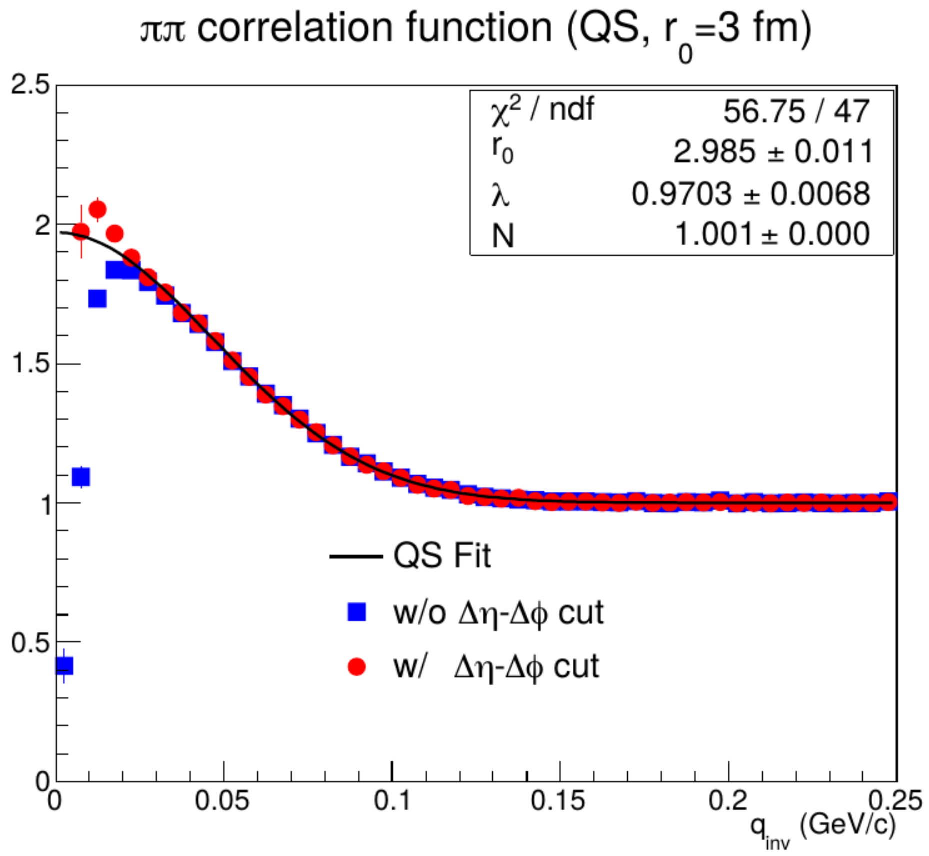


Δη-Δϕ* cut:

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

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

Reconstructed correlation function



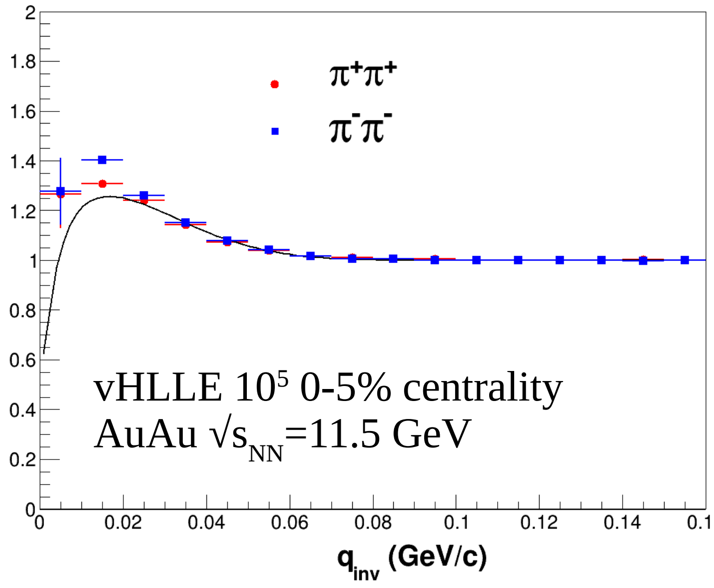
- UrQMD AuAu 11 GeV reconstructed evnts
- With cut $\Delta\eta<0.04$ and $\Delta\phi^*<0.02$
- Without cut on $\Delta\eta$ and $\Delta\phi^*$
- Pion femtoscopic CF can be correctly reconstructed if two-tracks cuts are applied
- Good knowledge of tracking procedure is necessary

First physics (very preliminary)

- If we will have something like:
- Bi+Bi 10^6 minimum bias events (with highest possible energy)

- pi-pi one dimension correlation function 10^5 (0-10% centrality)
- mT-dependence
- Have to do MC simulations in order to have realistic estimation

- Energy to compare with other experiment (STAR, AGS, …) ?



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 [see Olga's talk]
- New MpdFemto package [see Grigory's talk]
  - Test within MpdRoot
  - Two Track Cut tests (merging, splitting)
  - Finite Momentum Resolution tests
- New miniDST format [see Grigory's talk]
  - 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 [see Olga's talk]

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.

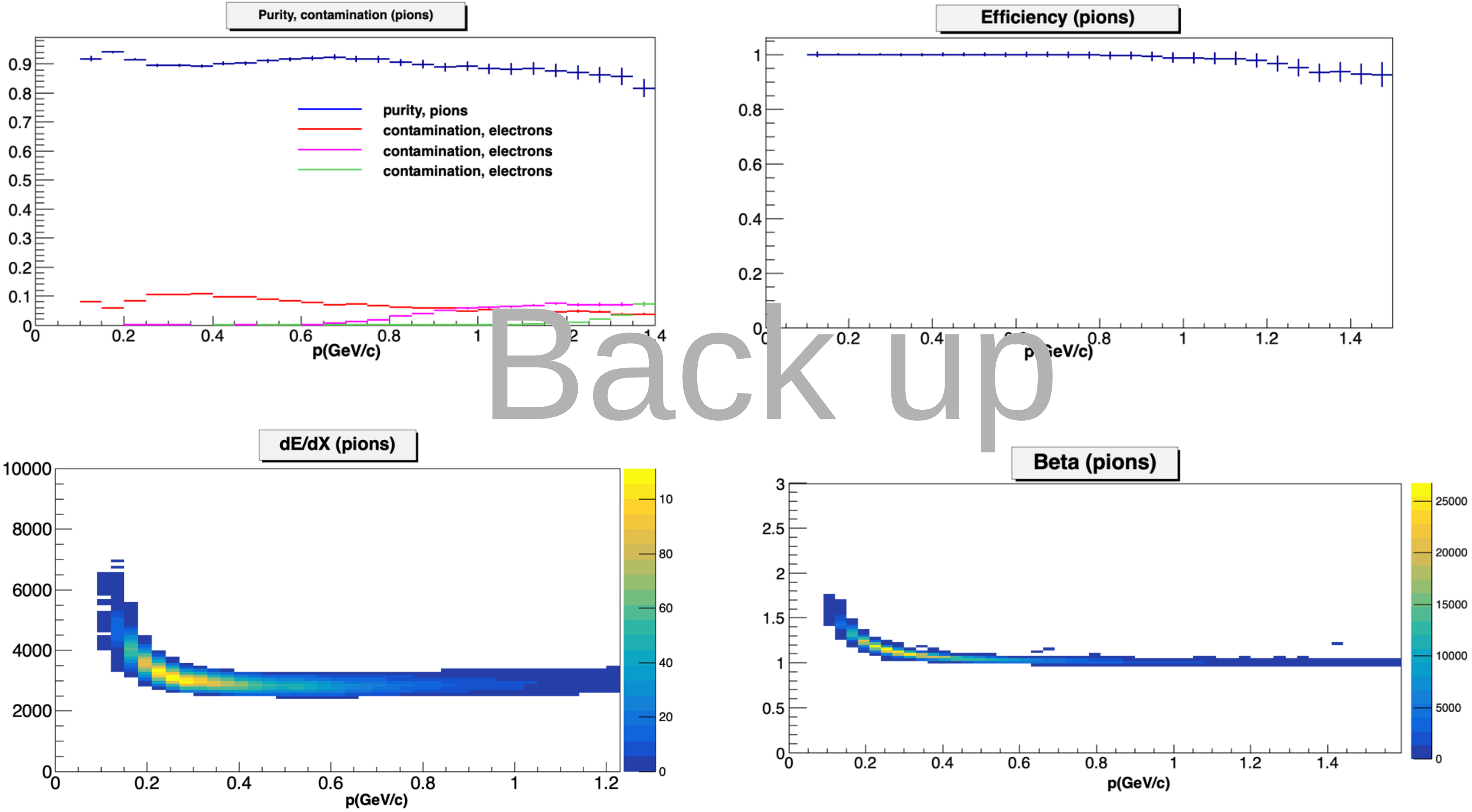
- Development of the data analysis methods and software integrated in the Multi-Purpose Detector (MPD) software environment was performed and will be continued

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

Thank you for attention!

Backup

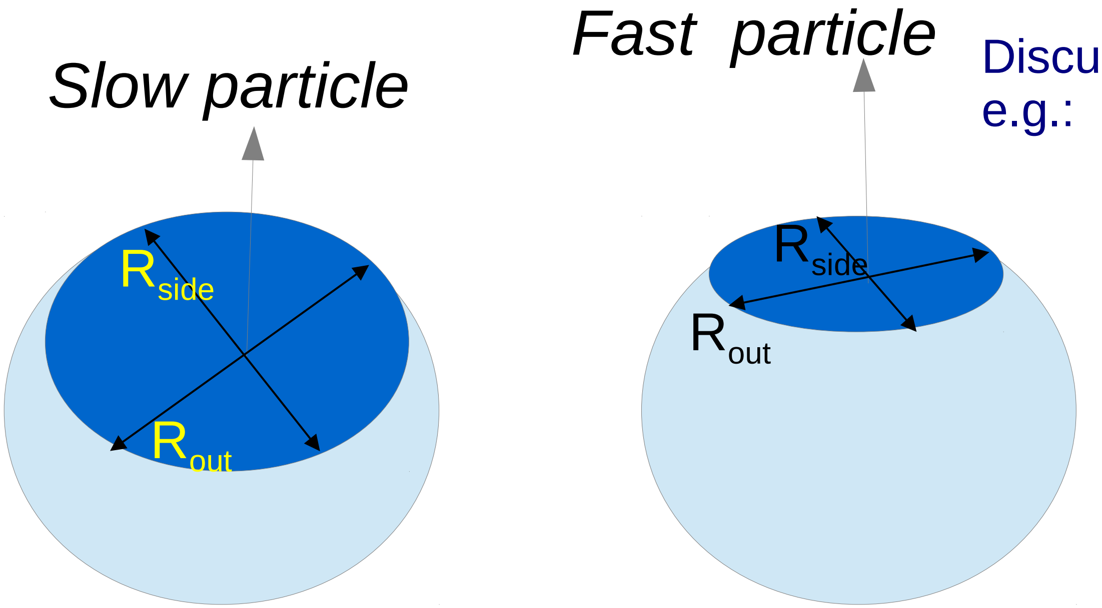
MPD response for femtoscopy(standard MPD PID)



Back up

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

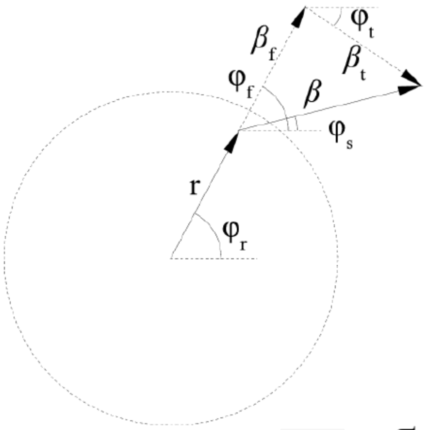
$R_{long} = \tau\,(T/m_T)^{1/2}$

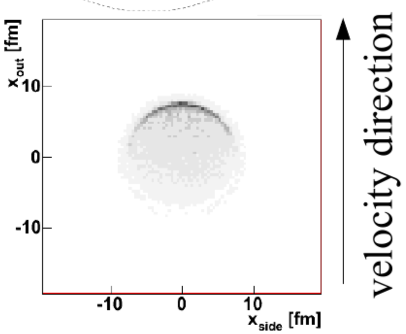
$R^2_{out} \sim R^2_{side} + 1/2(T/m_T)^2\beta_T^2\tau^2$

Femtoscopy with expanding source

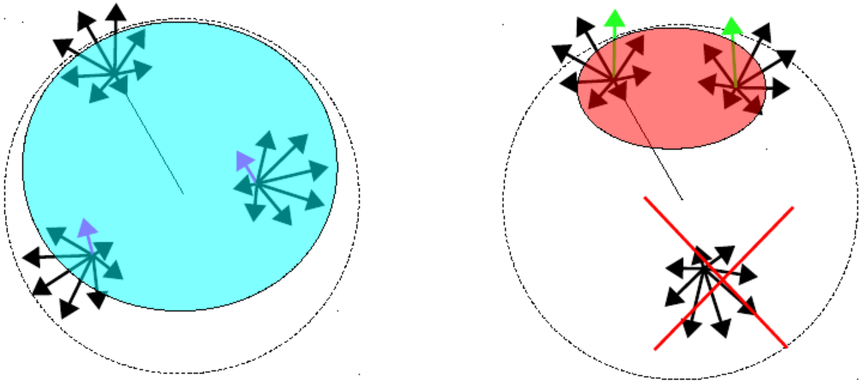
Interference probes only parts of the source at close momenta – **homogeneity regions.**

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

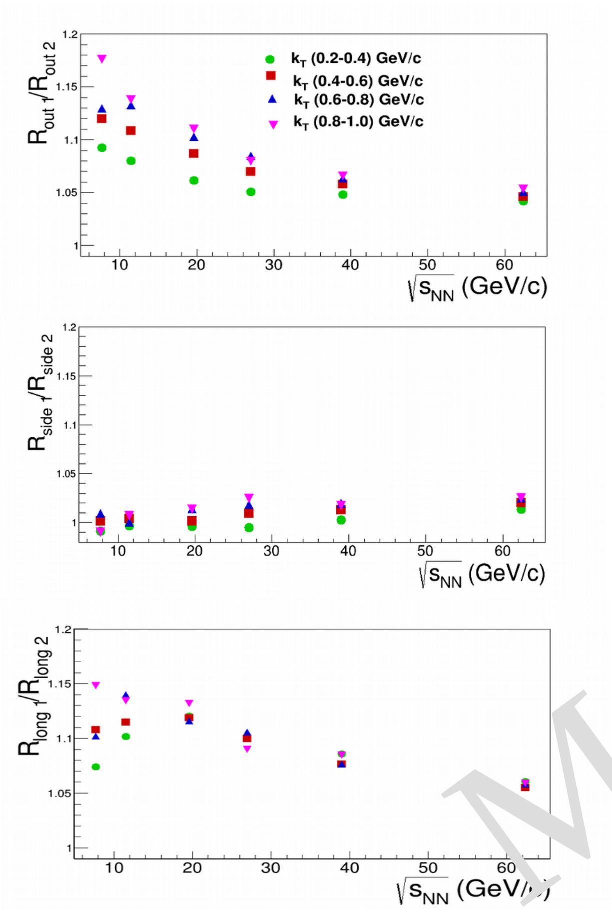




- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source



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