Femtoscopy and correlations at MPD: physics case, people, projections

within the RFBR Mega Grant # 18-02-40044

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

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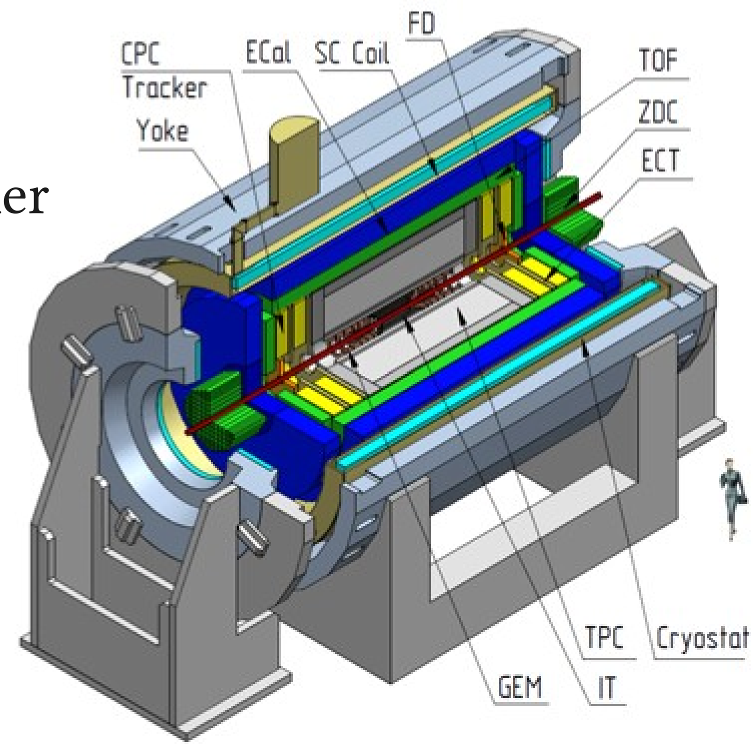


MPD Physics Seminar
21 Nov, 2019

Outline

- Femtoscopy & Factorial moments group activities
- Femtoscopy & Motivation
- Hybrid vHLLE+UrQMD model
- Comparison with STAR BES
  - pions
  - first results with kaons
- First tests with reconstructed data
- Factorial Moments
- Other activities
- 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 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

Plans for 2019:

- Simulation of Au+Au collisions with UrQMD and vHLLE+UrQMD models for different collision energies (done)

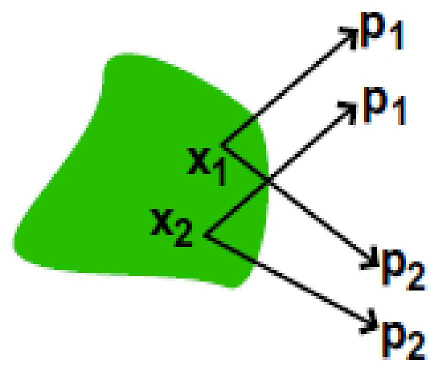
- Software development for: (done)
  - femtoscopic analyses
  - factorial moments of multiplicity distributions
  - other activities

- 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 (done)

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)

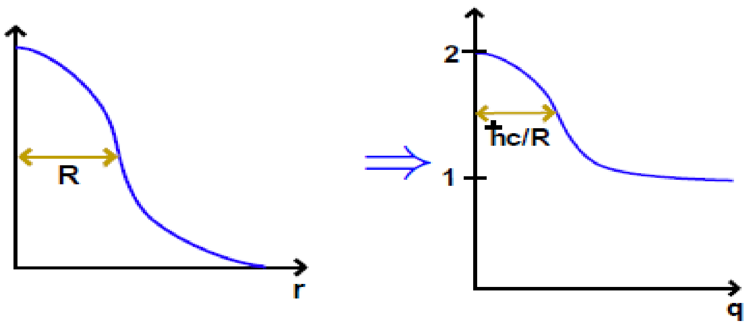


- Two particle Correlation Function (CF):

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



- Parametrization:

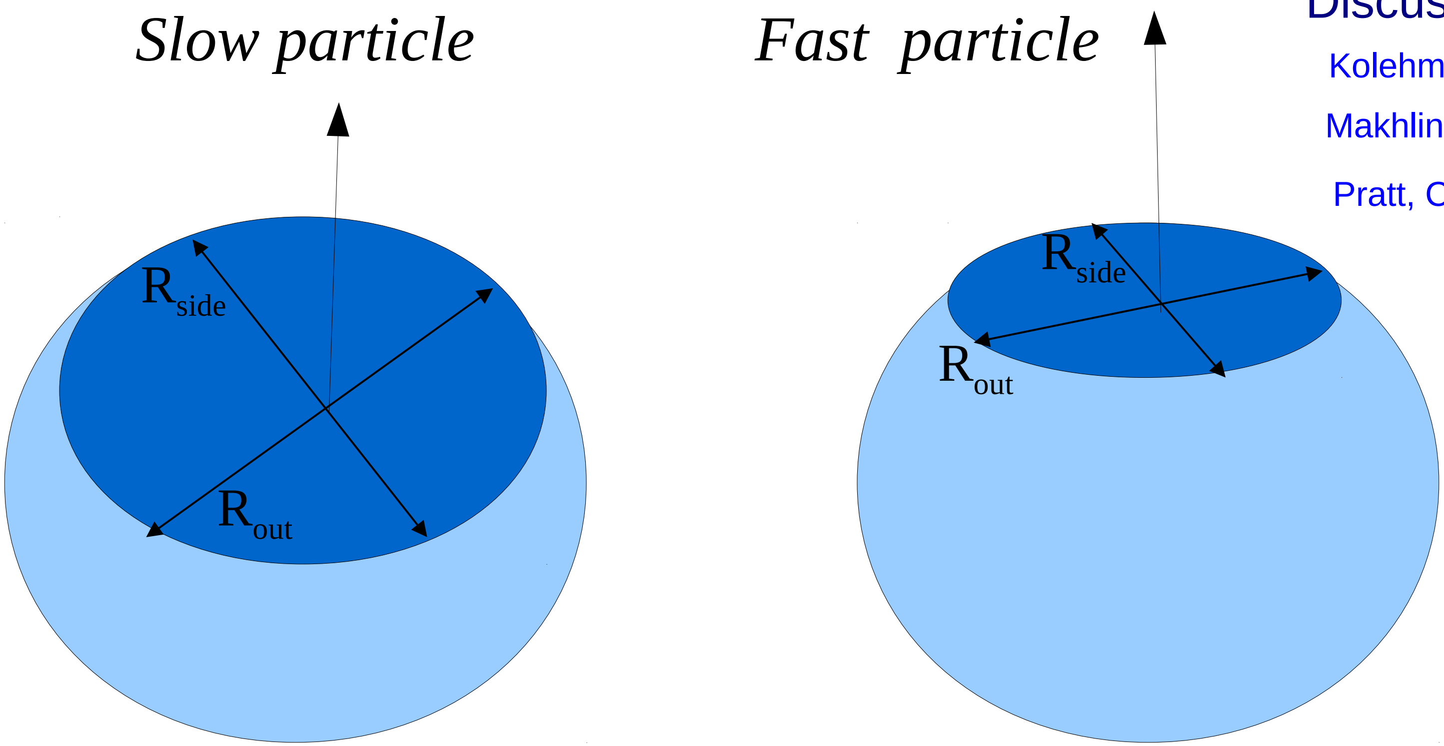
1D: $C(q_{inv}) = 1 + \lambda \exp(-R^2 q_{inv}^2)$ ***R*** Gaussian radius in Pair Rest Frame (**PRF**), ***λ*** correlation strength parameter

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

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

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

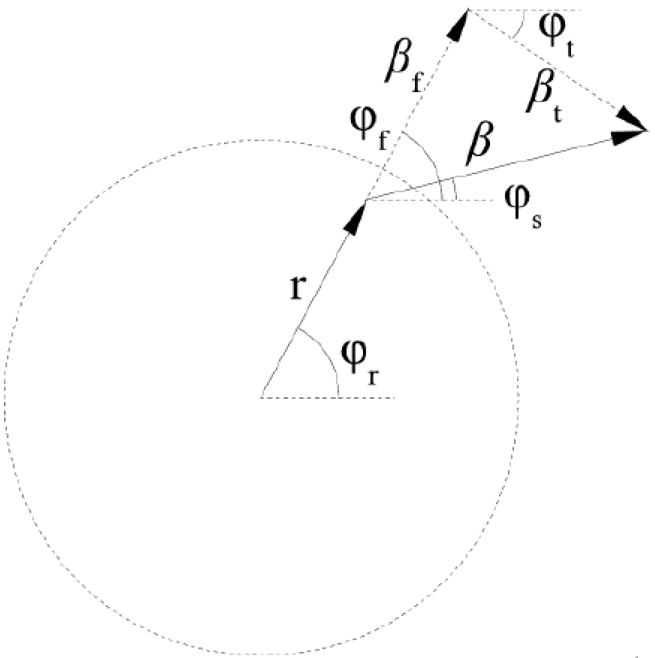
assuming a longitudinal boost invariant expansion

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

Femtoscopy with expanding source

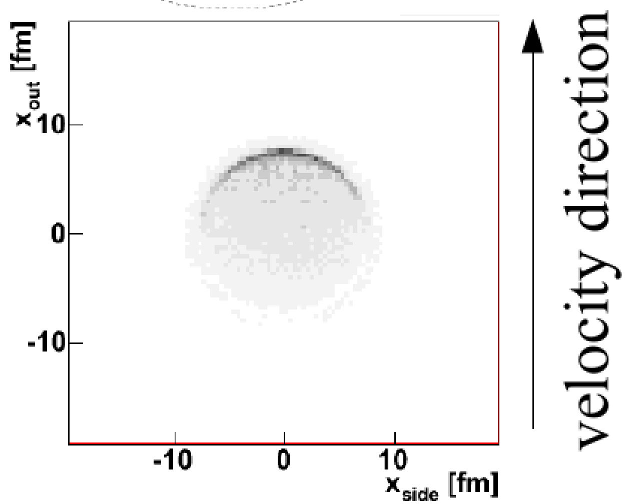
Interference probes only parts of the source at close momenta – **homogeneity regions.**

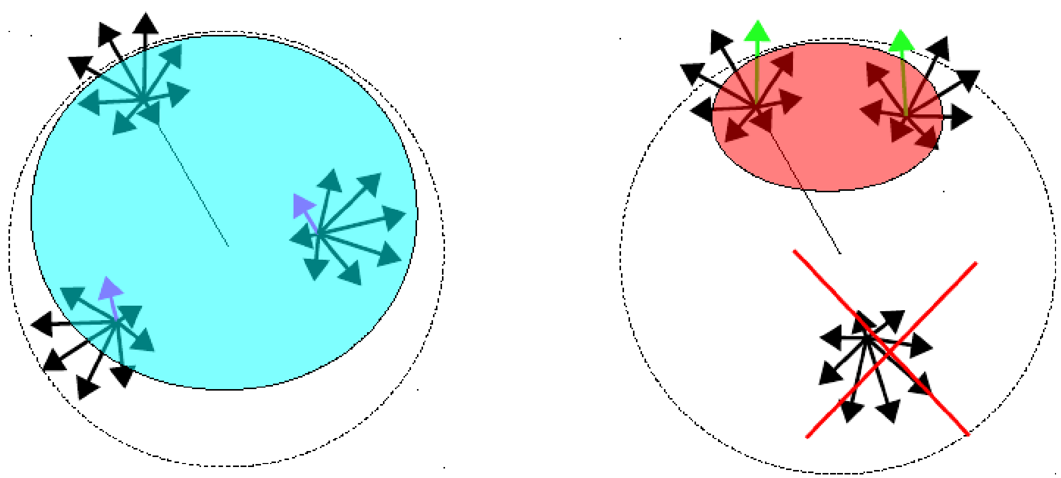
[Yu.M. Sinyukov, Nucl. Phys. A 566, 589 (1994);]
Figures and consideration from A. Kisiel Phys.Rev. C81 (2010) 064906



- 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

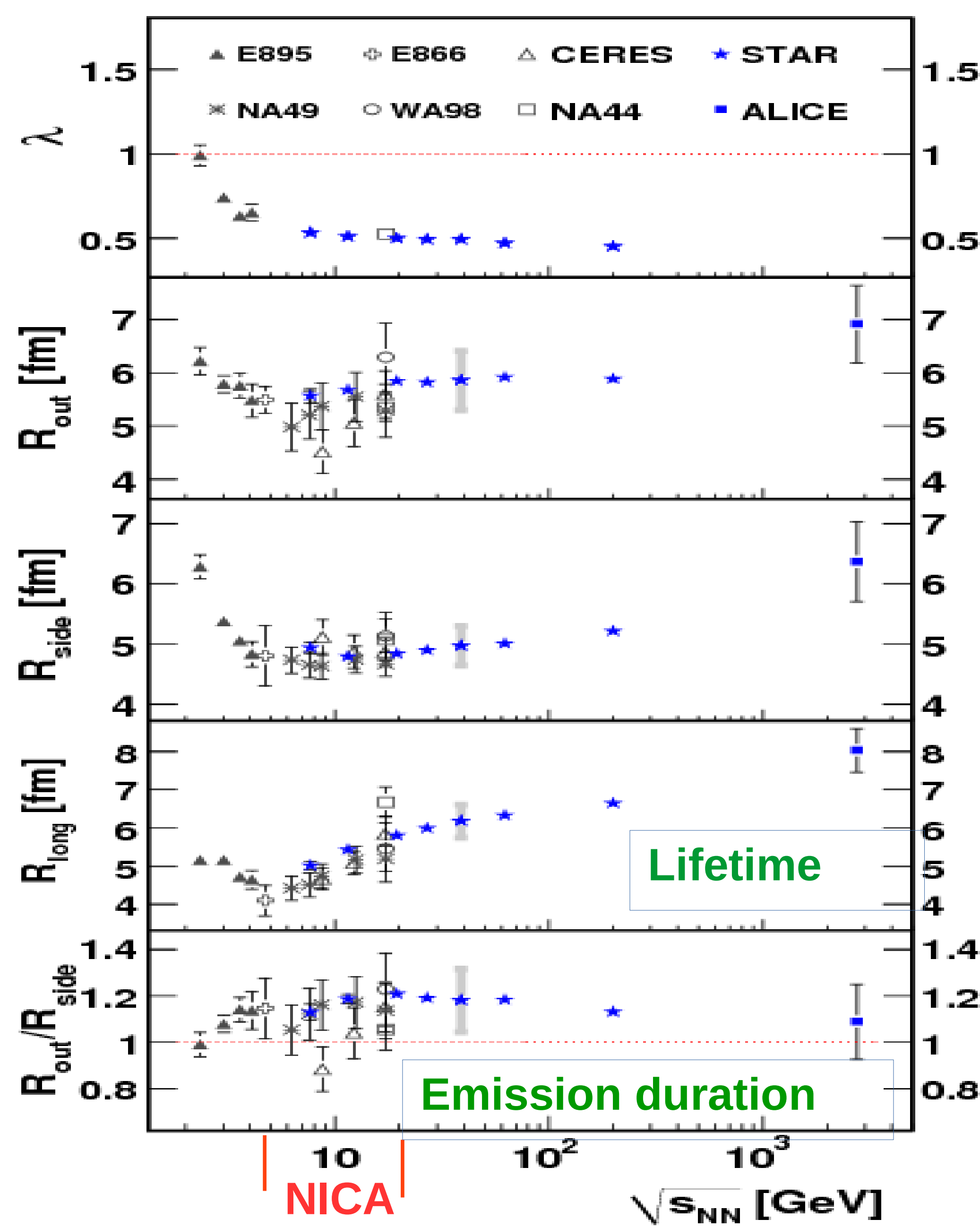




Motivation: Correlation femtoscopy.

- Femtoscopy allows one:
  - to obtain spatial and temporal information on particle-emitting source at kinetic freeze-out;
  - to study collision dynamics depending on EoS
- 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)
- RHIC Beam Energy Scan program (BES-I): √sNN = 7.7, 11.5, 19.6, 27, 39 GeV pion and kaon femtoscopic radii were measured
- NICA energy range: √sNN = 4 -11 GeV

STAR, Phys.Rev. C92 (2015) 1, 014904



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

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

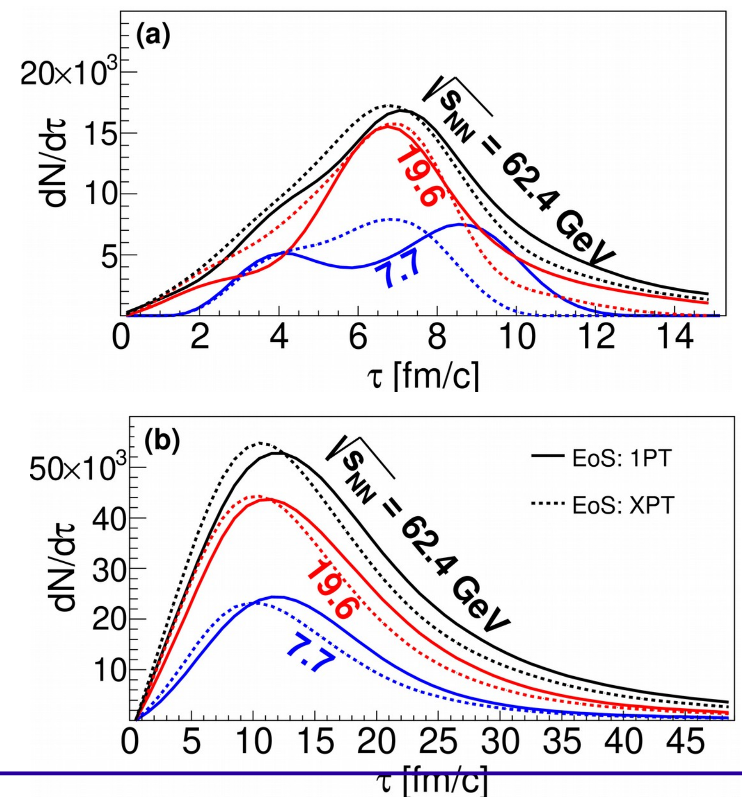
EoS to be used in the model

- 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

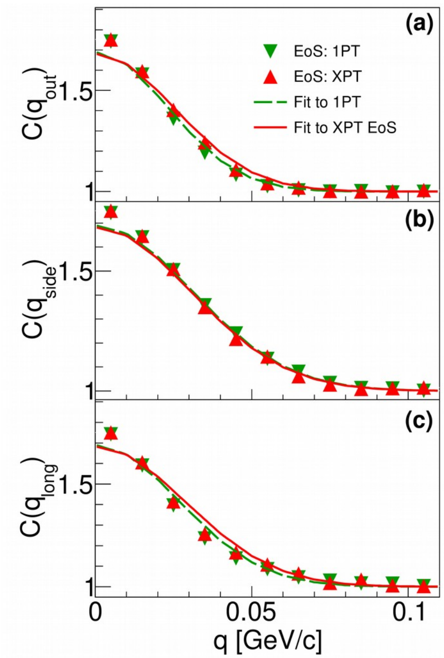


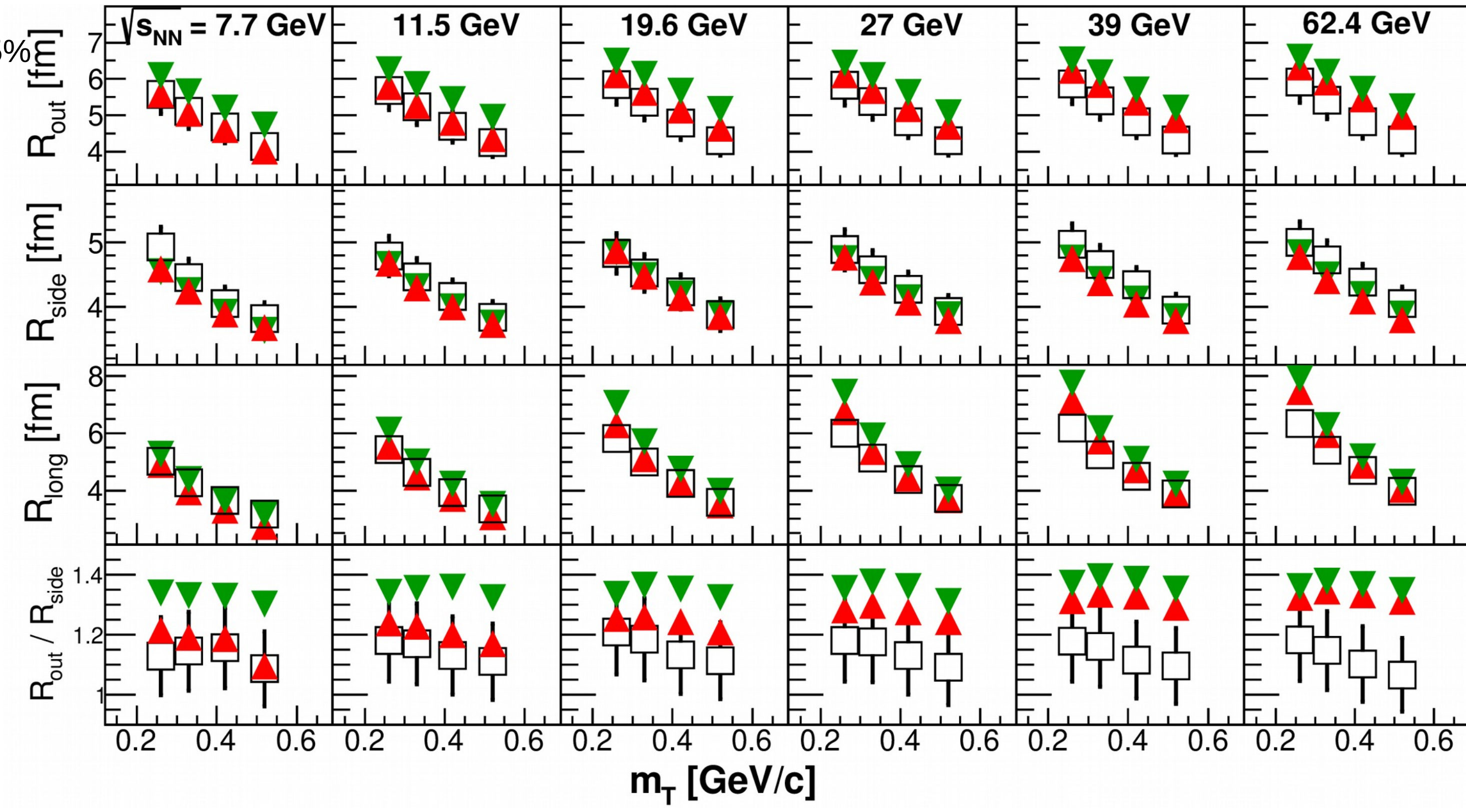
3D Pion radii versus m_T with vHLLE+UrQMD

P. Batyuk, Iu. Karpenko, R. Lednicky, L. Malinina, K. Mikhaylov, O. Rogachevsky D. Wielanek
Phys.Rev. C96 (2017) no.2, 024911

STAR, Phys.Rev. C92 (2015) 1, 014904: 0-5%
vHLLE+UrQMD: impact 0-3.3 fm

Projections of 3D Model CF



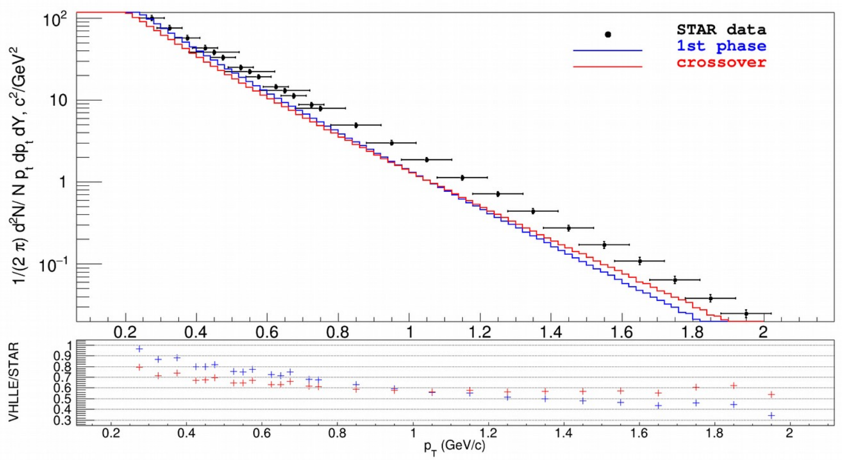


- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS describes better R(mT) dependencies, especially at low energies
- R_{out} (XPT) at high energies and R_{out} (1PT) at all energies are slightly overestimated
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT) by value of ~1-2 fm.**
- R_{out} /R_{side} (XPT) agrees with almost all STAR data points , while R_{out} /R_{side} (1PT) overestimates the data.

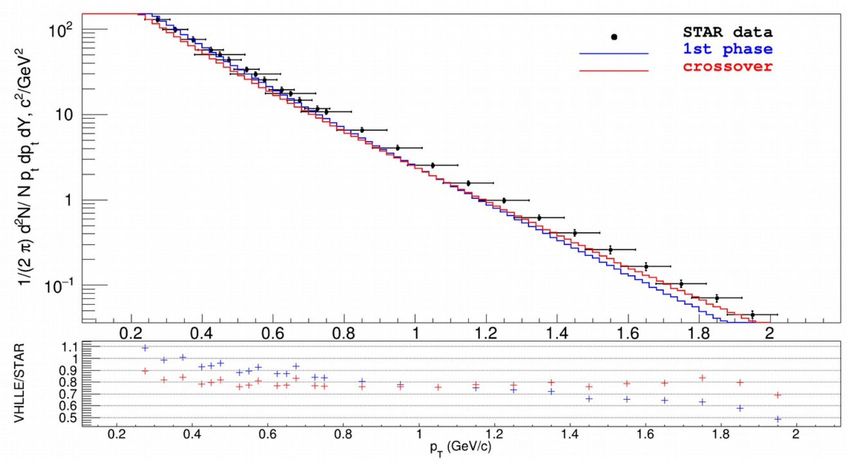
pT- spectra of π and K with vHLLE+UrQMD

STAR, PHYSICAL REVIEW C 96, 044904 (2017)

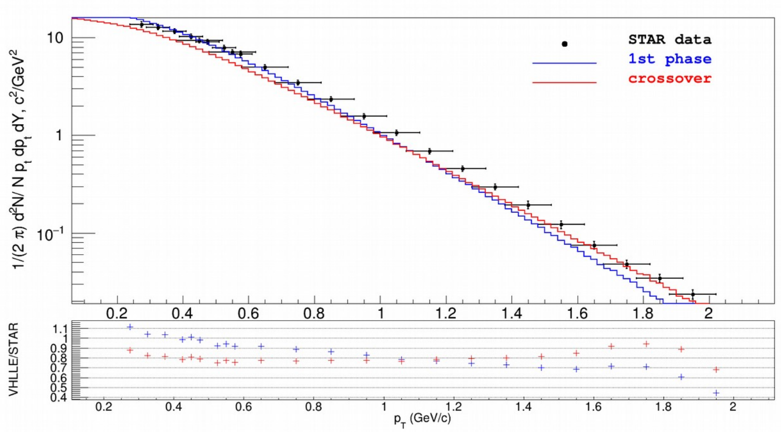
π^+, 7.7 GeV/s



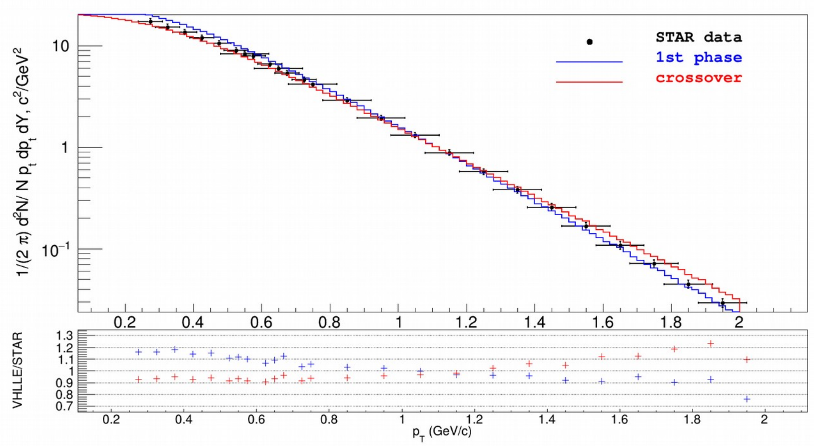
π^+, 11.5 GeV/s



K^+, 7.7 GeV/s



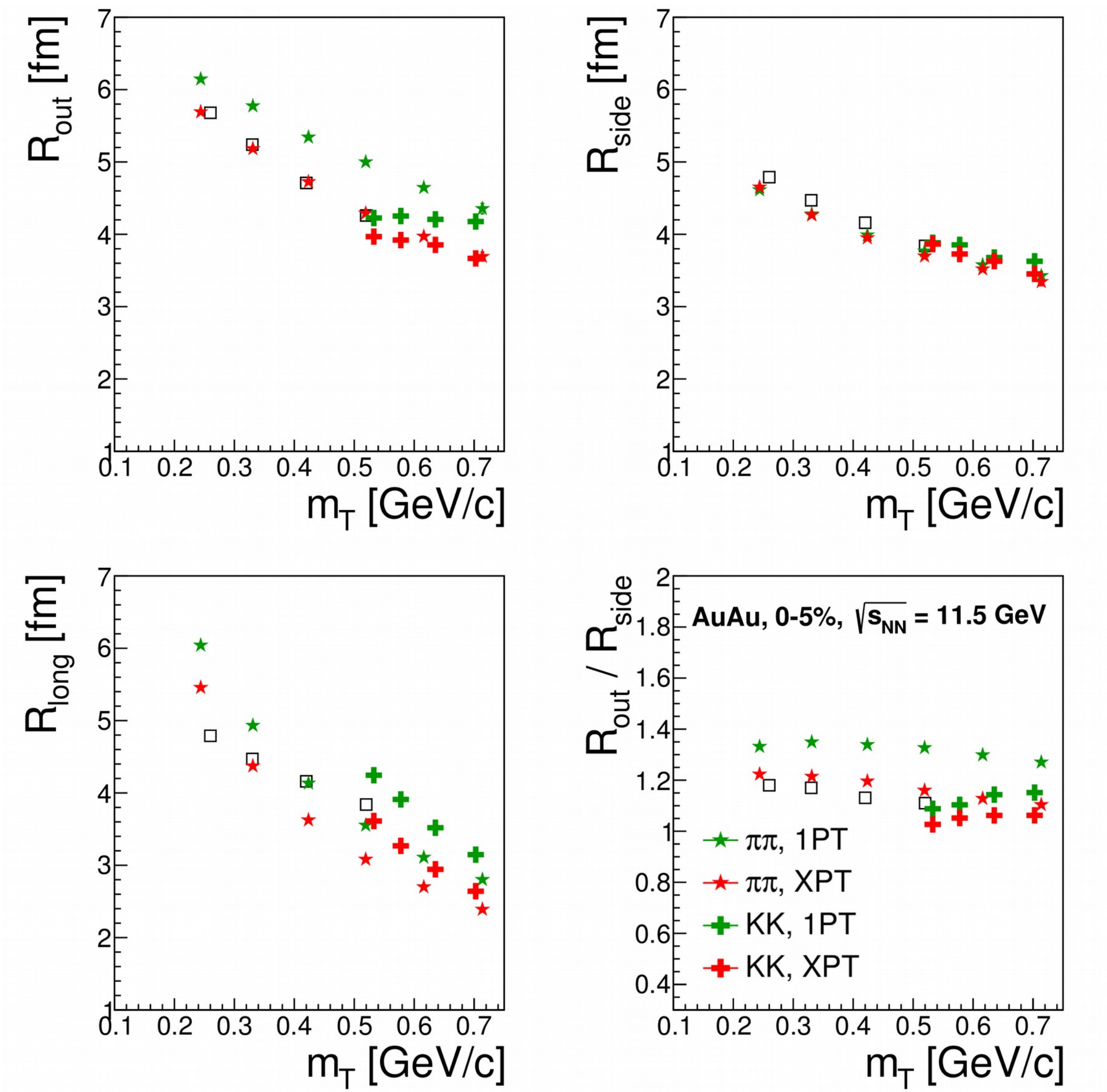
K^+, 11.5 GeV/s



vHLEE+UrQMD model with both EoS describe reasonably (<20%) pT-spectra of pions and kaons at pT< 1 GeV/c

Radii π and K vs. mT with vHLLE+UrQMD (11.5GeV)

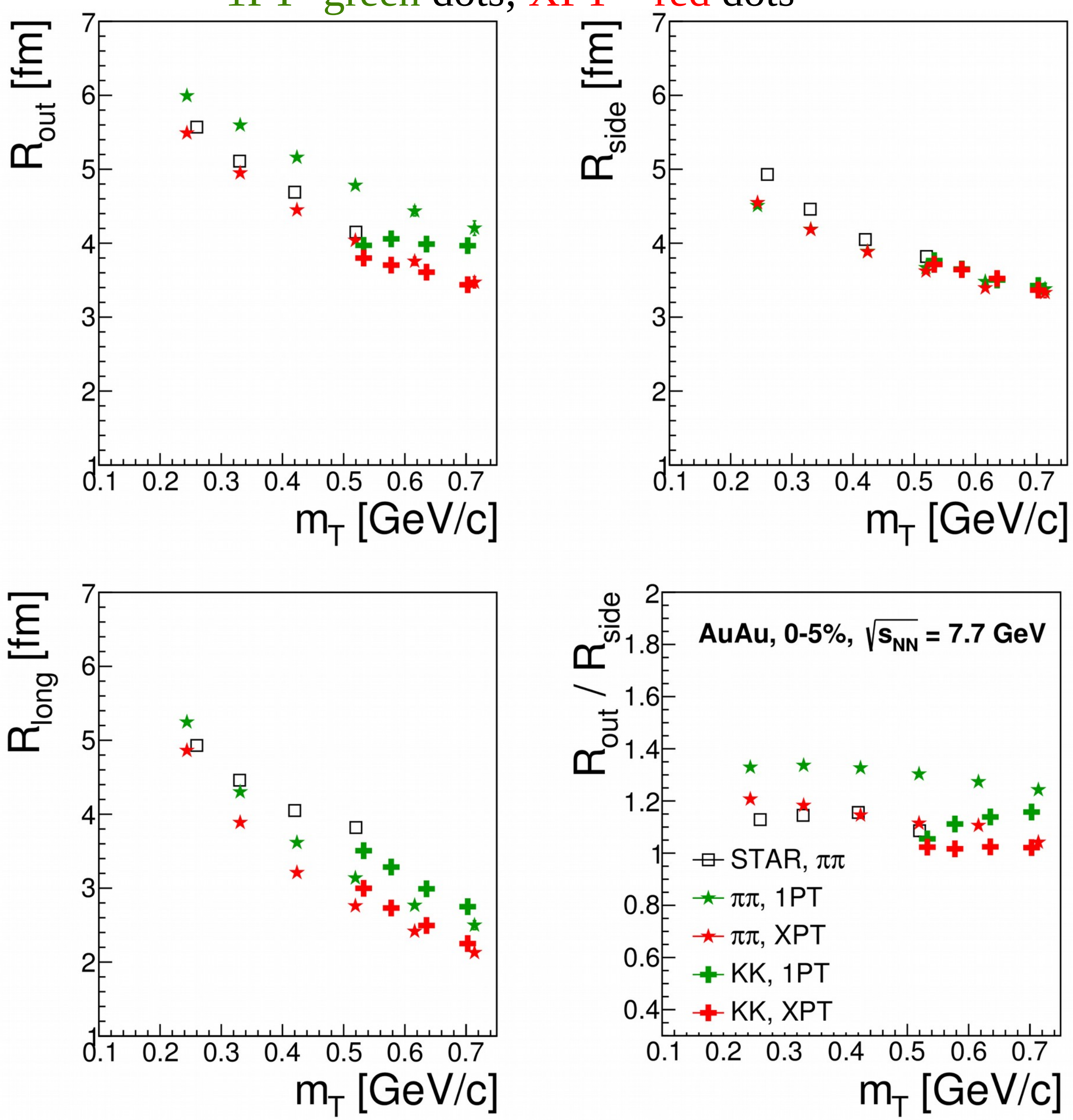
1PT -green dots; XPT – red dots



- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- 0-5% centrality
- 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

Radii π and K vs. mT with vHLLE+UrQMD (7.7GeV)

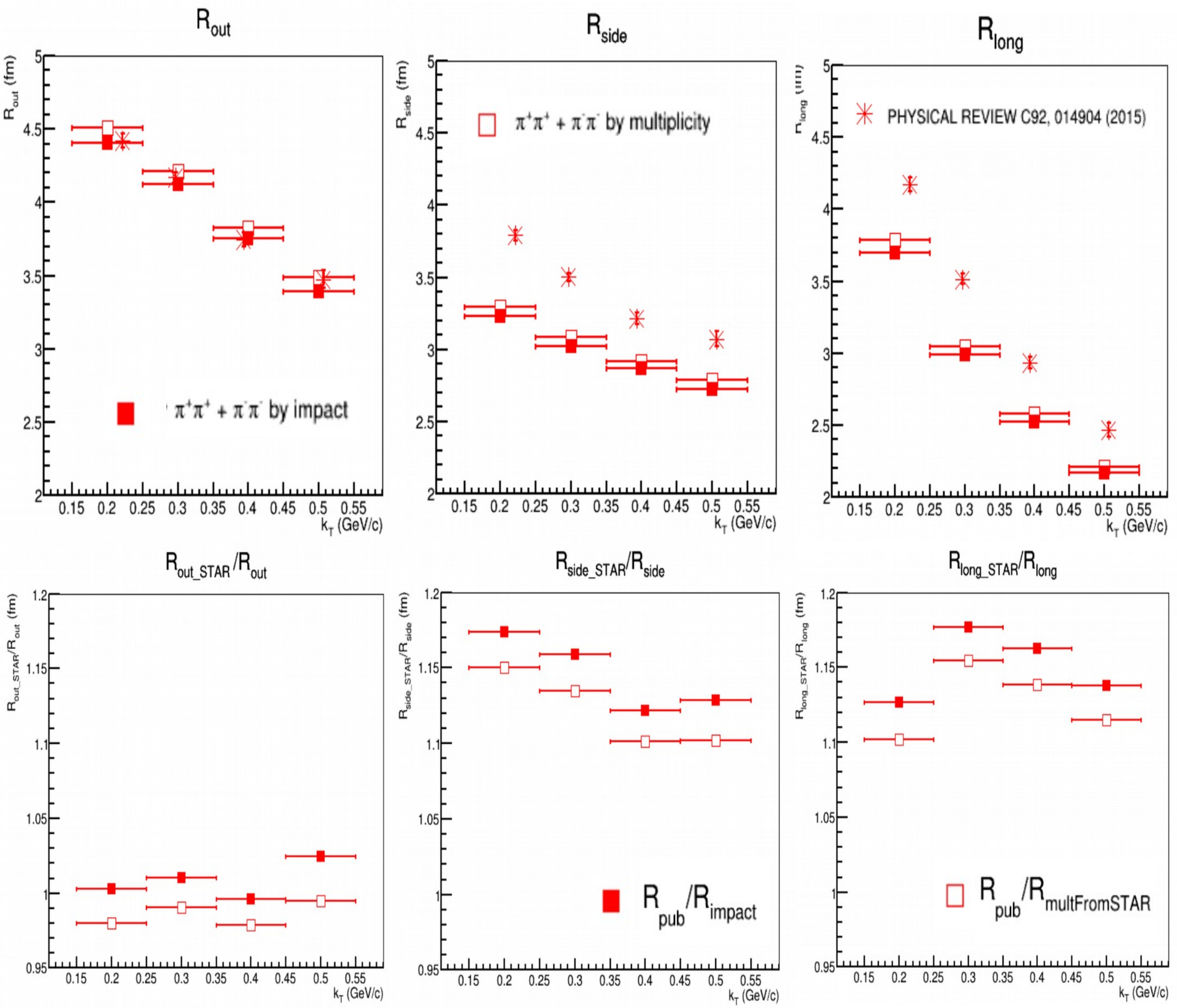
1PT -green dots; XPT – red dots



- AuAu, $\sqrt{s_{NN}}$ = 7.7 GeV
- 0-5% centrality
- **All as for 11.5 AGeV (slide 11) and model does not predict significant differences.**
- 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
- It is important to measure both kaons and pions

Pion R(kT) with UrQMD (7.7GeV)

- Analysis was performed using the MpdFemto package developed by our group



- Femtoscopic weigths were estimated using R. Lednicky codes incorporated in MpdFemto
- Centrality bin (20-30%) was estimated by:
  - Impact parameter: 6.6 — 8.1 fm (solid markers)
  - Reference multiplicity range (charged particles with pT > 0.1 GeV/c and η<0.5): 72 — 106 (open markers)
- Both centrality definitions give similar results (< 5% difference)
- Both agree with STAR data **PHYSYCAL REVIEW C92, 014904 (2015)**

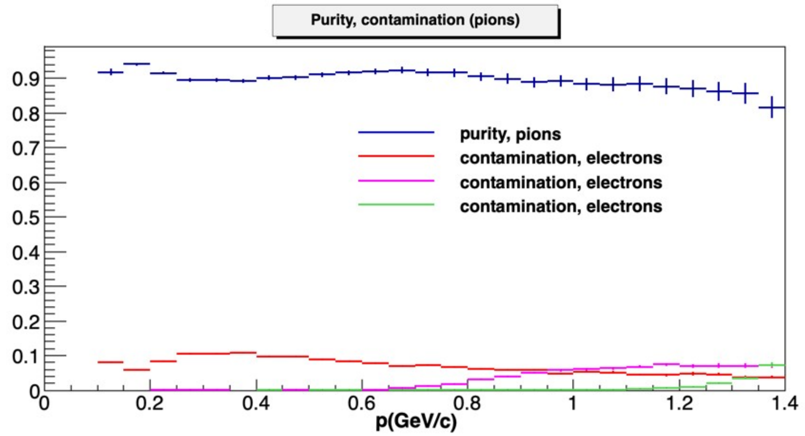
First tests with reconstructed data : pions PID

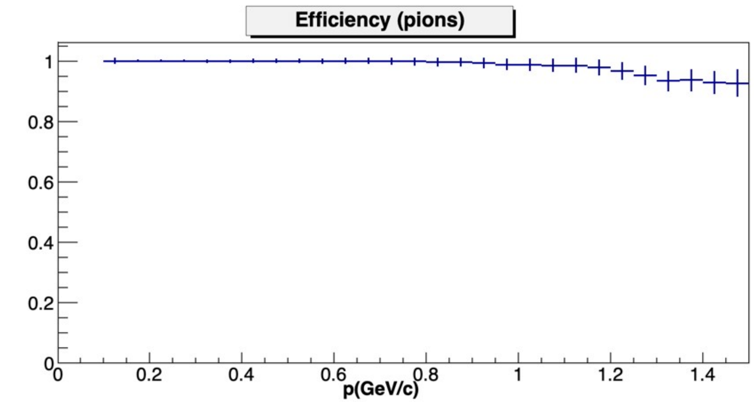
Combined (TPC + TOF) PID method of A. Mudrokh was used with sigM =2 distance from the average mass-squared value & sigE=2 – distance from the average dE/dx value, tuned for UrQMD

Data selection: Global tracks, $N_{hits} \geq 20$, $|\eta| < 1.0$

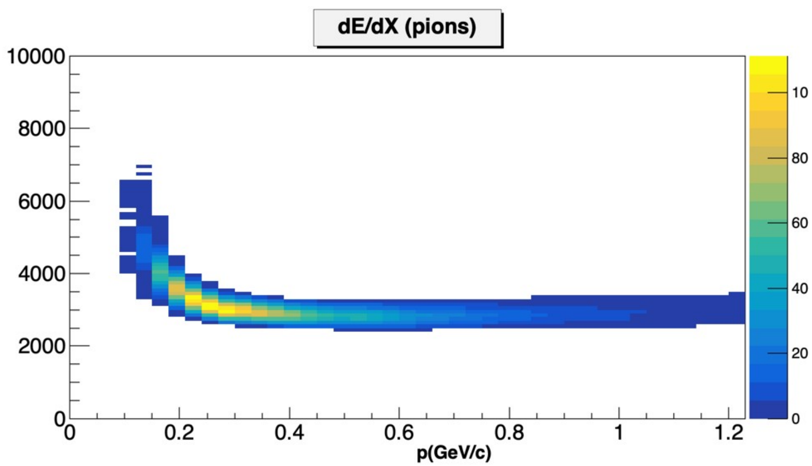
Purity =N_true_pions_reconstructed_as_pions / N_all_reconstracted as pions

Efficiency = N_all_generated_pions / N_of_them_reconstracted as pions

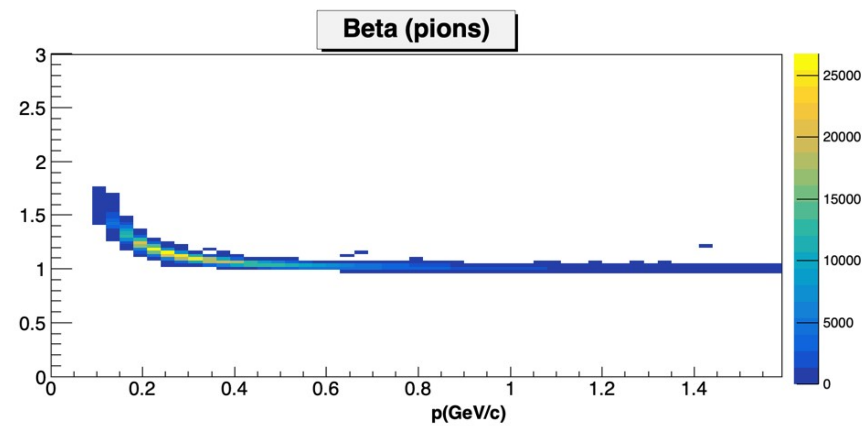




dE/dx of selected pions



beta of selected pions



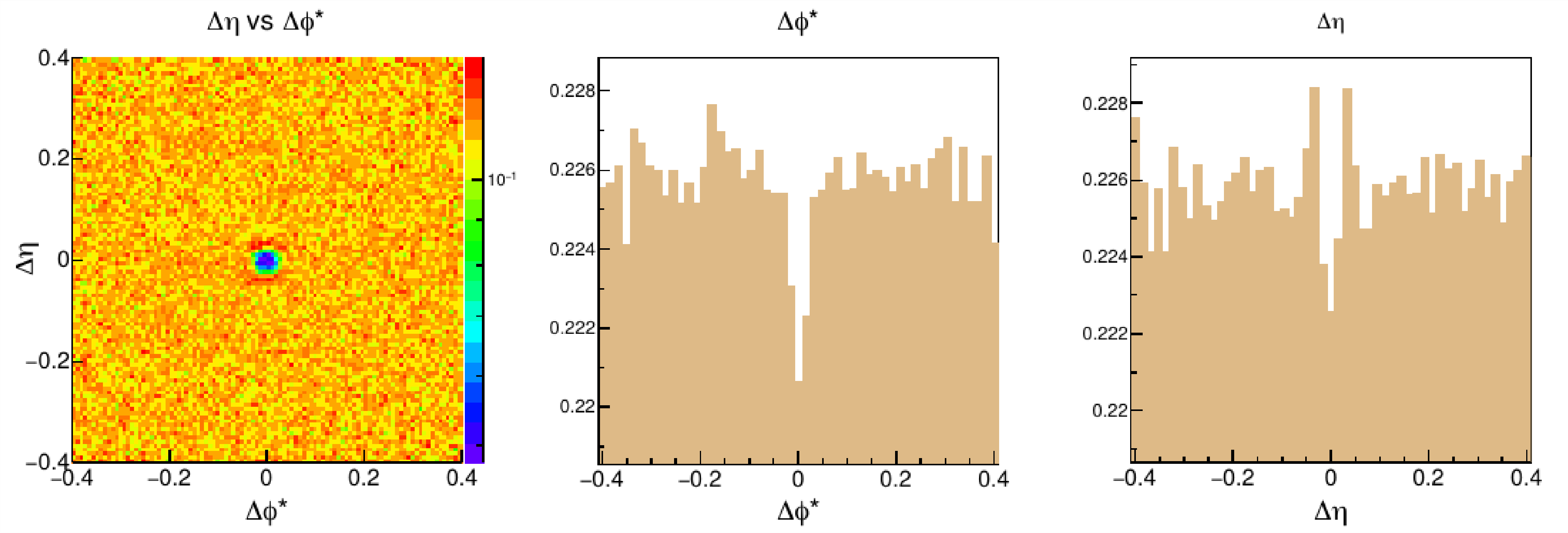
Pion selection looks reasonable, can be further improved.

First tests with reconstructed data : two-tracks effects

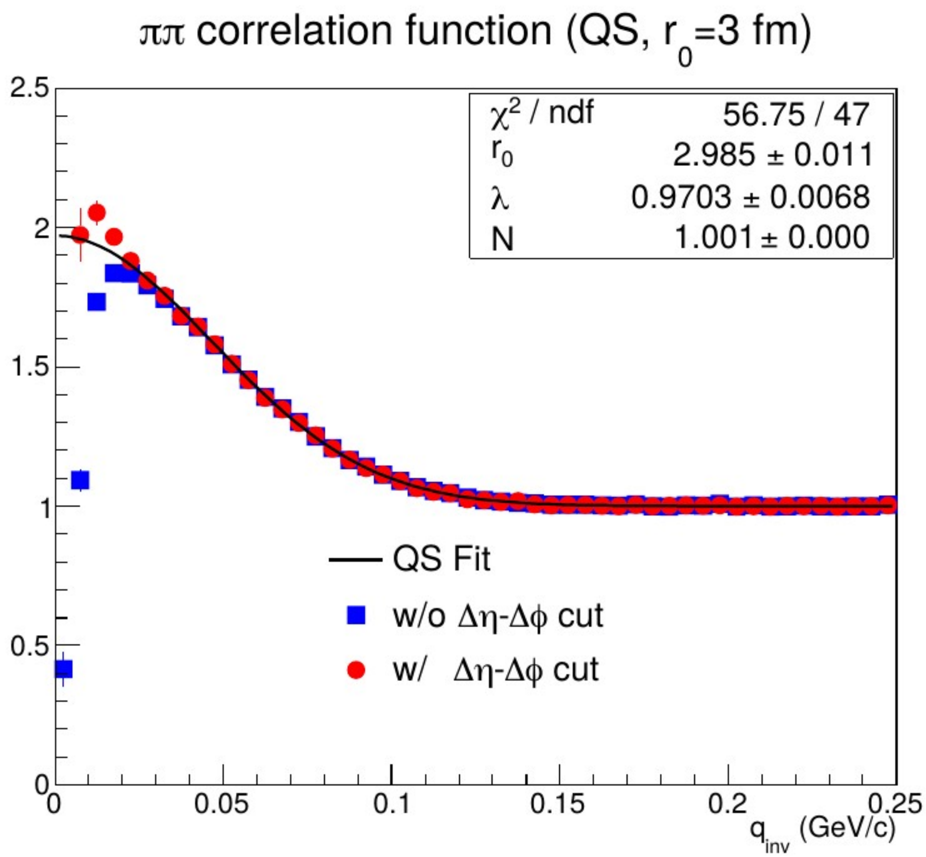
Δη-Δφ* with MPD reconstructed tracks

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

R is a given cylindrical radius
Φ1,2 are azimuthal angles of track at reconstructed vertex



First tests with reconstructed data : two-tracks effects



cut Δη<0.04 and Δφ*<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)

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

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

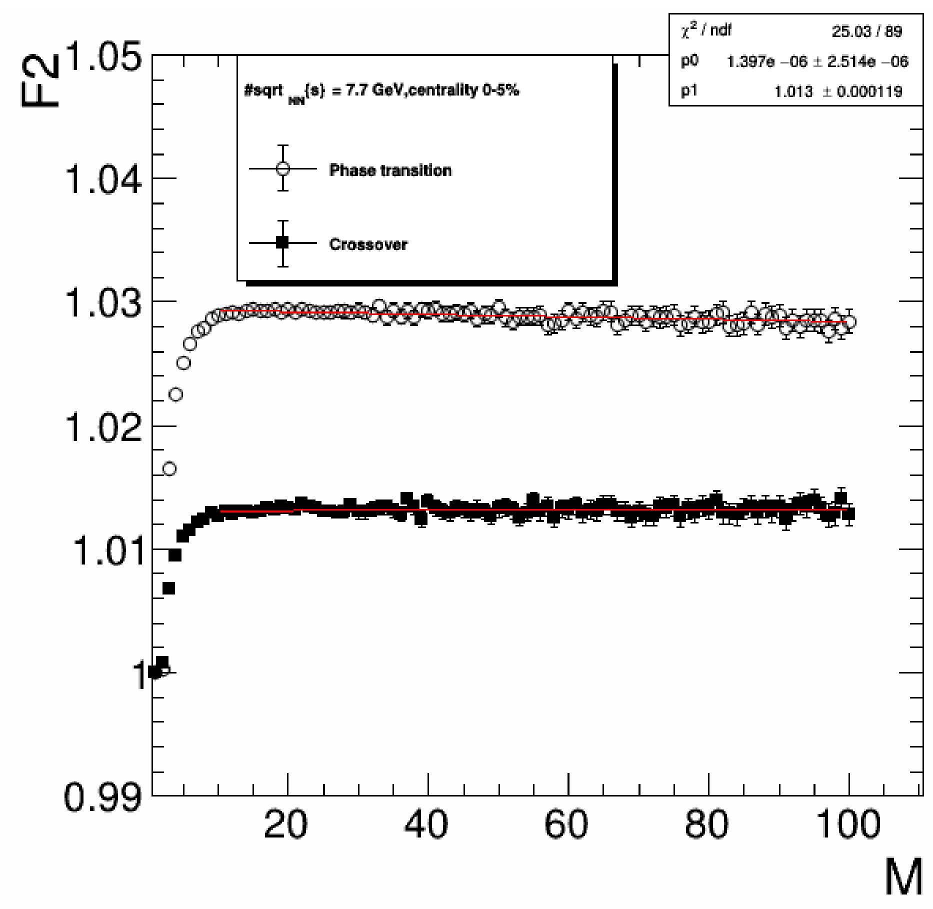
Note: there is a set of definitions of moments and cumulants.

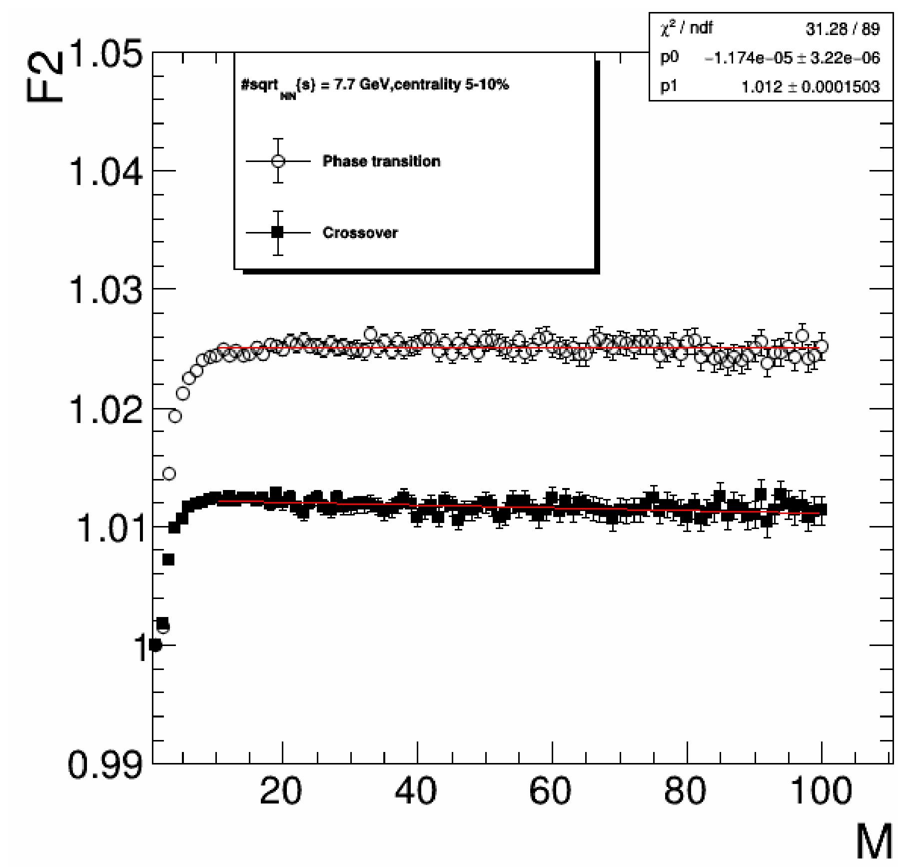
of the rapidity distribution on the size δy (*Δ*y/M, M is the number of bins, *Δ*y is the size of the mid rapidity window):

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.

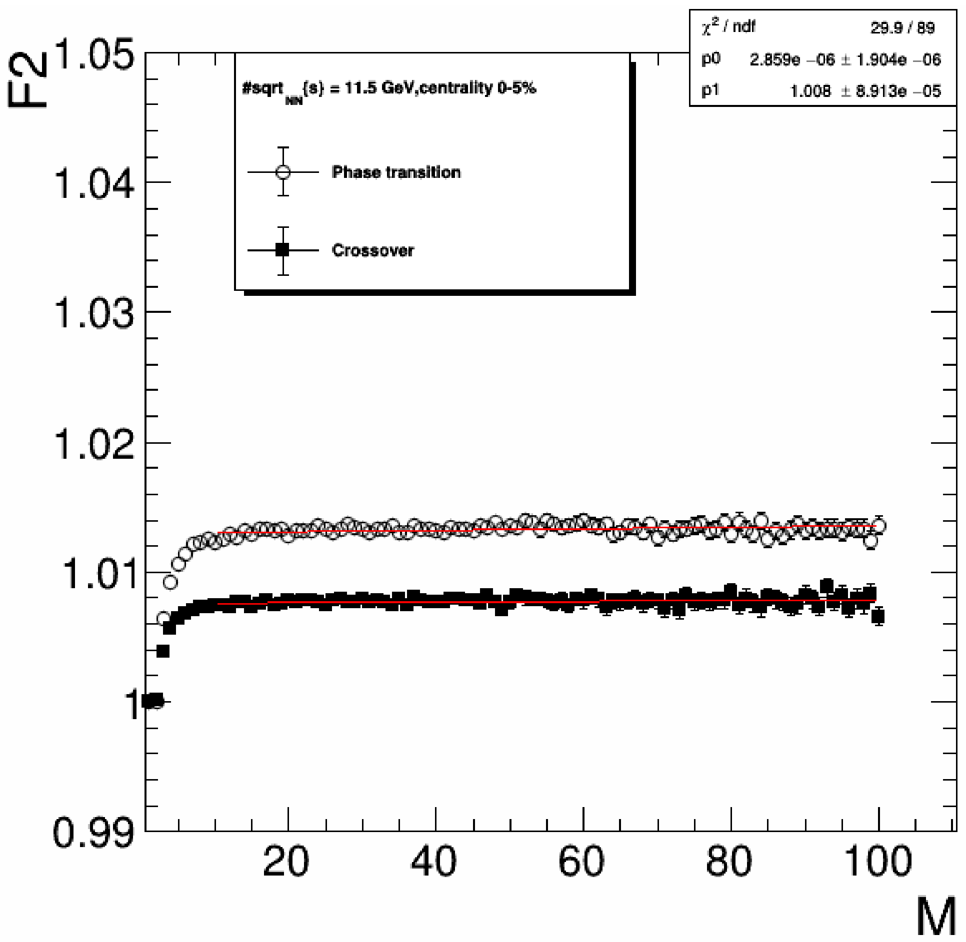
Factorial Moments with vHLLE+UrQMD (7.7GeV)

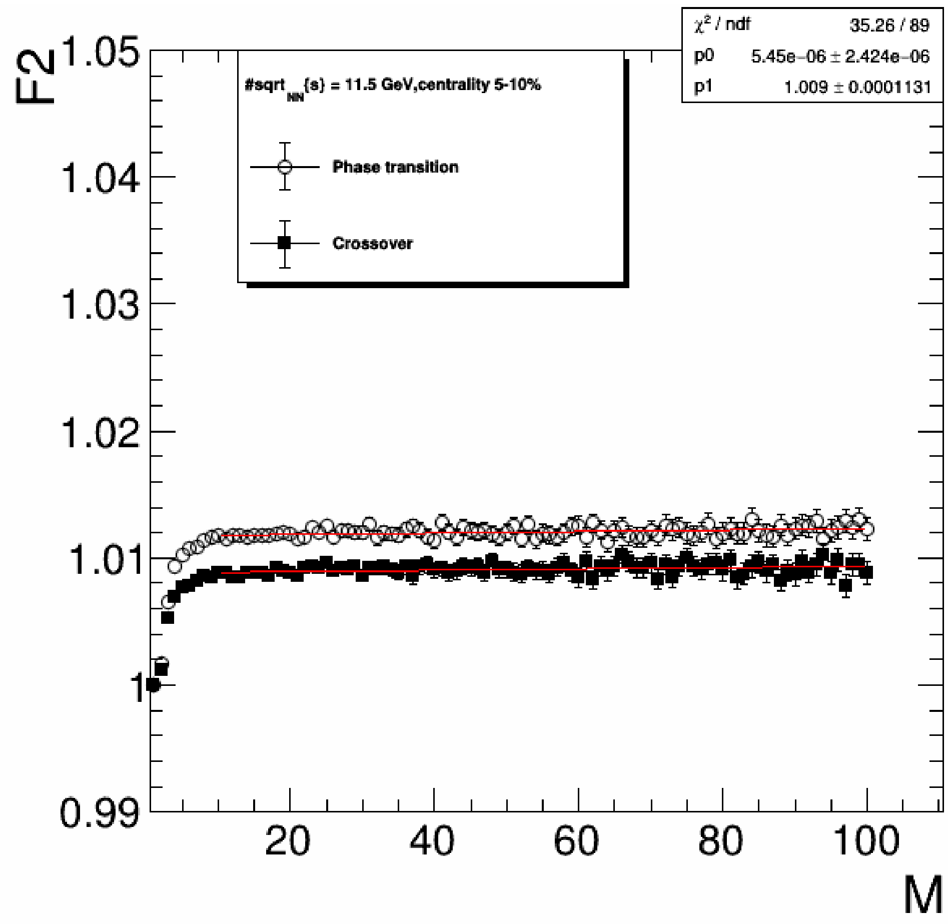




Fit the level of maximum with polinom of the first order: a+b x M
b is of the order of 10^{-6}

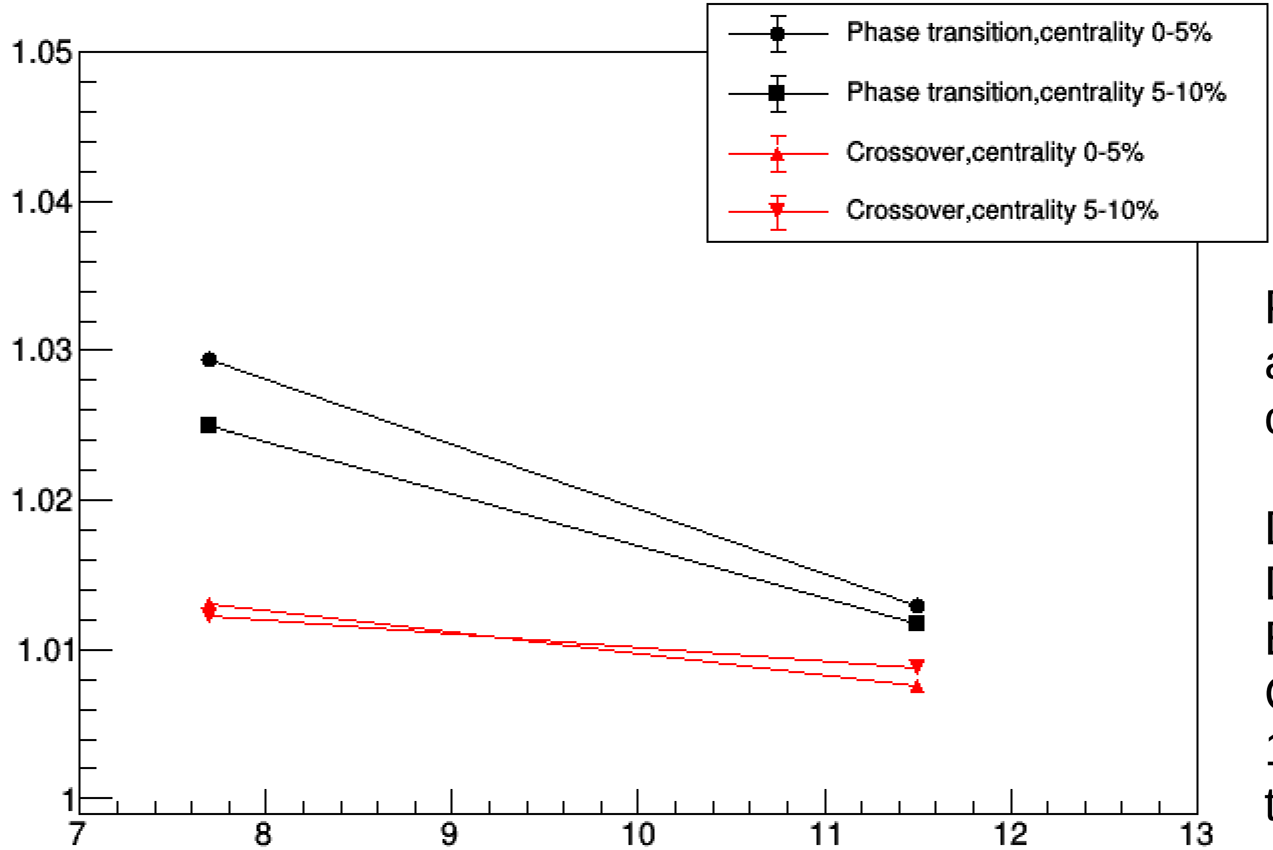
Factorial Moments with vHLLE+UrQMD (11.5 GeV)





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

Other activities we do:

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)

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

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

Additional slides

vHLLE+UrQMD model

Pre-thermal phase → hydrodynamic phase → hadronic cascade

UrQMD | vHLLE | UrQMD

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 $\tau 0$ is taken to be equal to the average time for the two colliding nuclei to completely pass through each other:

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

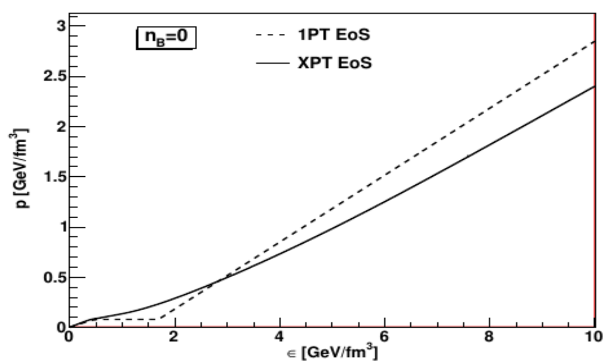
At $\tau = \tau 0$ energy, momentum and baryon/electric charges of hadrons are distributed to fluid cells ijk around each hadron's position according to Gaussian profiles

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

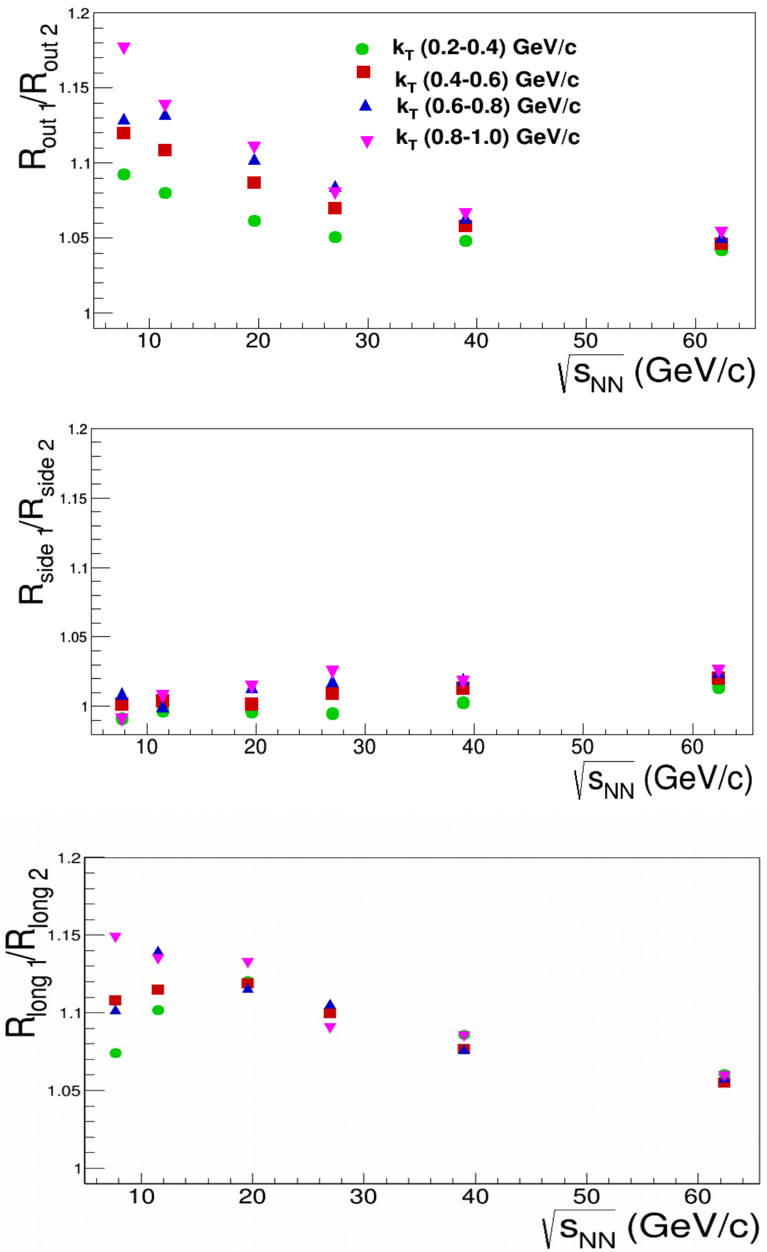


Fluid to particle transition, or particlization, is set to happen at a hypersurface of constant (hydrodynamic) energy density sw = 0.5 GeV/fm3 ,

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.

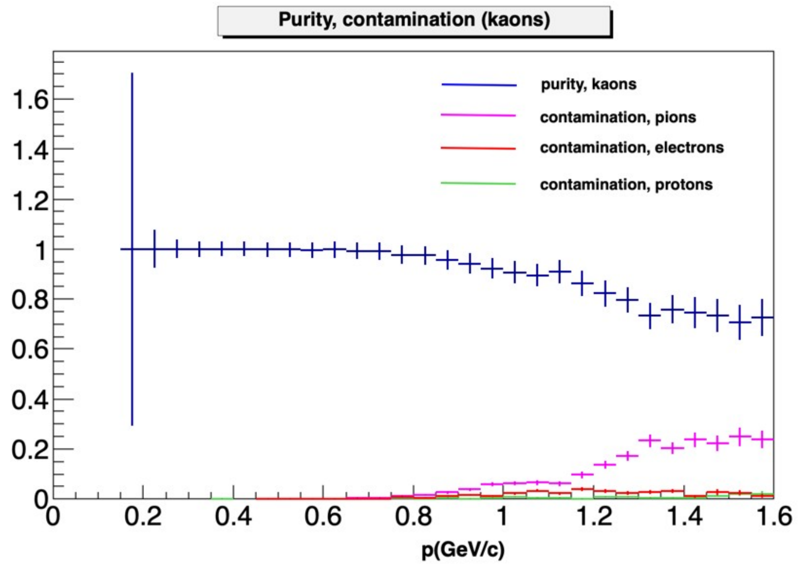
Ratio of $R_{out,side,long}$(1PT)/$R_{out,side,long}$ (XPT) vs. $\sqrt{s_{NN}}$

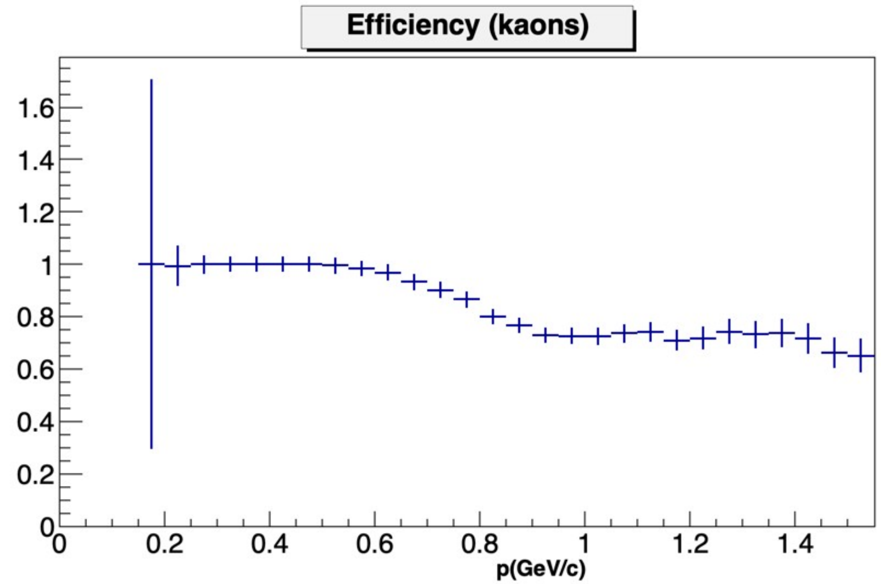


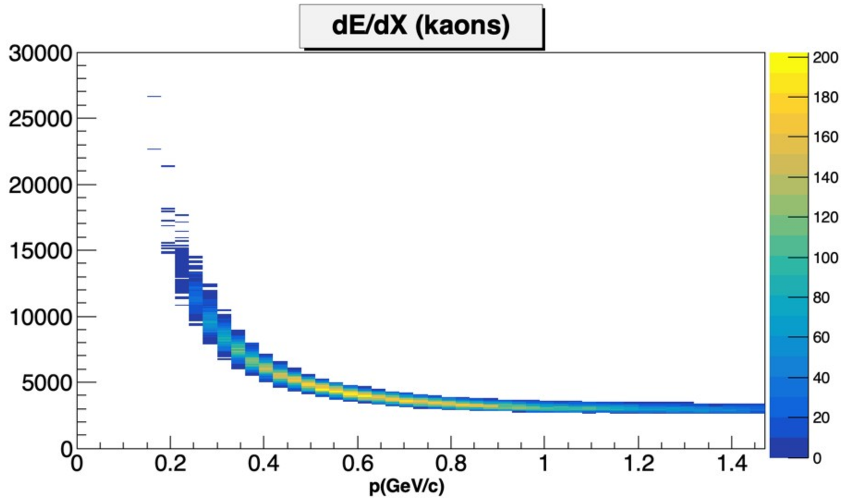
- Pion k_T divided into 4 bins
- R_{side} ratio practically coincide for both scenarios
- R_{out} and R_{long} ratios for 1PT EoS are greater than for XPT EoS and demonstrating a strong k_T -dependence at low energy

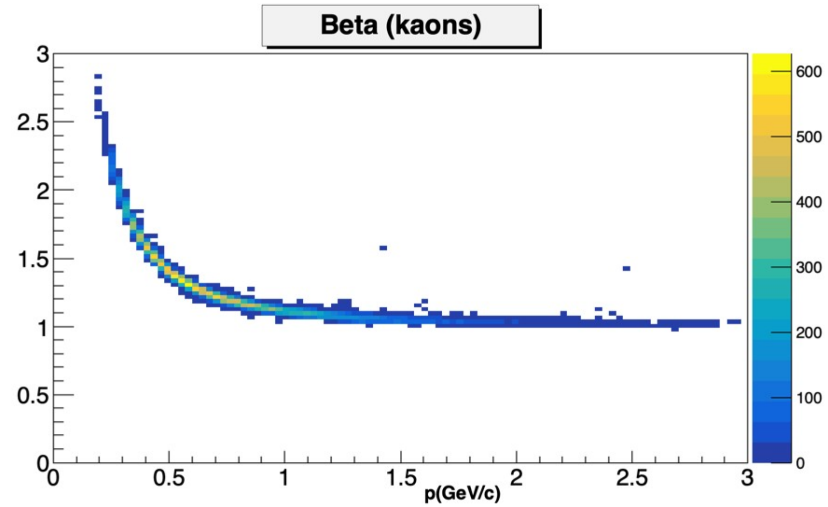
- The difference comes from a weaker transverse flow developed in the fluid phase with 1PT EoS as compared to XPT EoS and its longer lifetime in 1PT EoS

First tests with reconstructed data : kaons PID









First tests with reconstructed data : protons PID