VIth MPD Collaboration meeting
28-30 October 2020,JINR, Dubna

Femtoscopy correlations with MPD at NICA

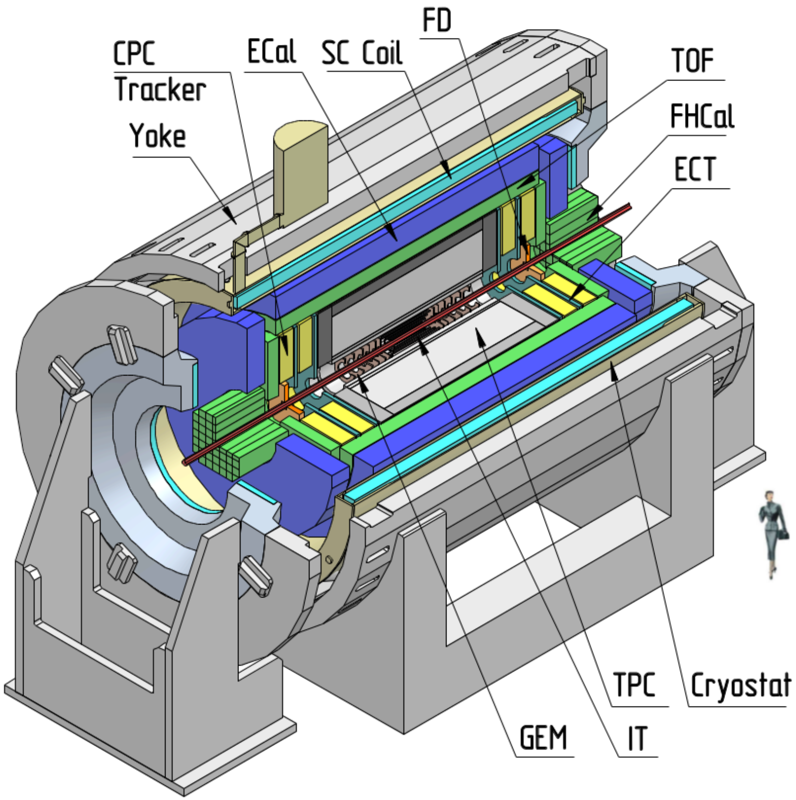
on behalf of PWG3 (Correlations and Fluctuations)
Supported by the RFBR grant 18-02-40044

P. Batyuk[1], M. Cheremnova[2], O. Kodolova[2], E. Khyzhniak[4],
L. Malinina[1,2], K.Mikhaylov[1,3], G.Nigmatkulov[4], G. Romanenko[2]

[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 model
- New kaon results
- Tests with reconstructed data
- Factorial Moments
- Femto software
- Conclusions



Activities within RFBR grant 18-02-40044

- Three Master and 1 PhD student in Femto group

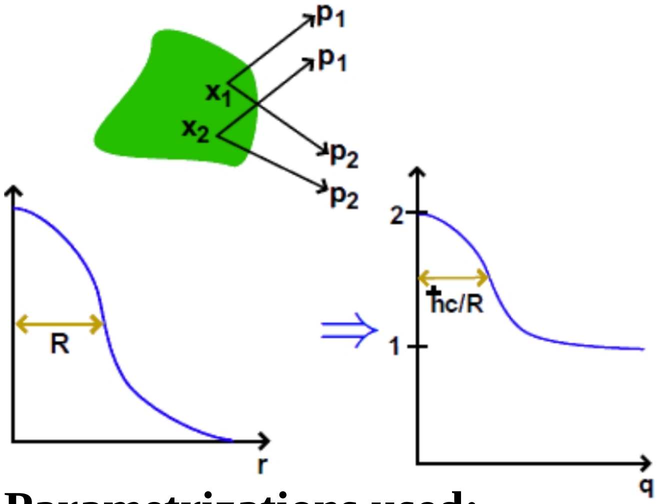
- PWG3 Meetings: about 20 events(2020) → https://indico.jinr.ru/category/346/

- MPD Physics Seminars(+3 in 2019):
  G.Nigmatkulov. «The MpdMiniDst data format (Part 1)». 16 July 2020
  G.Nigmatkulov. «The MpdMiniDst data format (Part 2)». 6 Aug 2020

- Conferences(+3 in 2019):
  ICPPA-2020: 3 talks
  NUCLEUS-2020: 1 talk
  RFBR Grants for NICA: 3 talks
  VI MPD Collabration meeting: 2 talks

- Publications(+1 in 2019):
  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
  + 5 proceedings(ICPPA, NUCLEUS and RFBR) will be published

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

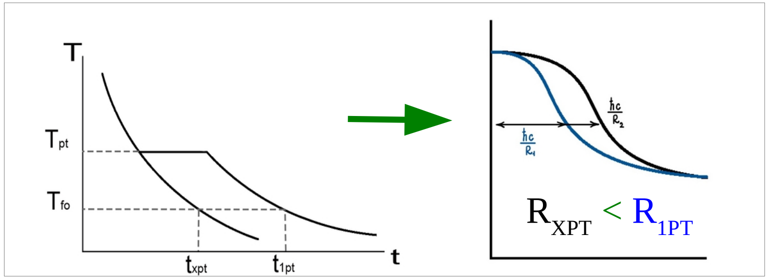
experiment: $$C(q)=\frac{S(q)}{B(q)},q=p_1-p_2$$

S(*q*) – distribution of pair momentum difference from same event
B(*q*) – reference distribution built by mixing different events

Parametrizations used:

1D CF: $$C(q_{inv})=1+\lambda\,e^{-R^2q_{inv}^2}$$

R – Gaussian radius in PRF,
λ – correlation strength parameter



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

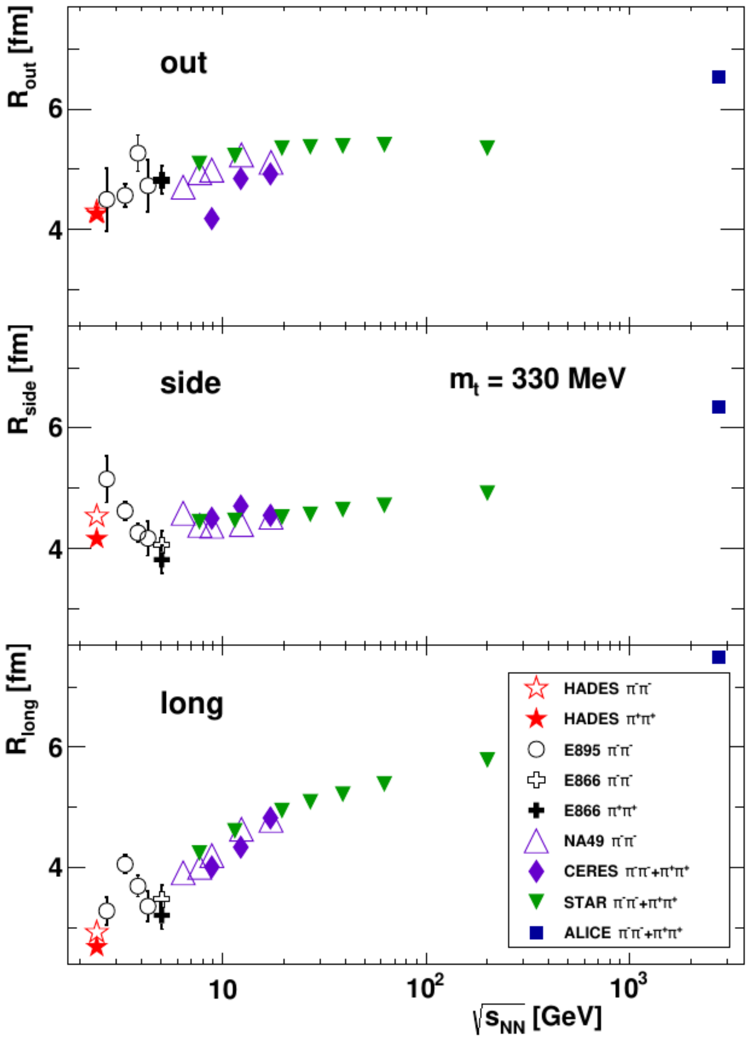
R and *q* are in Longitudinally Co-Moving Frame (**LCMS**)
long || beam; out || transverse pair velocity $\boldsymbol{v}_T$; side normal to out,long

Motivation

- **Femtoscopy 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 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

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

Pre-thermal phase → Hydrodynamic phase → Hadronic cascade

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: vHLLE

(3+1)-D viscous hydrodynamics

EoS to be used in the model

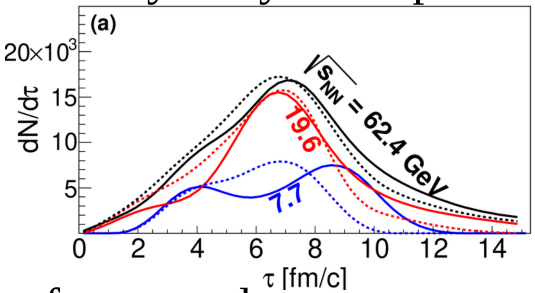
- Chiral EoS — crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model
  1st-order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

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

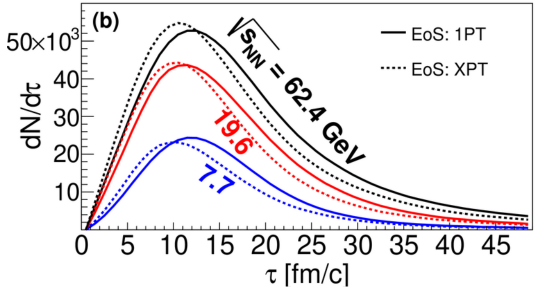
Hadronic cascade: UrQMD

Pion emission time

after hydrodynamic phase

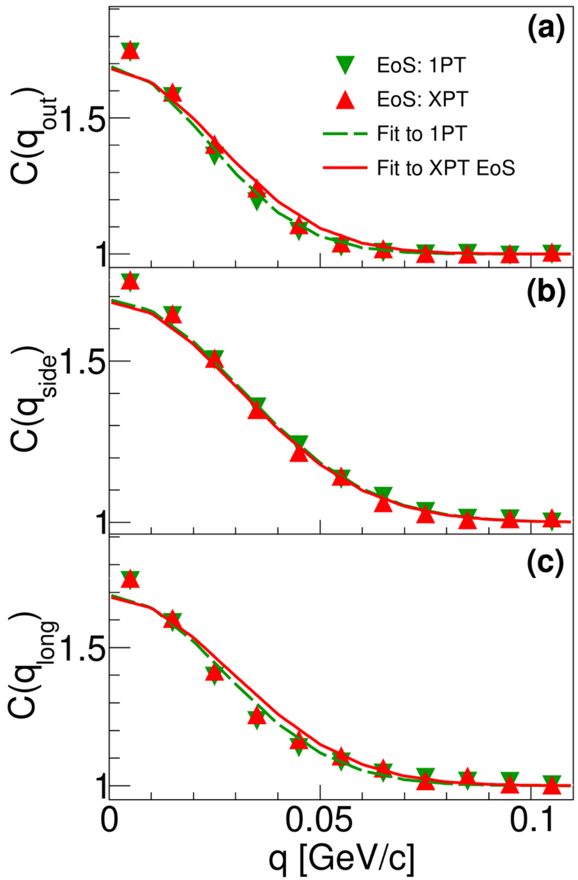


after cascade

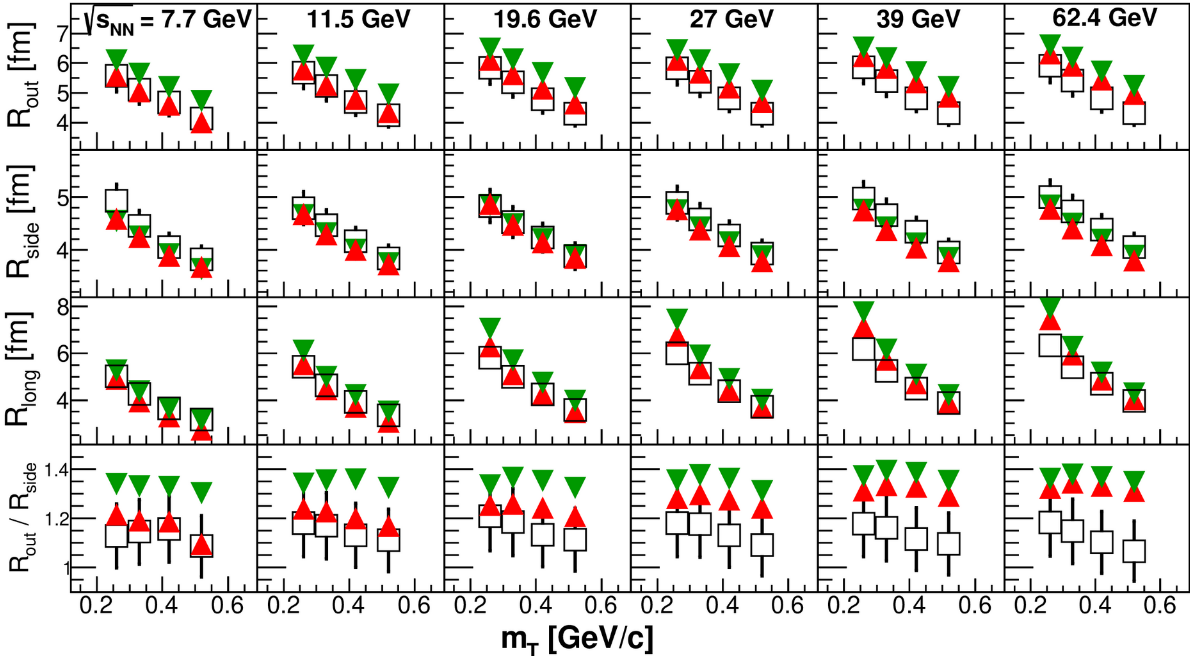


3D Pion radii versus m_T with vHLLE

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.

Correlation Functions from UrQMD

- Examples of the correlation functions of pions and kaons obtained for Au+Au collisions at $\sqrt{s_{NN}}$=11.5 GeV (UrQMD)
- Correlation functions were fitted with:

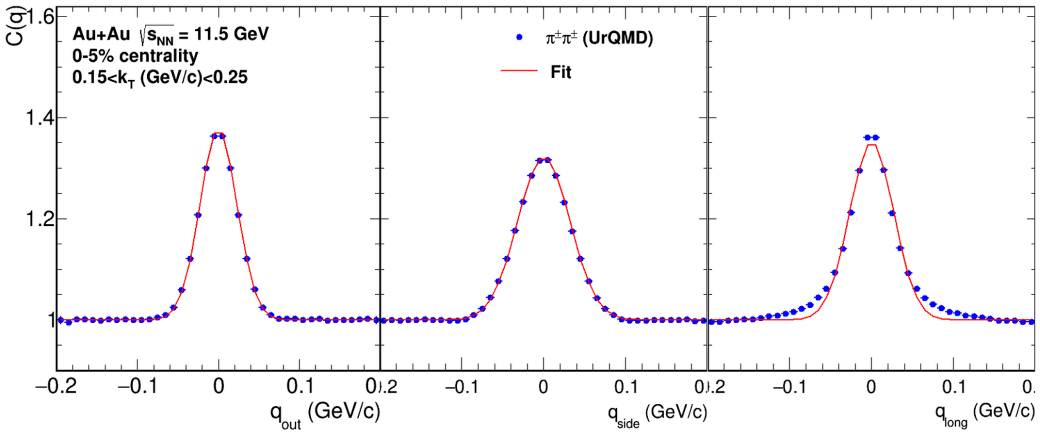
$$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda e^{-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2}$$

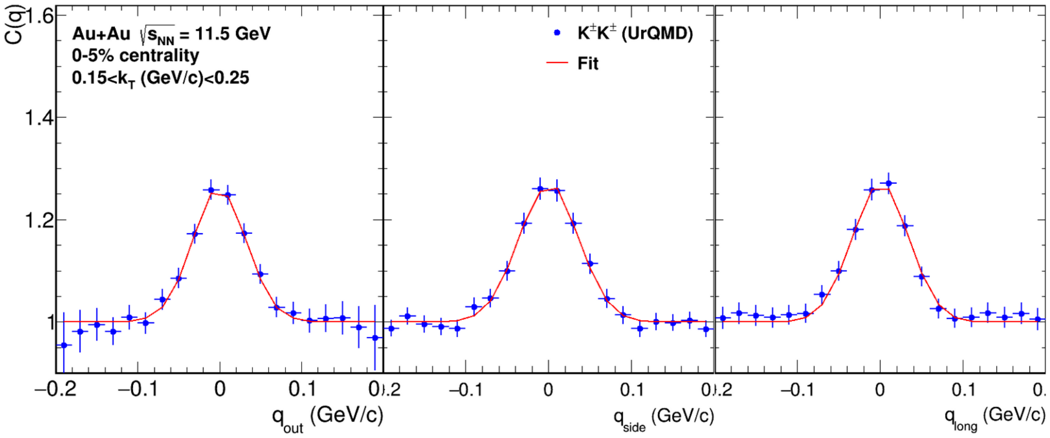
where:

R_{side} – size of the emission region

R_{out} – sensitive to the emission duration

R_{long} – proportional to the system lifetime





Correlation Functions from vHLLE

- Examples of the correlation functions of pions and kaons obtained for Au+Au collisions at $\sqrt{s_{NN}}$=11.5 GeV (vHLLE)
- Correlation functions were fitted with:

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

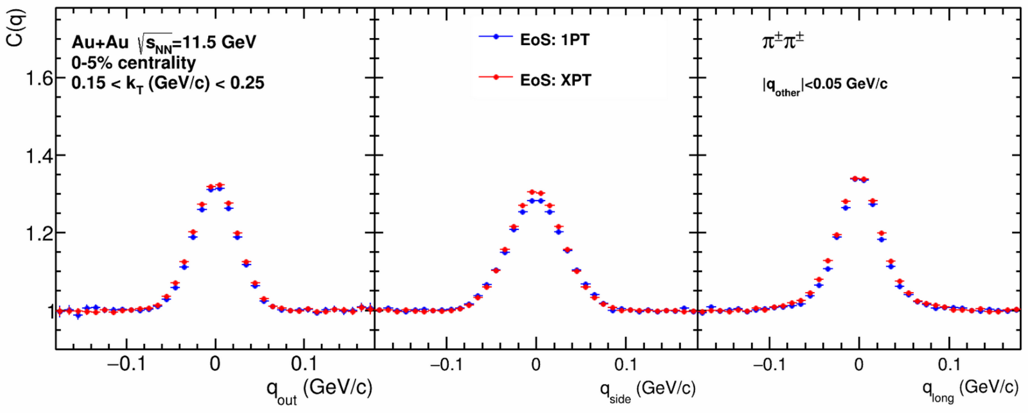
where:

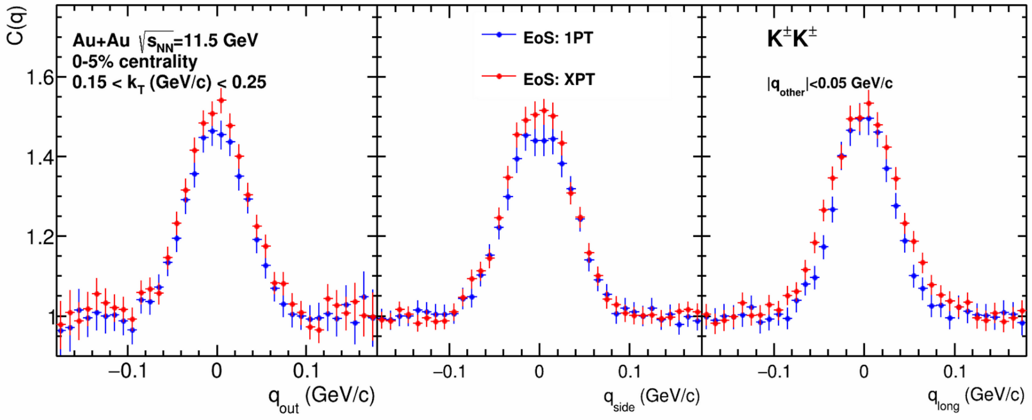
R_{side} – size of the emission region

R_{out} – sensitive to the emission duration

R_{long} – proportional to the system lifetime

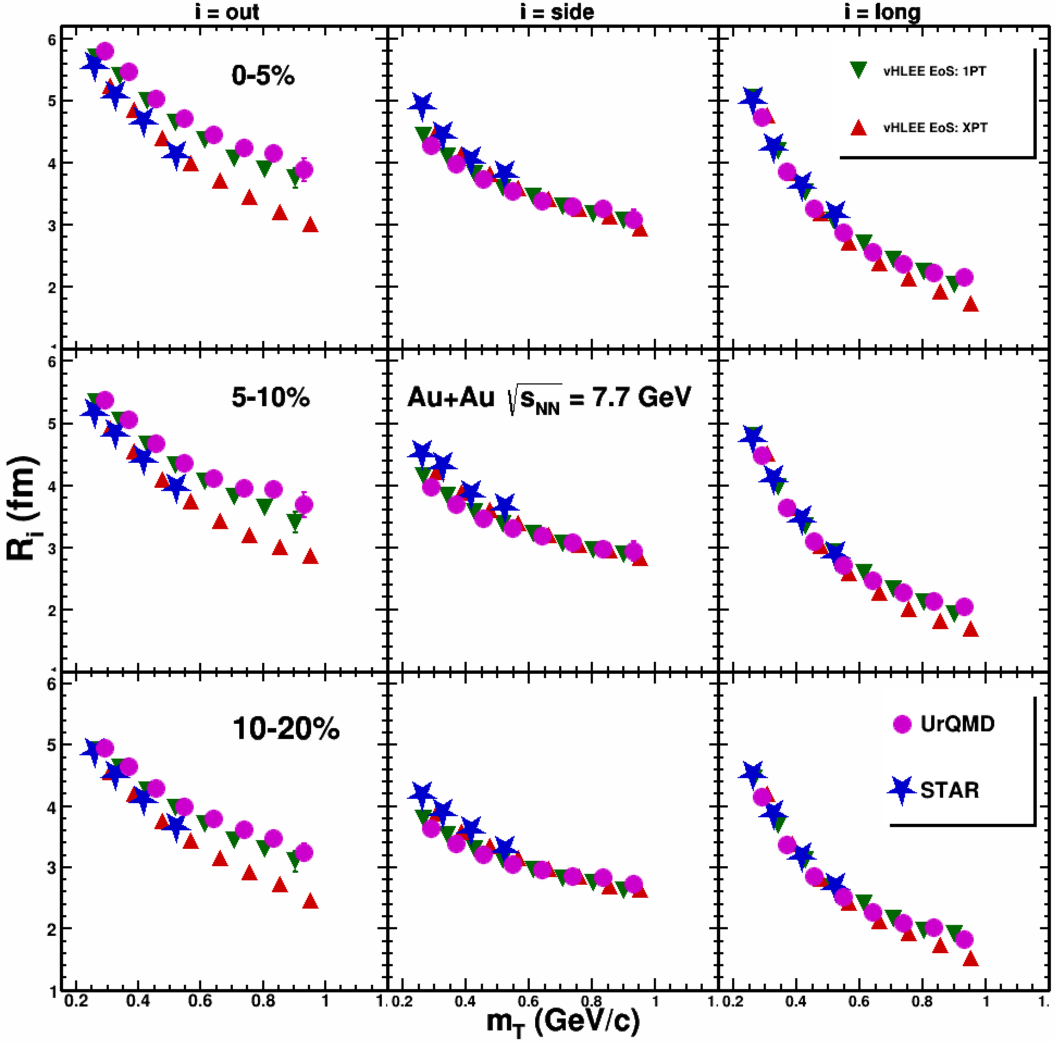
- Both K and π CF XPT wide than 1XP
  → XPT size smaller than 1XP





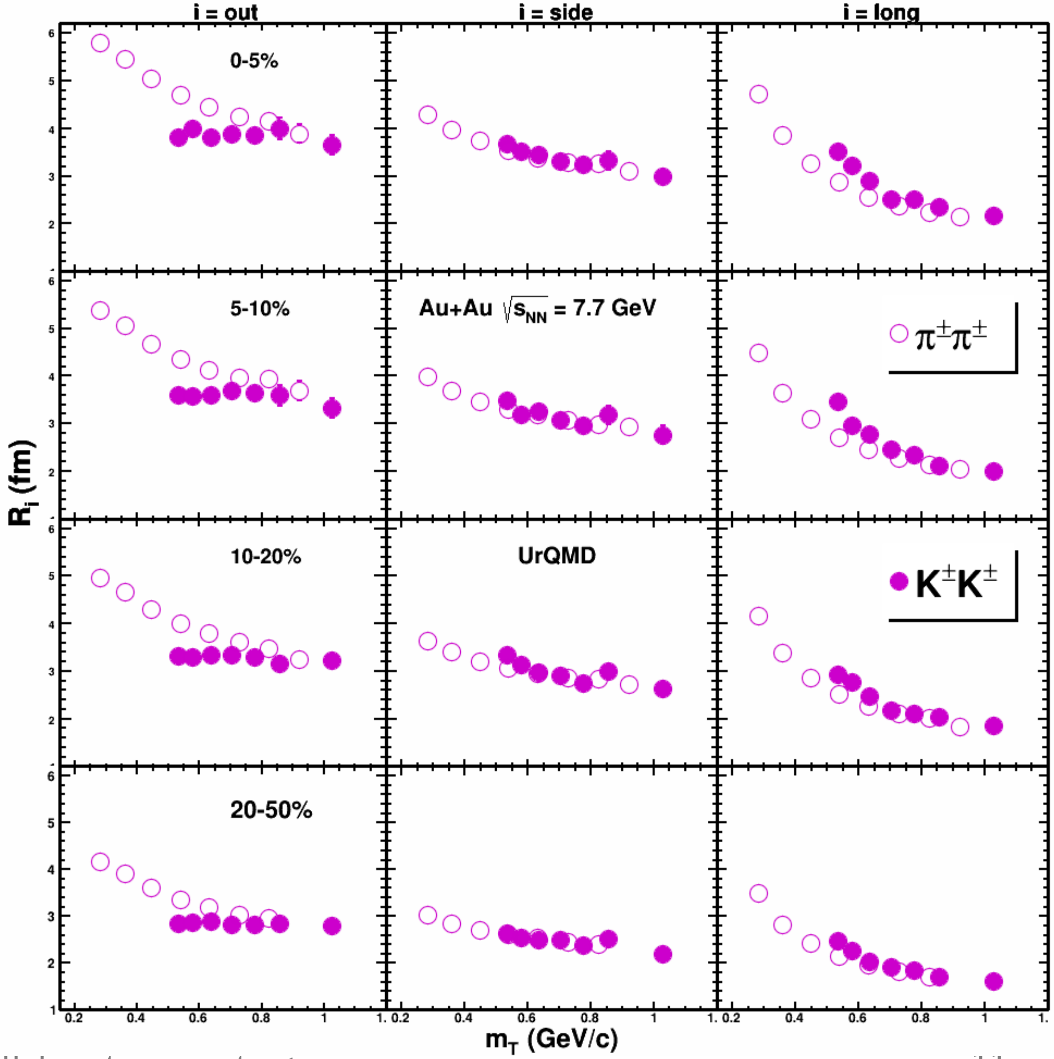
Femtoscopic R_π from UrQMD and vHLLE

- Femtoscopic radii of pions decrease with increasing transverse mass
  → Influence of radial flow
- R_{side} increases going from peripheral to central collisions
  → Geometrical picture of ion-ion collision
- UrQMD shows similar results to vHLLE with 1PT
- vHLLE with XPT reasonably describe STAR data



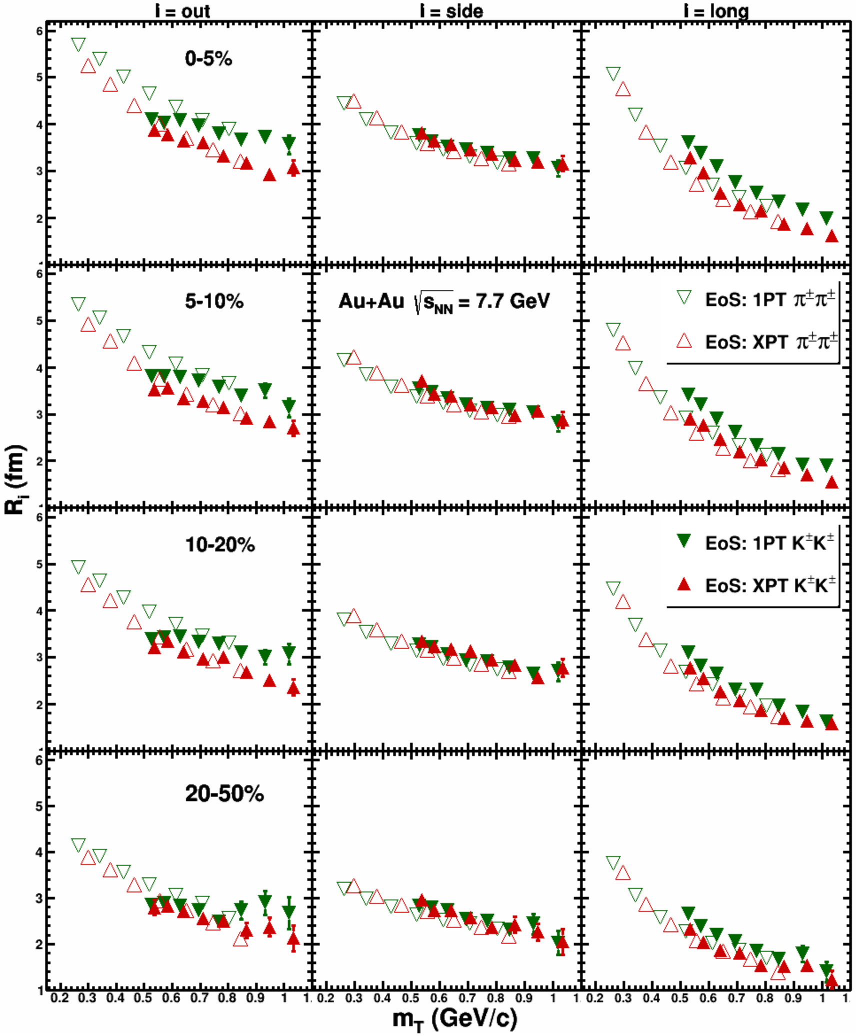
Femtoscopic Radii of Pions and Kaons from UrQMD

- Femtoscopic radii of pions decrease with increasing transverse mass
  → Influence of radial flow
- R_{side} values for pions and kaons are similar
  → Similar size of the particle-emitting region
- R_{long} for kaons is generally larger than that for pions at the same m_T
  → Influence of resonances?
- R_{out} pions and kaons behave differently
  → Different emission duration?
  → Change of the production mechanism?



Femtoscopic Radii of Pions and Kaons from vHLLE

- Pion and kaon results for the cross over (XPT) and 1st-order (1PT) phase transitions
- Femtoscopic radii of pions decrease with increasing transverse mass → Influence of radial flow
- R_{side} values for pions and kaons are similar
  → Similar size of the particle-emitting region
- R_{out} for both pions and kaons show similar behavior
  → Similar particle emission duration?
- R_{long} for kaons is generally larger than that for pions at the same m_T
  → Influence of resonances?

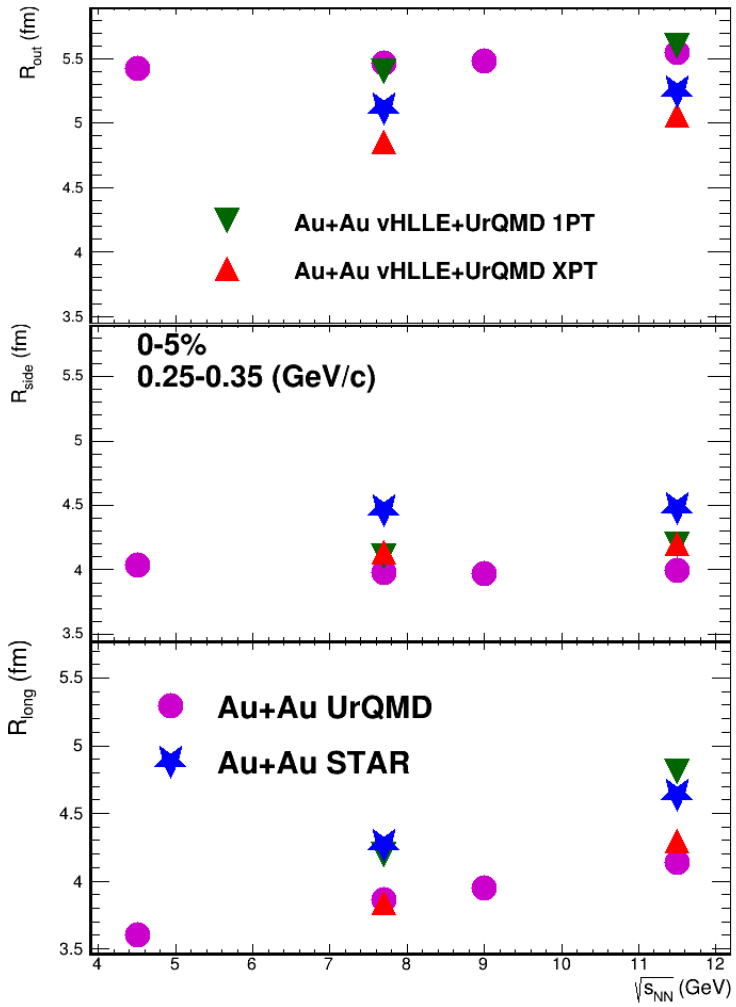


Energy dependence of pion femtoscopic radii

- Estimated pion radii for NICA energy range ($\sqrt{s_{NN}}$ = 4-11 GeV)

- Pion radii slightly increase with increasing collision energy

- Excitation function of R_{long} suggests a slight increase of the system lifetime with increasing $\sqrt{s_{NN}}$



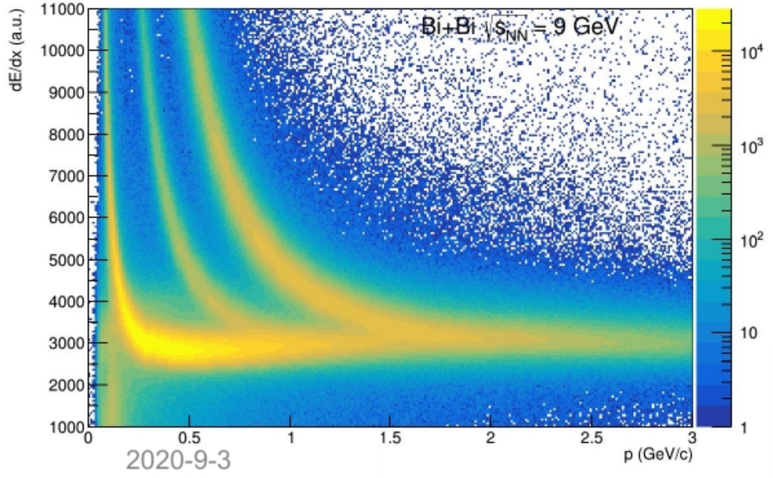
Monte-Carlo data

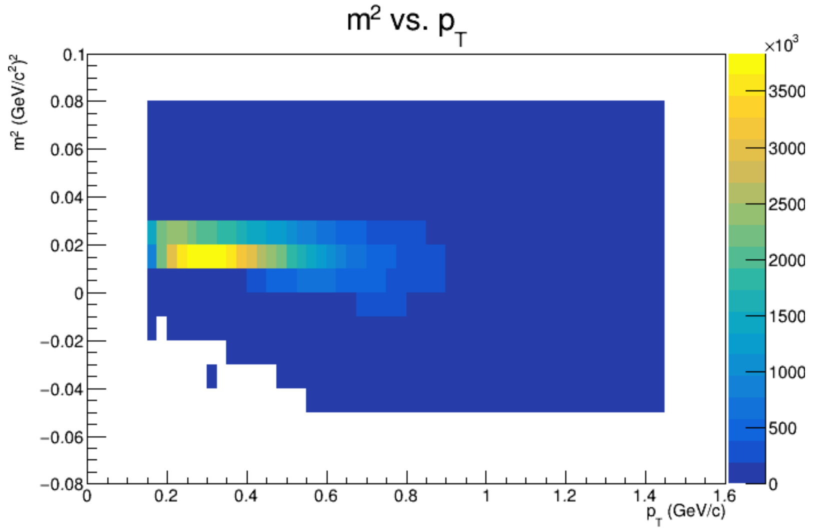
- Monte-Carlo simulation request
- UrQMD Minimal Bias 10 million evens
- BiBi at $\sqrt{s_{NN}}$=9 GeV
- MiniDST format

- 5 k_T bins (0.15-0.65) GeV/c, with step 100 MeV/c

- Kinematic conditions for pions
  0.15<pT<1.45 GeV/c
  |eta|<1.0

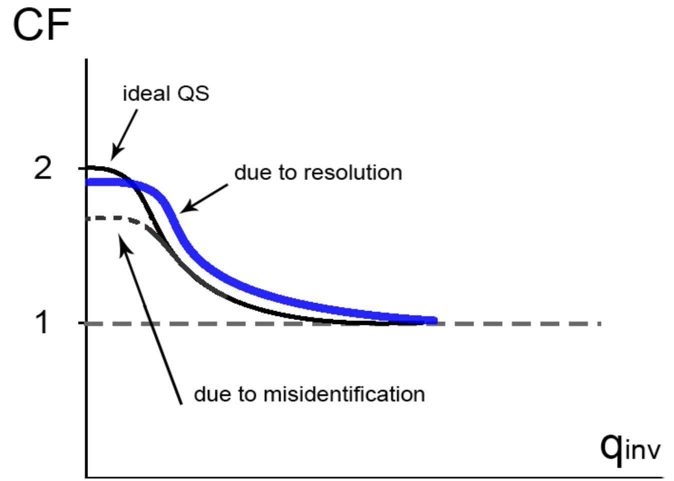
- Nhits TPC > 15
  DCA < 3 cm
  |VertexZ| < 75
  PID : Nsigma for pion selections in TPC & TOF = 2



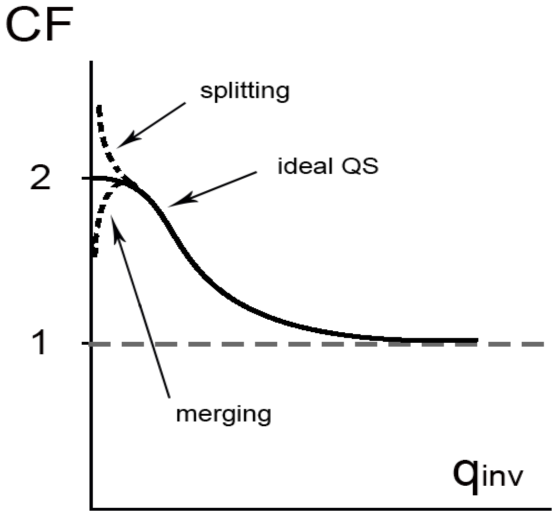


Detector effects affecting the correlation function

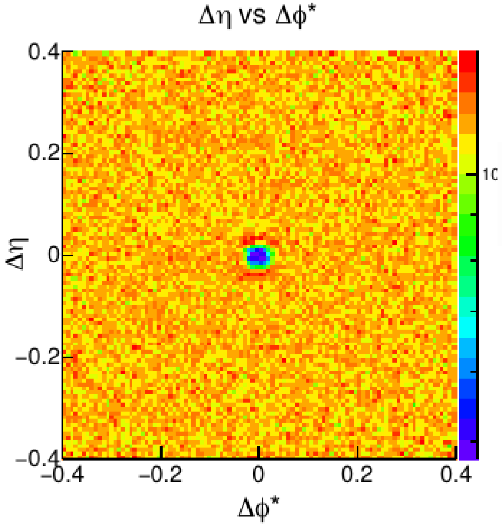
- Single track effects:
  → the momentum resolution effects smear CF, making it wider and extracted radii smaller
  → CFs should be corrected by resolution
  → the particle misidentification influences only λ-parameter of CF, radii do not change.
  → CF should be corrected by pair purity.



- 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.



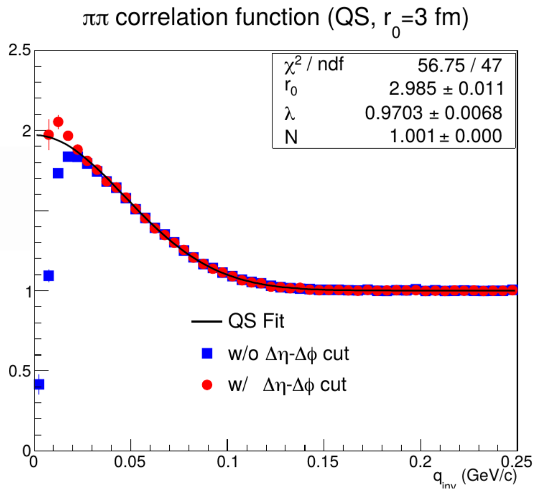
Two track effects

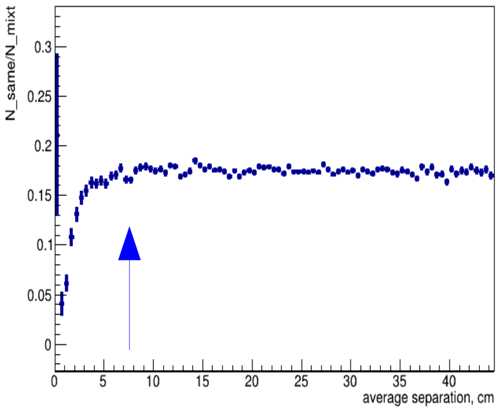


- Δη-Δφ* cut:

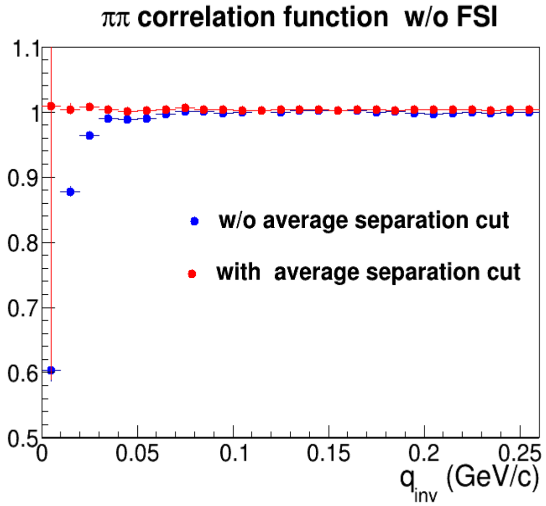
$$\Delta\phi^* = \phi_1 - \phi_2 + \arcsin\left(\frac{z \cdot e \cdot B_z \cdot R}{2p_{T1}}\right) - \arcsin\left(\frac{z \cdot e \cdot B_z \cdot R}{2p_{T2}}\right)$$

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





- Average track separation cut:
  → ratio real/mixed vs average distance
  → dip at low distance due to merging(or bump due to splitting)
- Cut on distance > 7 cm
  → remove the dip →



Factorial moments

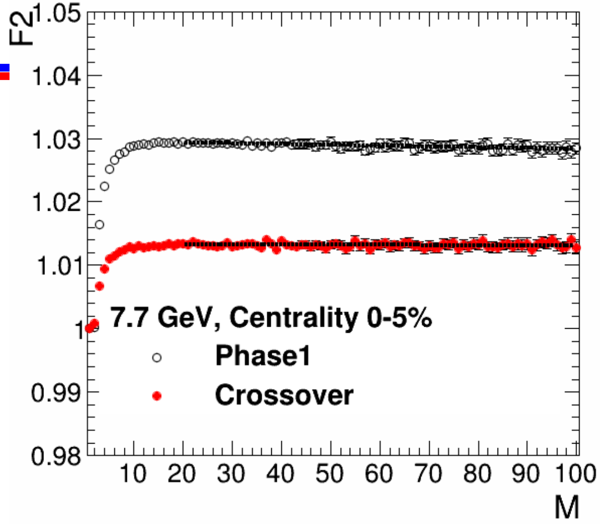
- Olga Kodolova and Maria Cheremnova (see talks at ICPPA, RFBR)
- A. Bialas and R. Peschanski(Nucl. Phys. B273 (1986) 703) to study the dependence of the normalized factorial moments of the rapidity distribution on the bin size δy:

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

- δy = Δy/M; M - number of bins; Δy - size of mid rapidity window; N - number of particles in Δy;
- k_j - the number of particles in bin j

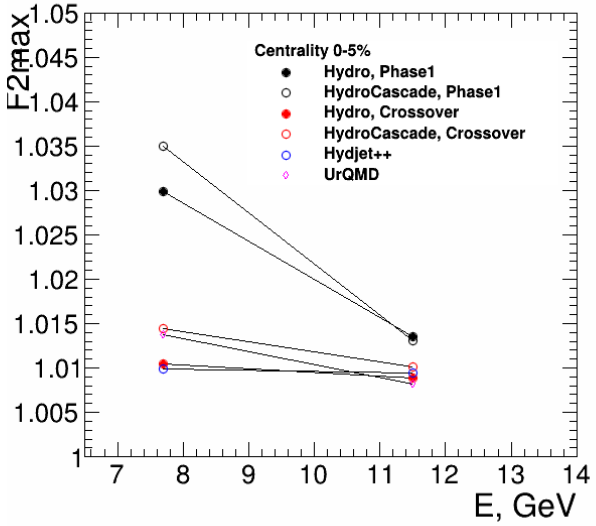
- If fluctuations are purely statistical no variation of moments as a function of δy is expected
- Observation of variations indicates the presence of physics origin fluctuations

Sensitivity of factorial moments



- Different energy behavior F2 vHLLE (1PT and XPT EoS)

- No-phase transition (UrQMD, HYDJET++) do not reveal the energy dependence as vHLLE



Packages for data storage and femtoscopic analysis

- Grigory Nigmatkulov and Pavel Batyuk (RFBR, VI MPD)

Summary

- The new data format (MpdMiniDst) that may satisfy most MPD physics needs:
  - Was developed and implemented in MpdRoot
  - Contains most of the detector subsystems
  - Easy to use
  - Already used in several analyses

- Package for femtoscopic analysis (MpdFemtoMaker):
  - Developed and implemented in MpdRoot
  - Applied to study identical pion and kaon correlations using the UrQMD and vHLLE models
  - Allowed us to study the influence of two-particle effects on correlation function in MPD and develop two-track selection criteria to suppress these parasitic effects

10/22/2020 G. Nigmatkulov and P. Batyuk. The Conference "RFBR Grants for NICA"

Conclusions

- We performed the first model estimation of kaons femtoscopic radii using the UrQMD and vHLLE models

- Kaon radii dependence as a function of transverse mass shows:
  R_{side} values for pions and kaons are similar for vHLLE and behaviour is different for UrQMD
  R_{long} for kaons is generally larger than that for pions

- Sensitivity of both pion and kaon source size to the nature of the phase transitions

- Factorial moments are sensitive to phase transition within vHLLE model

- Results were presented at ICPPA, NUCLEUS and RFBR conferences
- Proceedings will be published

Thank you for attention!

Backup

T

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:

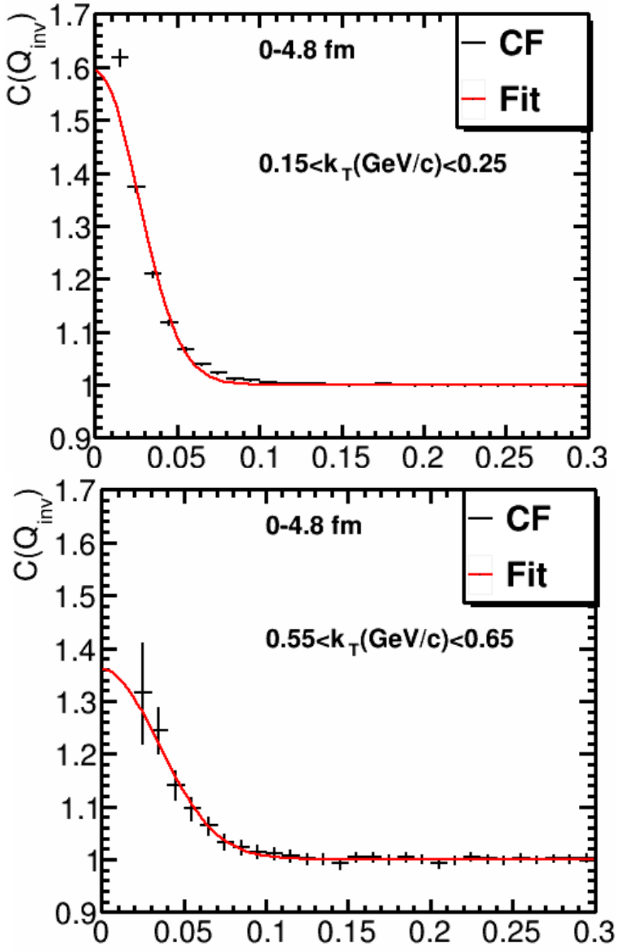
- Development of the data analysis methods and software that will be integrated in the Multi-Purpose Detector (MPD) software environment
- Analysis of the simulated with different event generators (in particular, UrQMD and vHLLE) Au+Au collisions at NICA energies
- Study the dependence of femtoscopic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

2020:

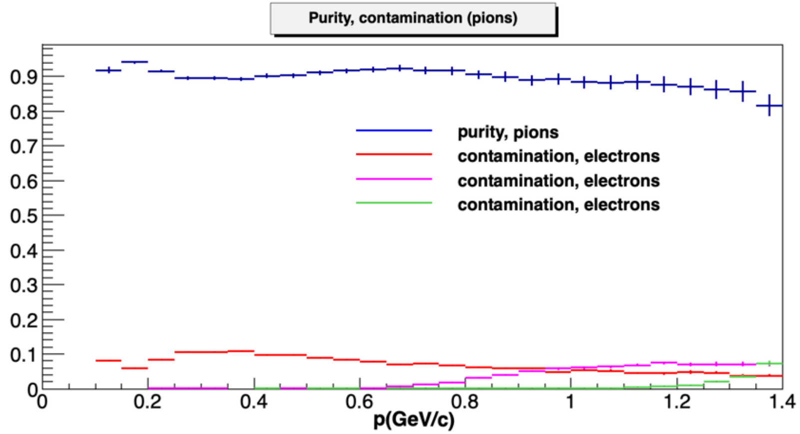
- Simulation of Au+Au collisions with UrQMD and vHLLE+UrQMD models for different collision energies (done)
- Software development for: (done)
  - femtoscopic analyses
  - factorial moments of multiplicity distributions
  - other activities
- Femtoscopic analysis and extraction of source functions for 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 (done)

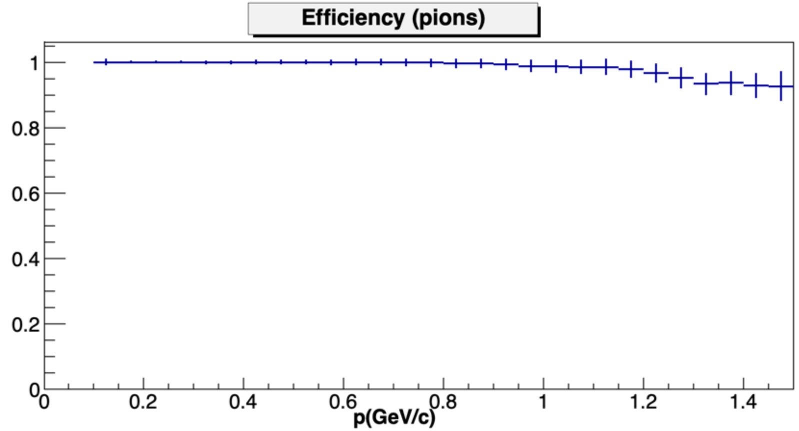
First physics (very preliminary, UrQMD MC)

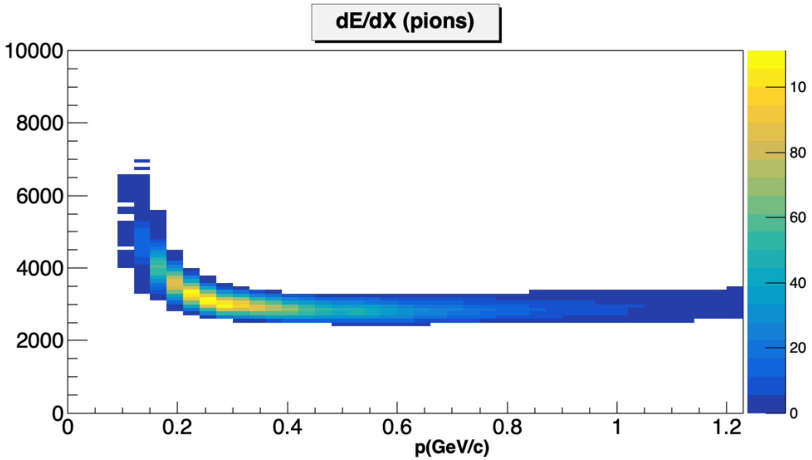
- First look with UrQMD
- Bi+Bi $\sqrt{s_{NN}}$ = 7.7 GeV, 200K "good" events 0-10% centrality
- $\sqrt{s_{NN}}$ =7.7 GeV → STAR data exists
- ππ one dimension correlation function for a few k_T ranges 0.15-0.25, 0.25-0.35,…,0.55-0.65 GeV/c
- Possible to study m_T dependence of 1D femtoscopic radius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

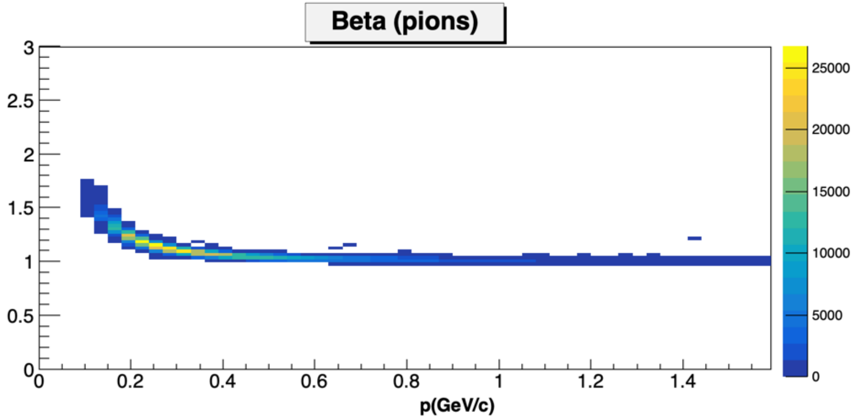


MPD response for femtoscopy(standard MPD PID)

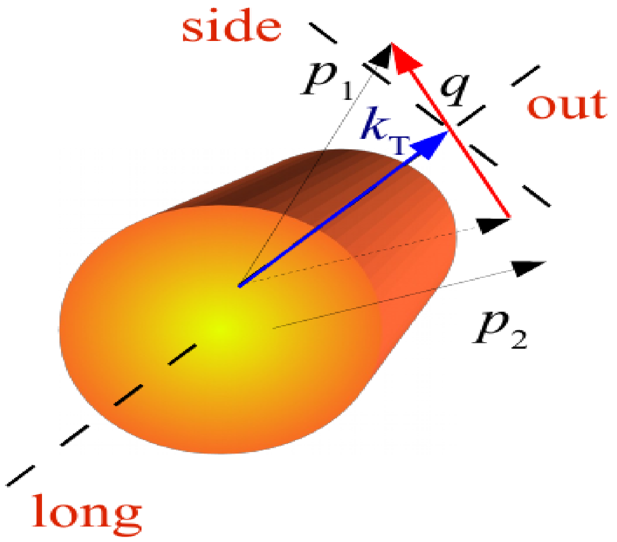








LCMS reference frame



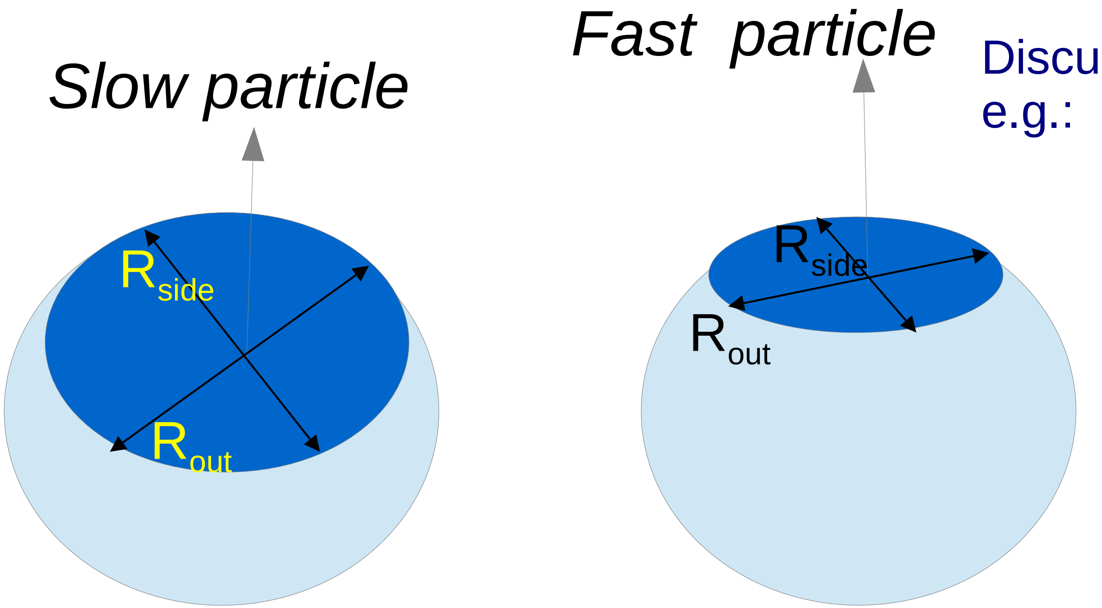
$$m_T = \sqrt{k_T^{\,2} + m_\pi^{\,2}}$$

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

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

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

β_T collective transverse flow

assuming a longitudinal boost invariant expansion

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

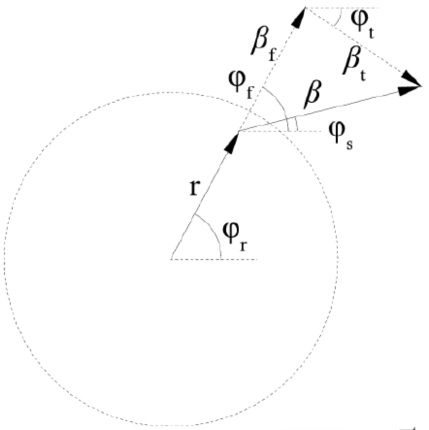
$R^2_{out} \sim R^2_{side} + 1/2(T/m_T)^2 \beta_T^2 \tau^2$

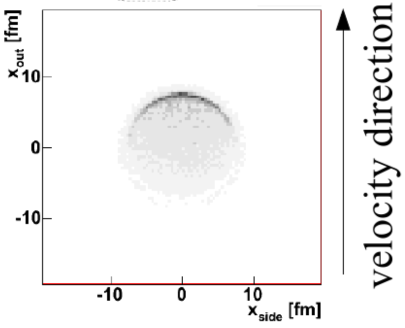
Femtoscopy with expanding source

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