



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



Femtoscopia correlations with MPD at NICA

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



*P. Batyuk¹, M. Cheremnova², O. Kodolova², E. Khyzhniak⁴,
L. Malinina^{1,2}, K. Mikhaylov^{1,3}, G. Nigmatkulov⁴, G. Romanenko²*

¹ Joint Institute for Nuclear Research, Dubna, Russia

² Skobeltsyn Research Institute of Nuclear Physics, Moscow State University, Moscow, Russia

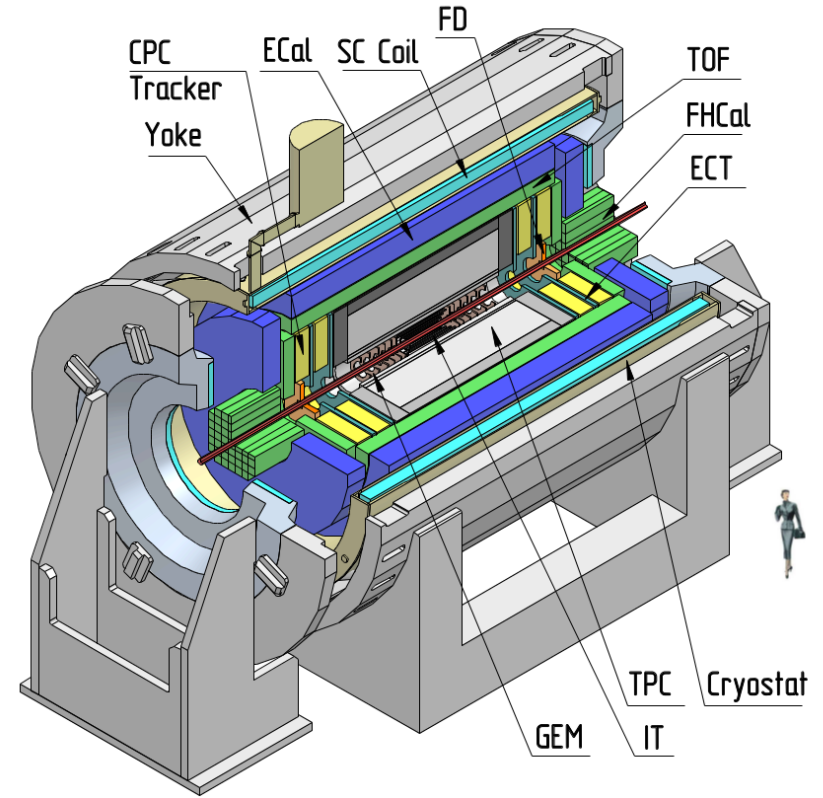
³ NRC Kurchatov Institute – ITEP, Moscow, Russia

⁴ National Research Nuclear University MEPhI, Moscow, Russia



Outline

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



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 vHLLÉ 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

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

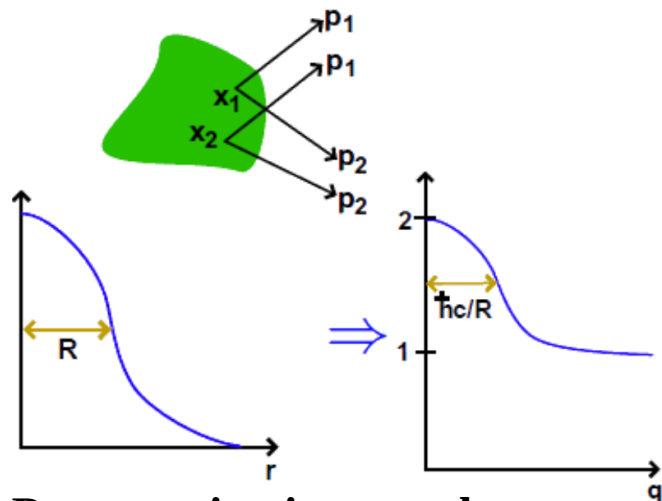
Goals:

- 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 (**ongoing**)

Femtoscscopy



Correlation femtoscopy :

Measurement of space-time characteristics \mathbf{R} , \mathbf{ct} 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:
$$C(q_{inv}) = 1 + \lambda e^{-R^2 q_{inv}^2}$$

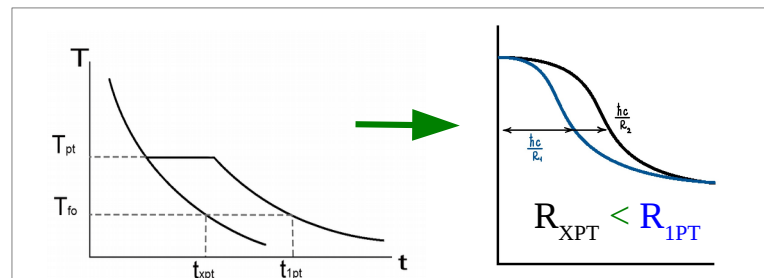
R – Gaussian radius in PRF,

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 \mathbf{v}_T ; side normal to out, long



Motivation

- **Femtoscropy allows one:**

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

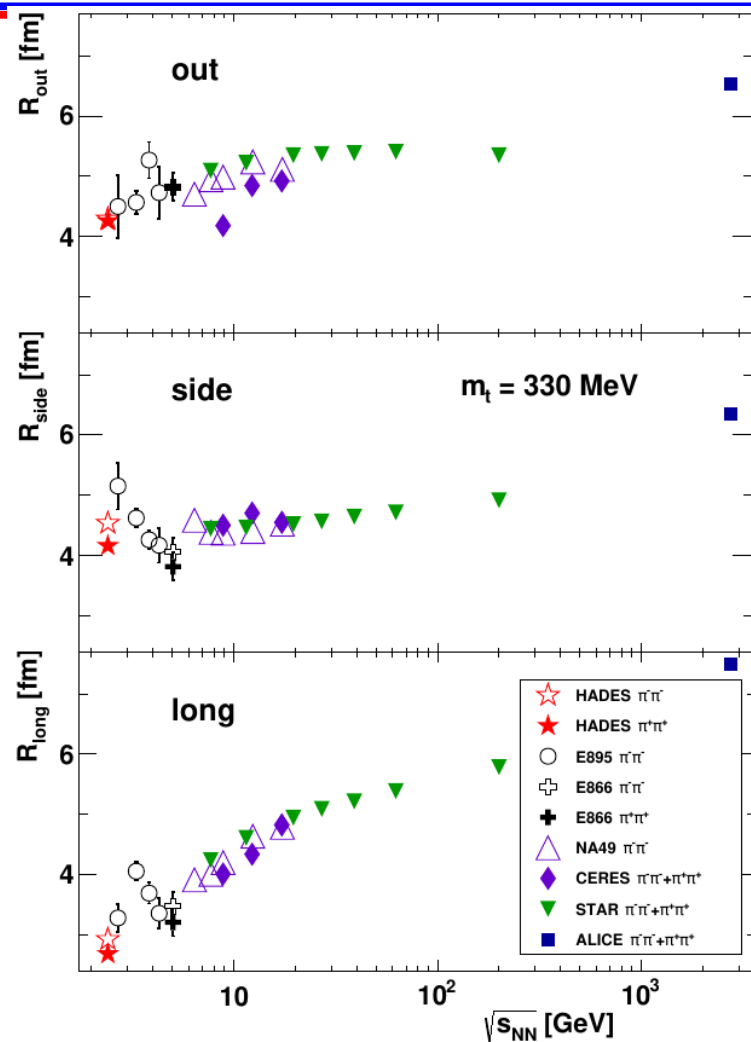
- **RHIC Beam Energy Scan program (BES-I):**

$$\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39 \text{ GeV}$$

- 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: $\sqrt{s_{NN}} = 4 - 11 \text{ GeV}$

- first collider measurements below 7.7 GeV
 - including K and heavier



Femtoscropy with vHLE+UrQMD

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

Pre-thermal phase

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

Hydrodynamic phase

vHLE

(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.

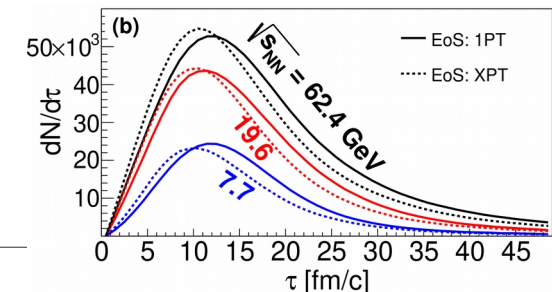
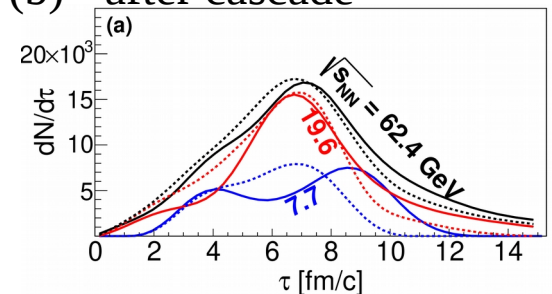
Hadronic cascade

UrQMD

Pion emission time

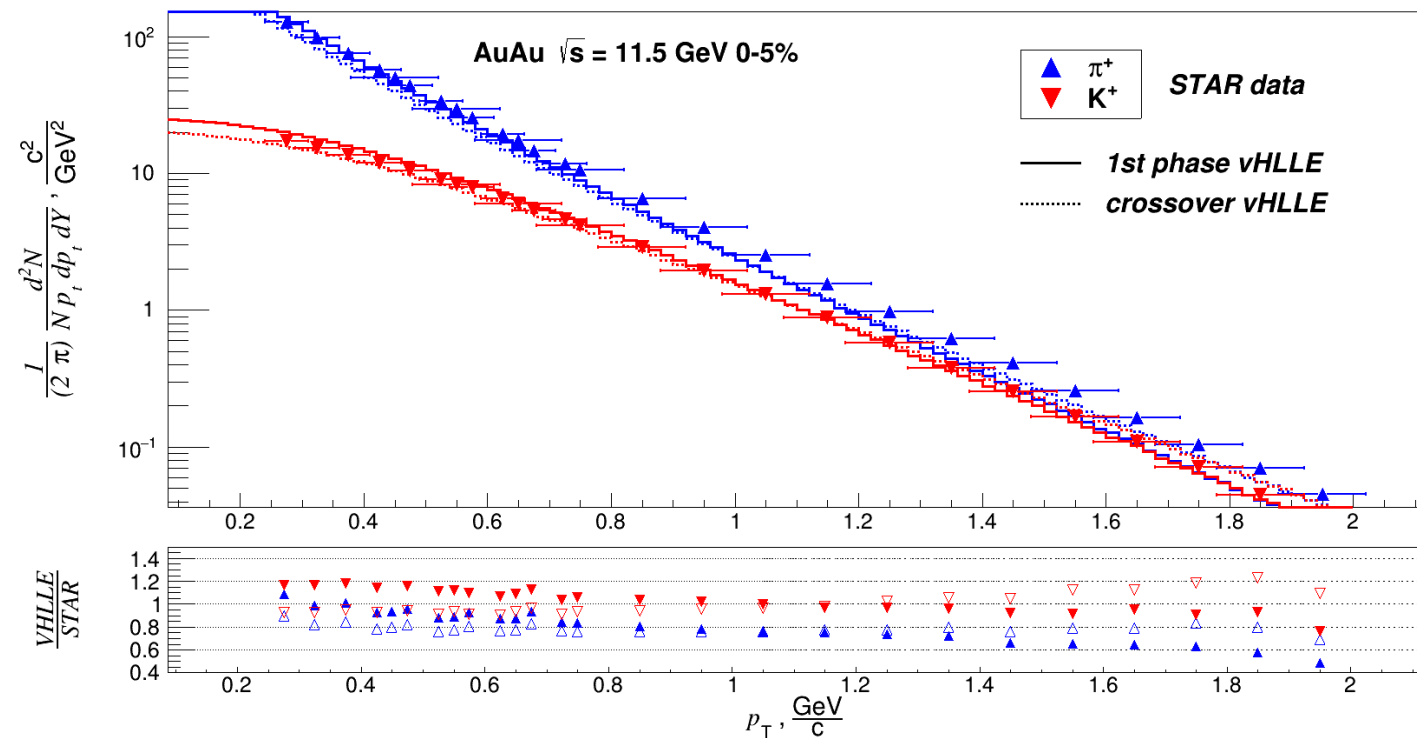
(a) - after hydrodynamic phase

(b) - after cascade



p_T - spectra of π and K with vHLLE+UrQMD

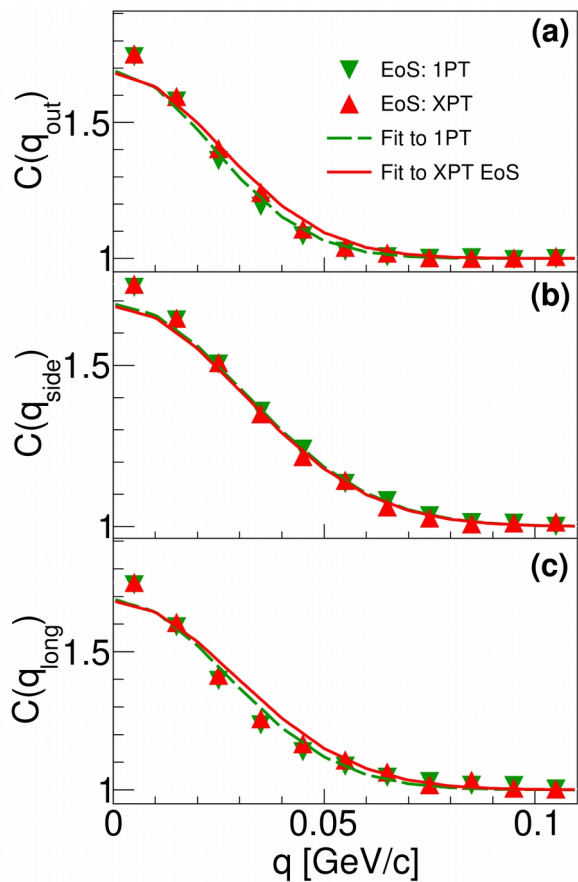
STAR data: PHYSICAL REVIEW C 96, 044904 (2017)



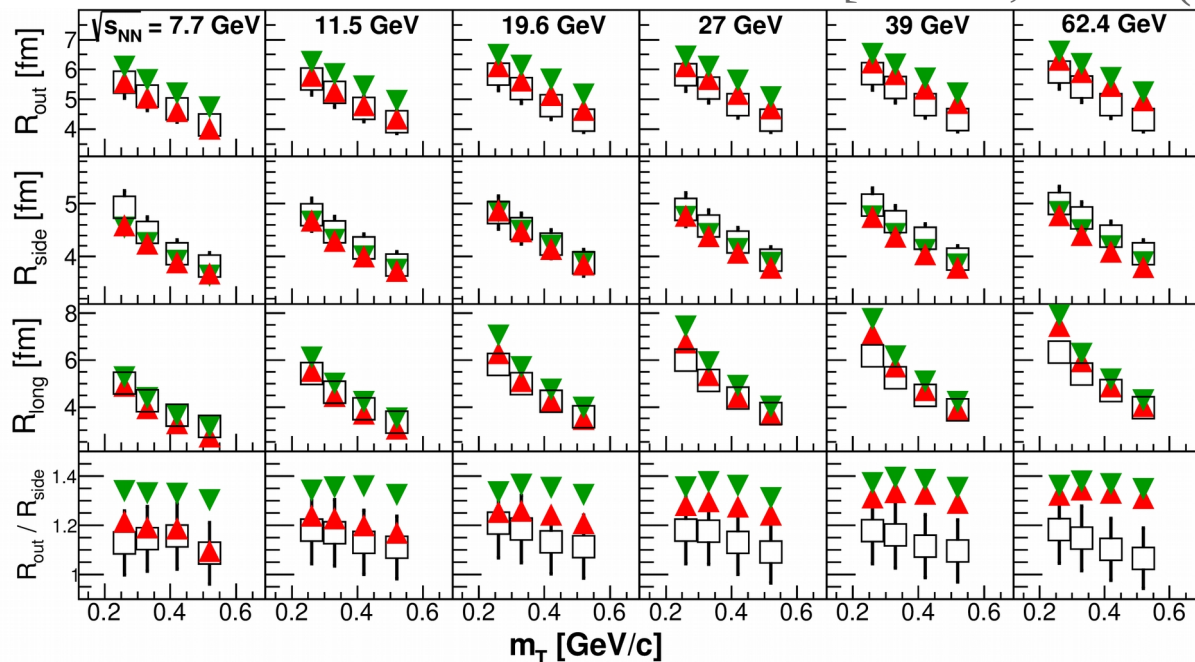
- vHLLE+UrQMD model with both EoS describe reasonably soft part of p_T -spectra of pions and kaons

3D Pion radii versus m_T with ν HLE+UrQMD

Model CF



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

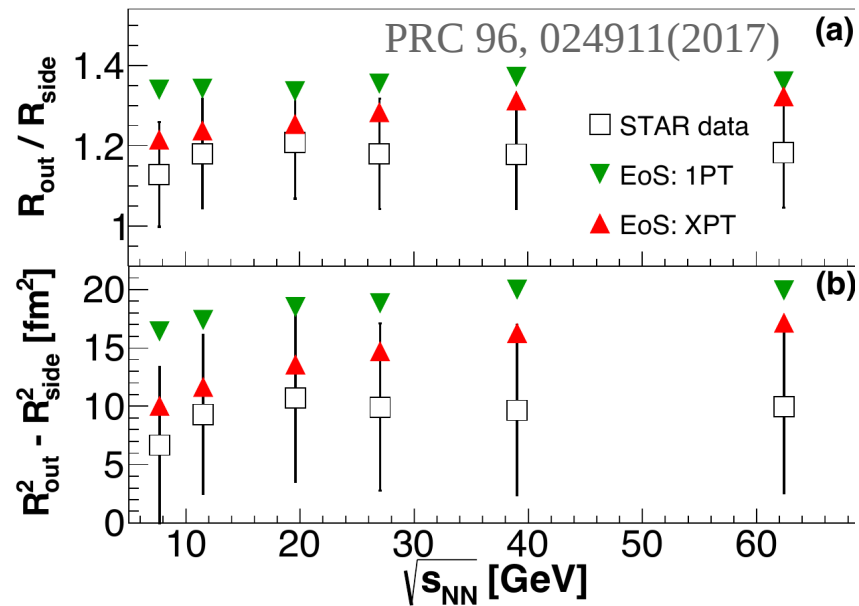
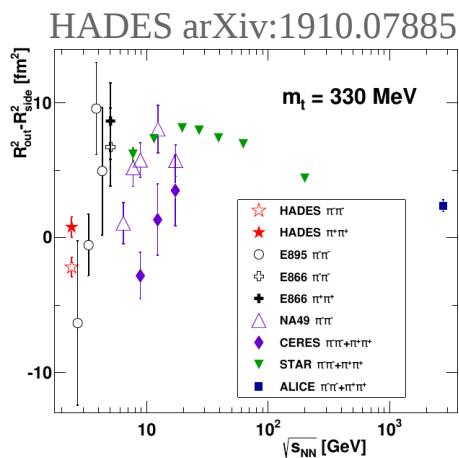
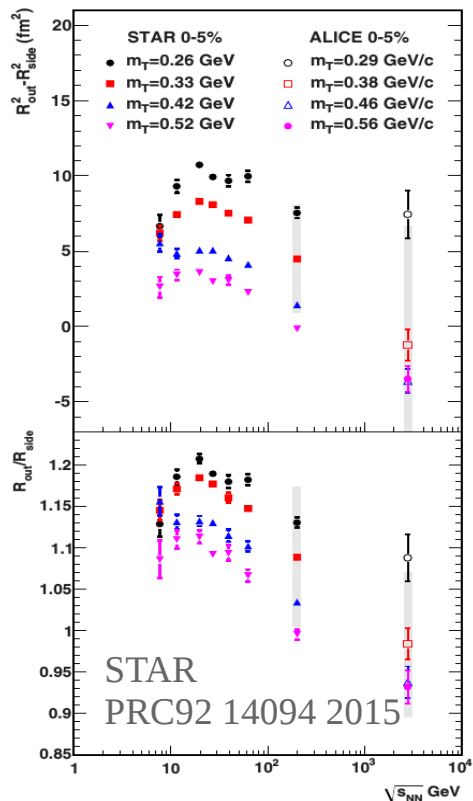


- Femtoscopic radii are sensitive to the type of the phase transition
- **Crossover EoS** does better job at lowest collision energies.
- R_{out} (XPT) at high energies and R_{out} (1PT) at all energies are slightly overestimated
- $R_{out,long}$ (1PT) $>$ $R_{out,long}$ (XPT) by value of $\sim 1-2$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

$R_{\text{out}}/R_{\text{side}}$ with vHLLE + UrQMD model

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

Present vHLLE+UrQMD calculations:

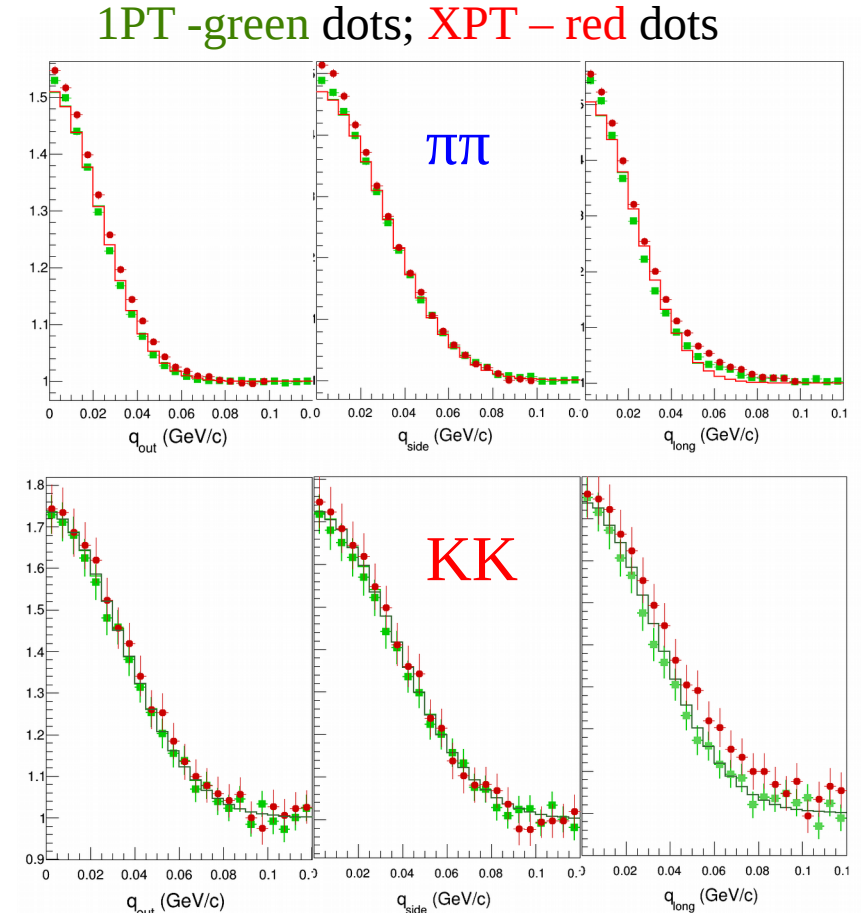


- $R_{\text{out}}/R_{\text{side}}$ (XPT) agrees with almost all STAR data points within rather large systematic errors, while $R_{\text{out}}/R_{\text{side}}$ (1PT) overestimates the data.
- XPT – a monotonic increase in both quantities

Kaon correlation functions with vHLLE+UrQMD (NEW!)

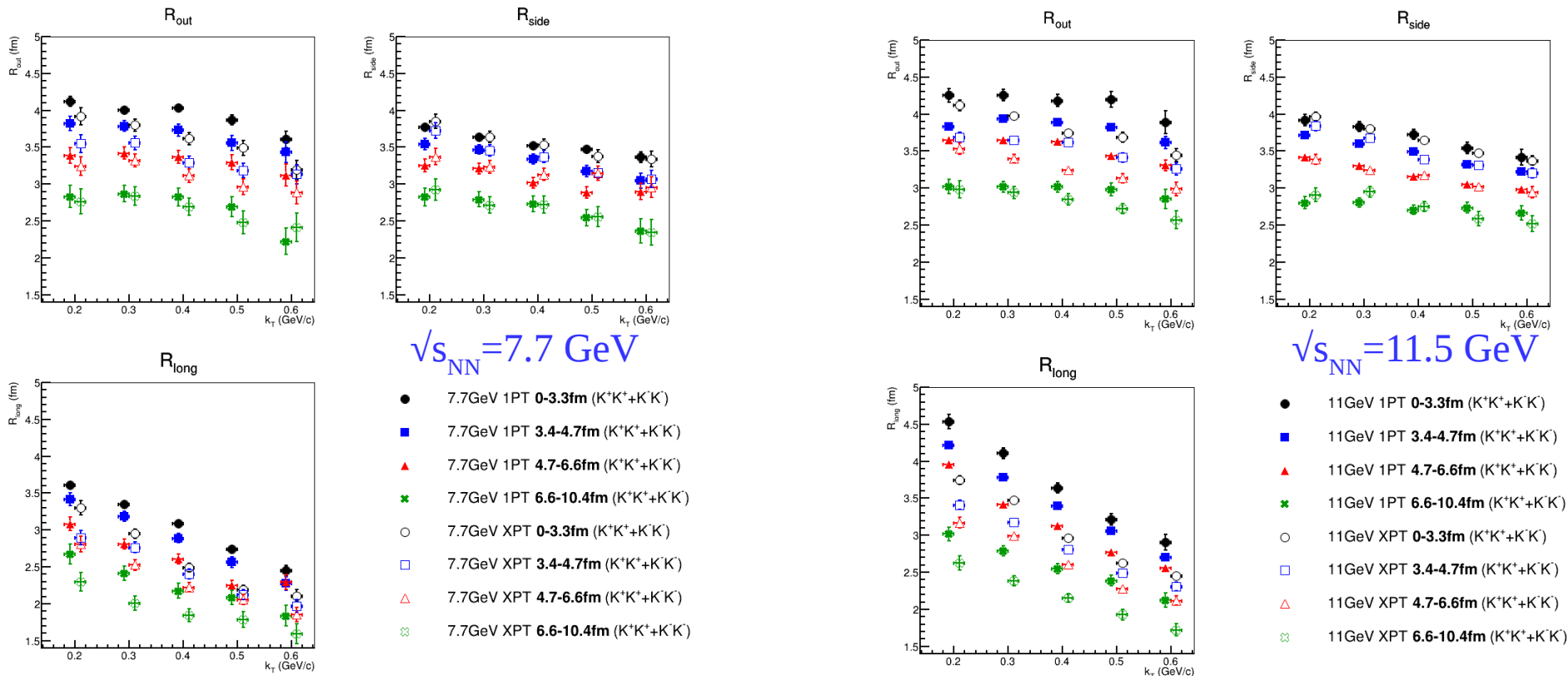
Analysis:

- MDP femto package (see Grigory Nigmatkulov's talk)
 - Au+Au, $\sqrt{s_{NN}} = 11.5$ GeV
 - central events (vHLLE+UrQMD)
 - 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 \rightarrow measurable with MPD



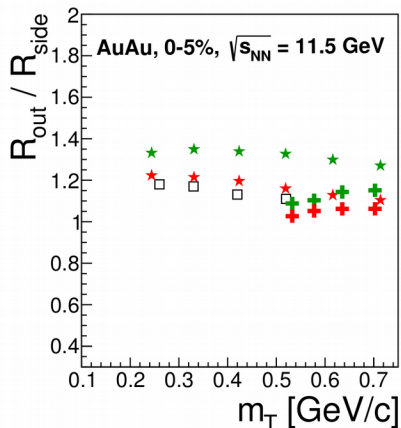
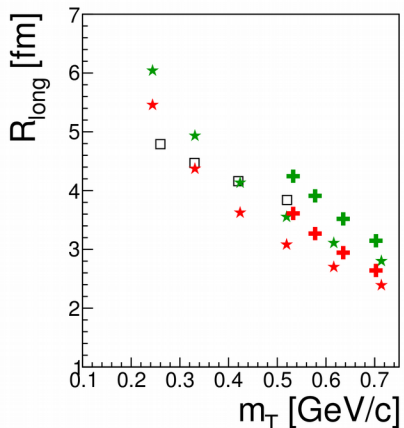
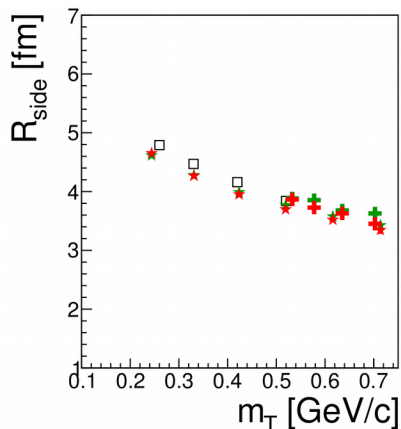
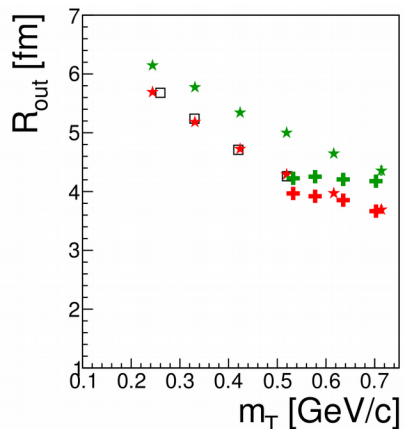
R vs. k_T with vHLLE $\sqrt{s_{NN}}=7.7$ and 11.5 GeV (preliminary)

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



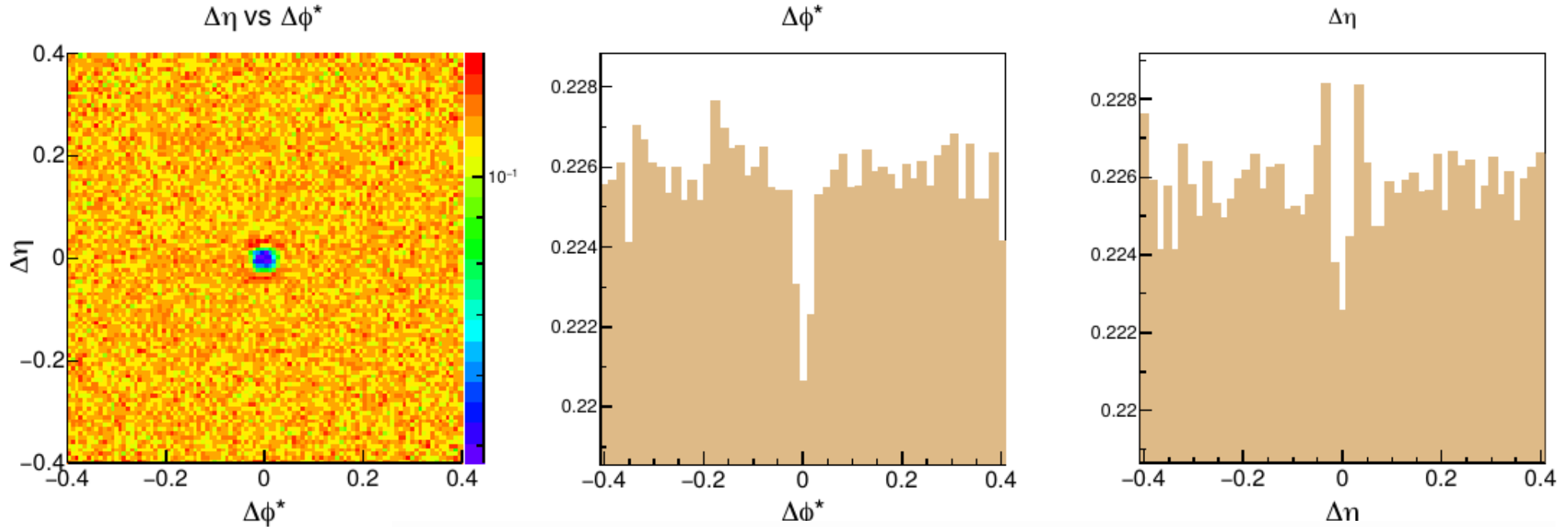
Radii π and K vs. m_T with ν HLE+UrQMD

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 $R_{long}(\pi\pi)$ kaons on average emitted later than pions
- $R_{out}/R_{side}(KK)$ 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

Detector effects: Two-track effects (merging/splitting)

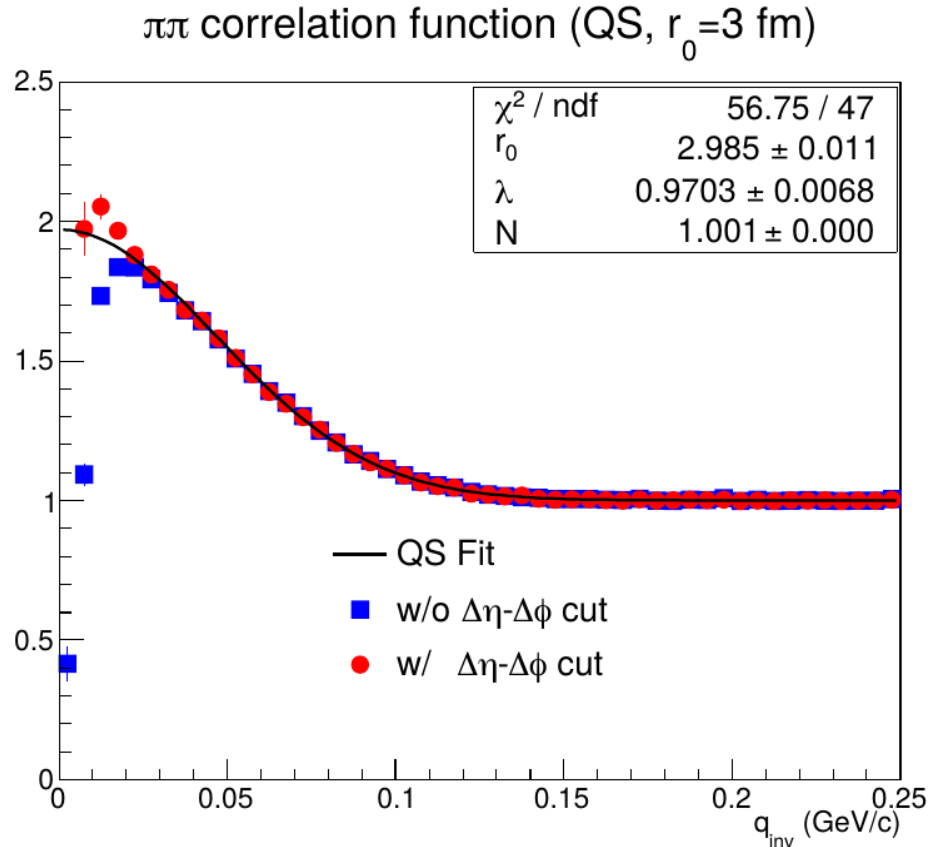


$\Delta\eta$ - $\Delta\phi^*$ cut:

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

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

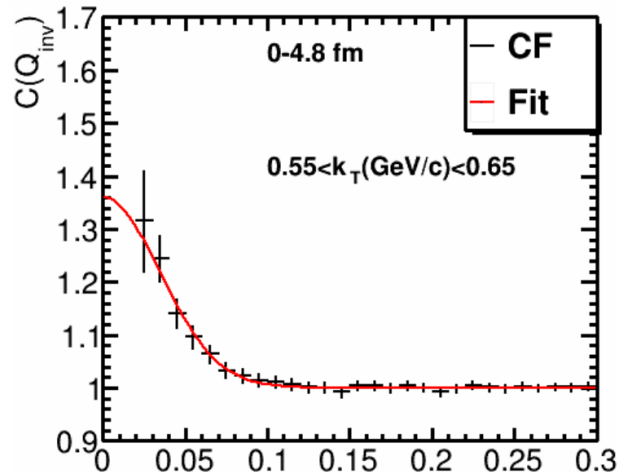
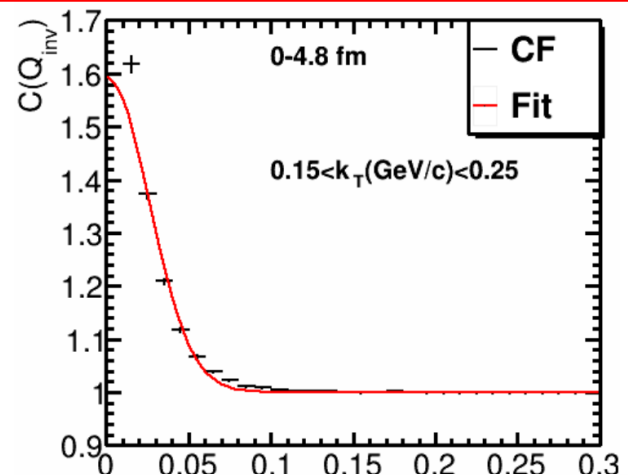
Reconstructed correlation function



- 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-track cuts are applied
- Good knowledge of tracking procedure is necessary

First physics (very preliminary, UrQMD MC)

- First look with UrQMD
- Bi+Bi $\sqrt{s_{NN}} = 7.7$ GeV, 200K “good” events 0-10% centrality
- $\sqrt{s_{NN}} = 7.7$ GeV \rightarrow STAR data exists
- $\pi\pi$ one dimension correlation function for a few k_T ranges
0.15-0.25, 0.25-0.35, ..., 0.55-0.65 GeV/c
- Possible to study m_T dependence of 1D femtoscopic radius
for a few centrality bins
- Need to have full simulation chain
(generator \rightarrow GEANT \rightarrow reconstruction) for realistic estimations



2020 plans

- Simulation of ion-ion collisions with different models and different EoS for $\sqrt{s_{NN}}=4-11\text{GeV}$ energies to be continued
 - 3d CF analysis of $\pi\pi$ and KK
 - m_T dependence within MPD detector acceptance
 - Factorial moment study [see Olga Kodolova's talk]
- New MpdFemto package [see Grigory Nigmatkulov's talk]
 - Test within MpdRoot
 - Two Track Cut effects study (merging, splitting)
 - Finite Momentum Resolution tests
- New miniDST format [see Grigory Nigmatkulov's talk]
 - Compact reconstructed and generated information (20 times less than MpdDST)
 - Event, track, TOF, ECal, FHCAL information
 - MiniDST created on-the-fly
- Software for factorial moment study will be developed [see Olga Kodolova's talk]

Conclusions

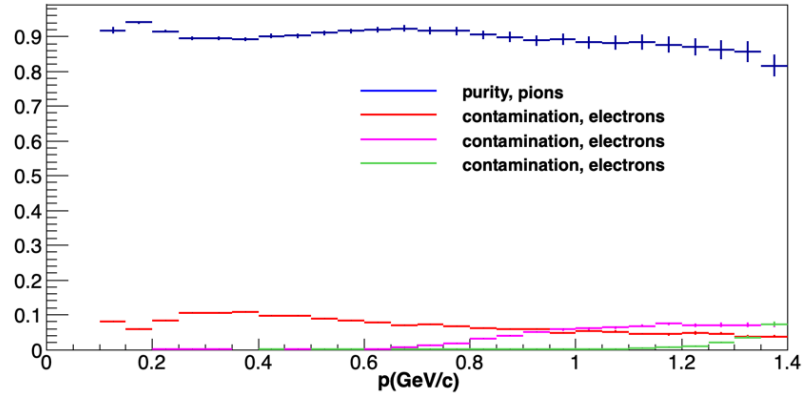
- Study of collective effects and dynamics of quark-hadron phase transitions via femtoscopic correlations of hadrons and factorial moments of particle multiplicity at NICA energies was performed
- First results look promising and this study is planned to be continued.
- Development of the data analysis 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!

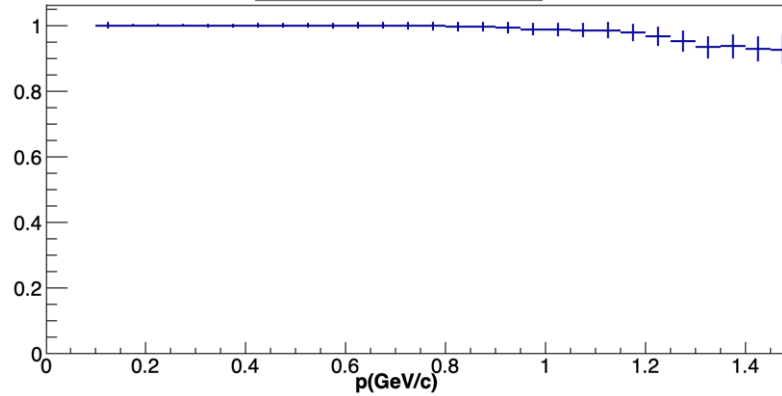
Backup

MPD response for femtoscopy(standard MPD PID)

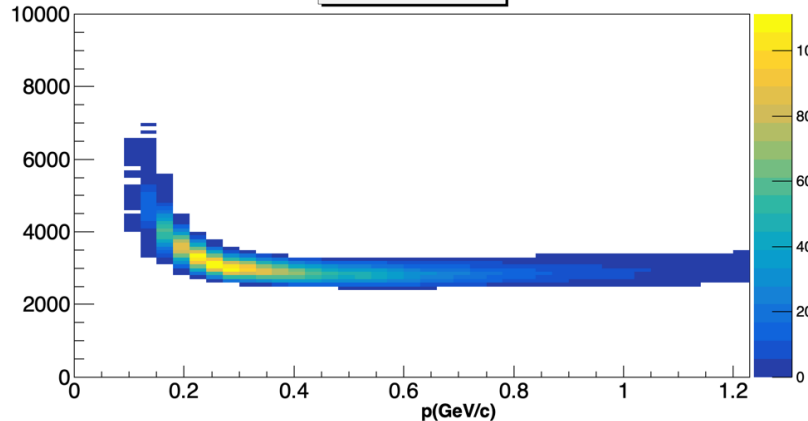
Purity, contamination (pions)



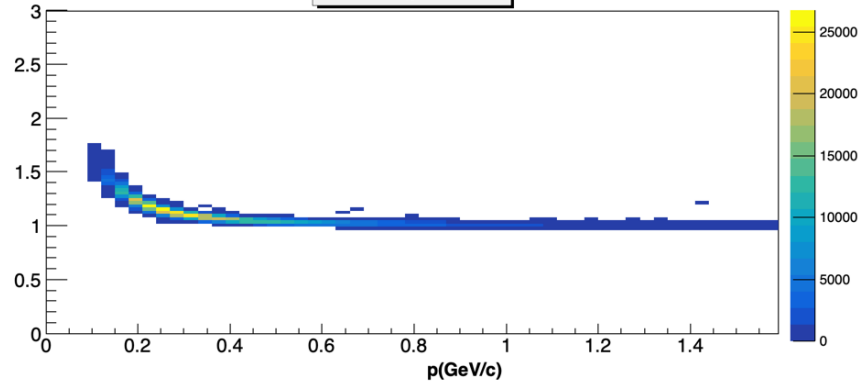
Efficiency (pions)



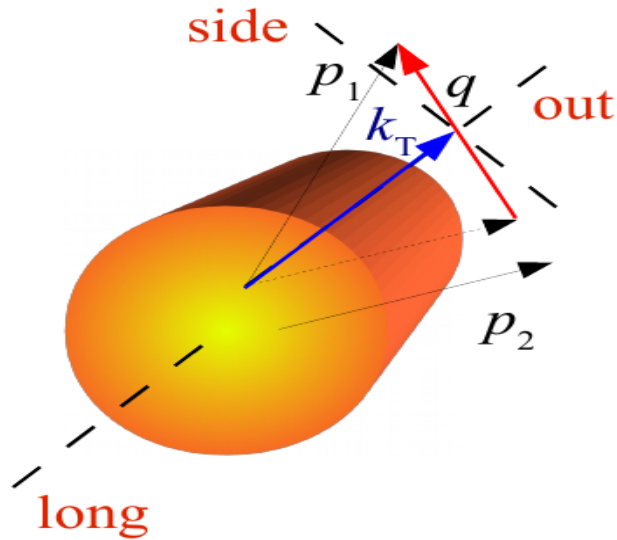
dE/dX (pions)



Beta (pions)



LCMS reference frame



$$m_T = \sqrt{k_T^2 + m_\pi^2}$$

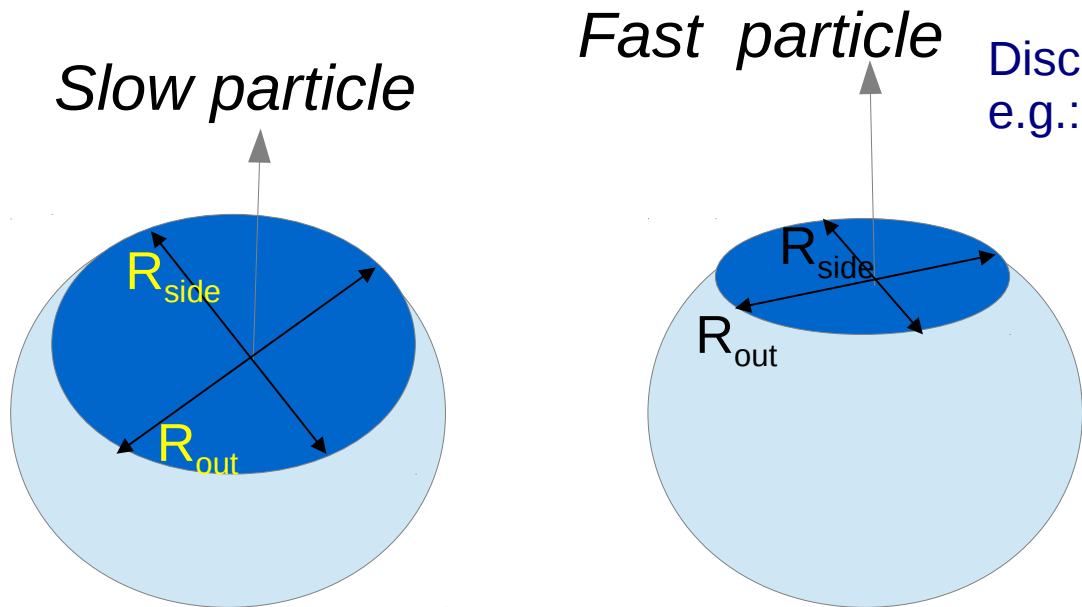
Longitudinally Co-Moving System (LCMS):

$$P_{1,long} = -P_{2,long}$$

- For charged pions measurement in 3 dimensions, giving 3 independent sizes in Longitudinally Co-Moving System
- The Bertsch-Pratt decomposition of q :
 - Long along the beam: sensitive to longitudinal dynamics and evolution time
 - Out along k_T : sensitive to geometrical size, emission time and space-time correlation
 - Side perpendicular to Long and Out: sensitive to geometrical size
- For statistically challenged analyses, measurement in one dimension (giving only one size) in Pair Rest Frame

Femtoscscopy with expanding source $\rightarrow m_T$ -dependence

- $\mathbf{x-p}$ correlations \rightarrow 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 \rightarrow 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

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

β_T collective transverse flow
assuming a longitudinal boost
invariant expansion

$$R_{\text{long}} \sim \tau (T/m_T)^{1/2}$$

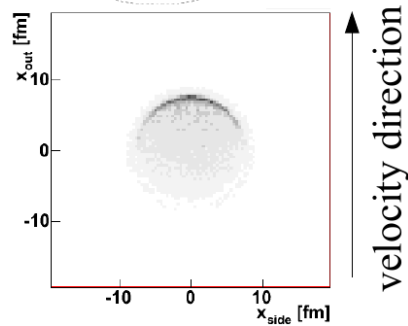
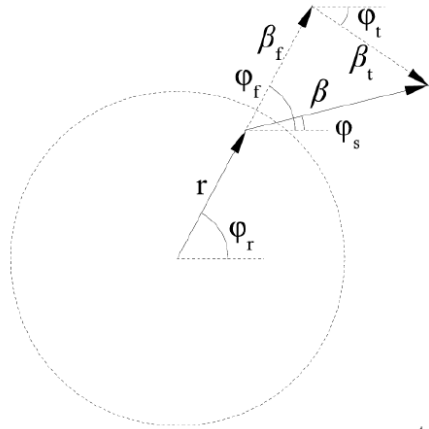
$$R_{\text{out}}^2 \sim R_{\text{side}}^2 + 1/2 (T/m_T)^2 \beta_T^2 \tau^2$$

Femtoscscopy 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

