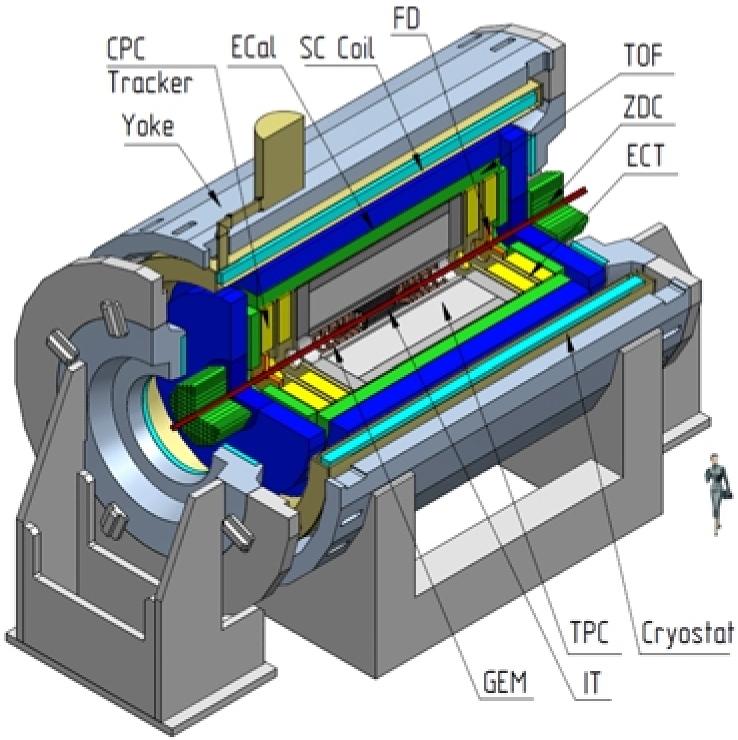
Study of strongly interacting matter properties at the energies of the NICA collider using the methods of femtoscopy and factorial moments

within the RFBR Mega Grant # 18-02-40044

People:

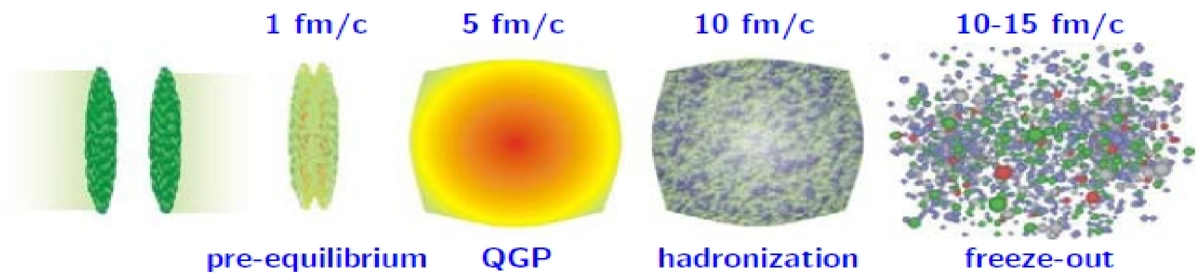
- Ludmila Malinina (SINP MSU, JINR),
- Konstantin Mikhaylov (ITEP & JINR), convener
- Grigory Nigmatkulov (NRNU MEPhI),
- Olga Kodolova (SINP MSU),
- Igor Lokhtin (SINP MSU),
- Gleb Romanenko (student, MSU),
- Marya Cheremnova (student, MSU)
– Yevheniia Khyzniak (PhD student, NRNU MEPhI)
– Chernishov Alexey (student MSU)
– Egor Alpatov (student NRNU MEPhI)

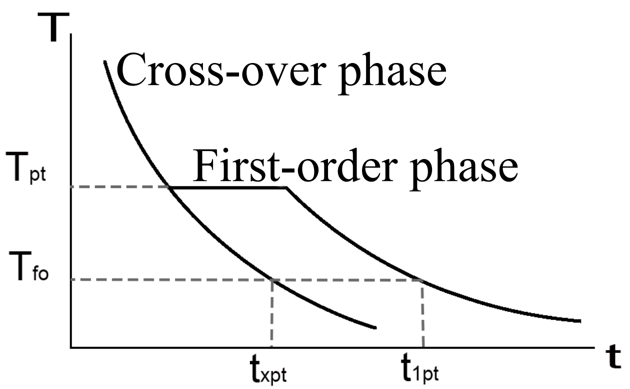


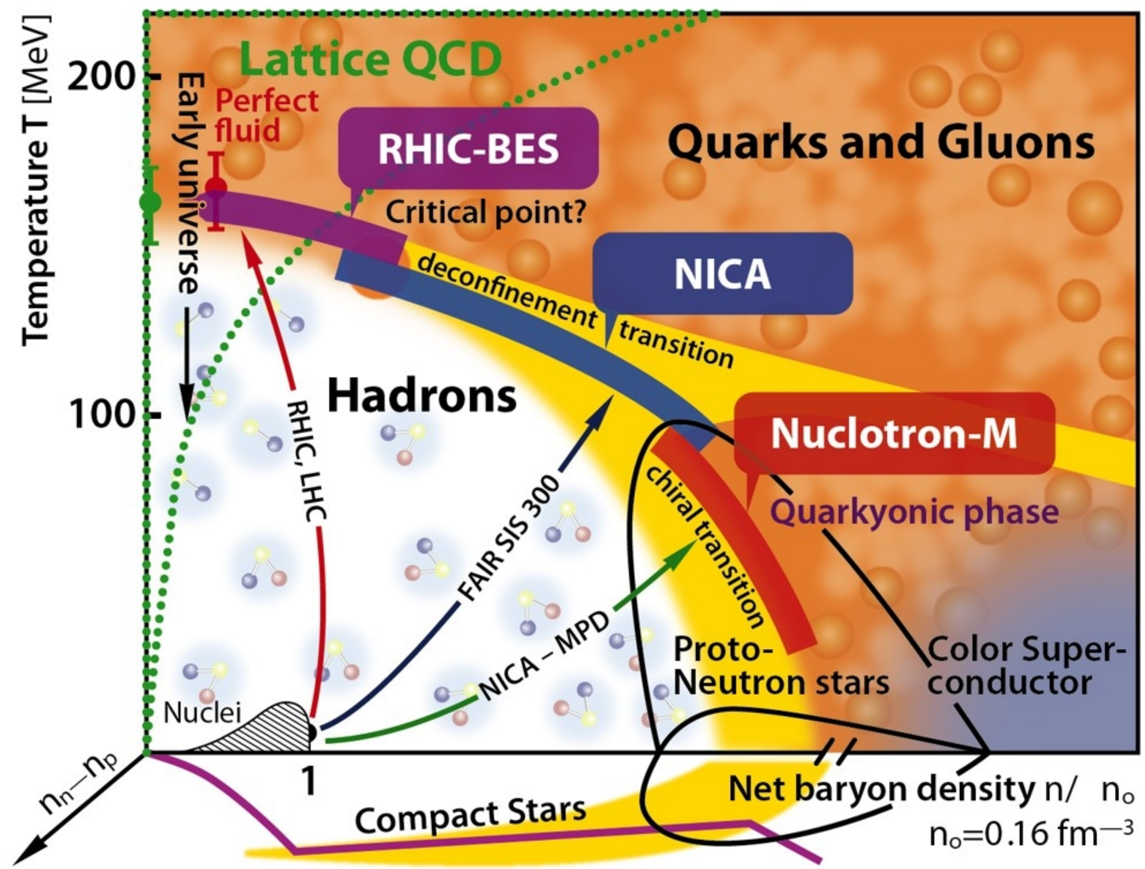
Motivation: Phase diagram QCD

- Crossover transition to QGP occurs at RHIC & LHC

- 1st order phase transition to QGP occurs at lower energies (?)







- Beam Energy Scan (BES) program: search for location of transition point from Crossover (XPT) to 1st order (1PT) phase transitions

- BES RHIC ($\sqrt{s}$=3-60 GeV)
- NA61@SPS (E_{lab}=10-158 GeV);
- projects: CBM@FAIR (GSI) и **MPD@NICA (JINR)**

Hybrid (hydro+hadron gas) vHLLE+UrQMD model

Pre-thermal phase → hydrodynamic phase → hadronic cascade

UrQMD — vHLLE — UrQMD

(3+1)-D viscous hydrodynamics

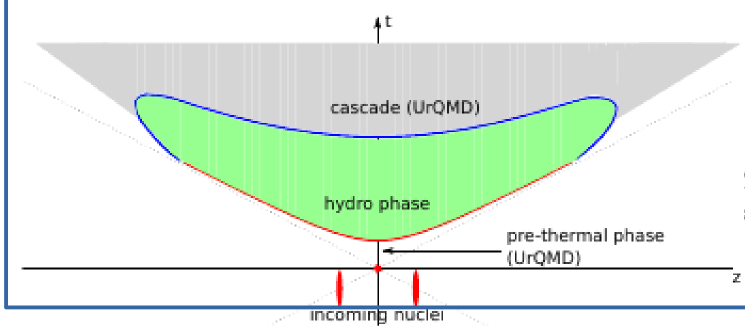
Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978,1509.3751 , talk QM2015

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 τ0 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 τ = τ0 energy, momentum and baryon/electric charges of hadrons are distributed to fluid cells ijk around each hadron's position according to Gaussian

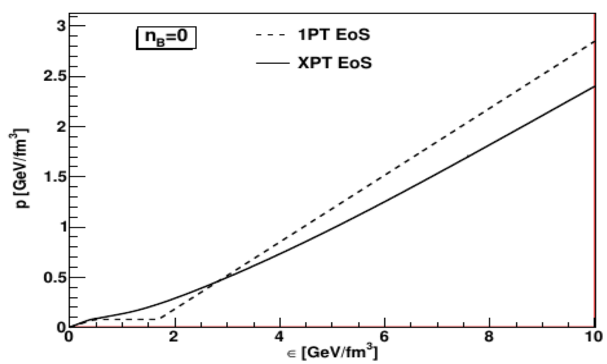


VHLLE (3+1)-D viscous hydrodynamics

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.

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	Hydrodynamic phase	Hadronic cascade
UrQMD	vHLLE (3+1)-D viscous hydrodynamics	UrQMD

The transition to hydrodynamics occurs at a hyper-surface of constant longitudinal proper time τ_0
Minimal value of the starting time τ0 is taken to be equal to the average time for the two colliding nuclei to completely pass through each other:

Parameters τ_0 , $R_\perp$, R_η and η/s adjusted using basic observables in the RHIC BES-I region.

Model tuned by matching with existing experimental data from SPS and BES-I RHIC

<u>EoS to be used in the model</u>

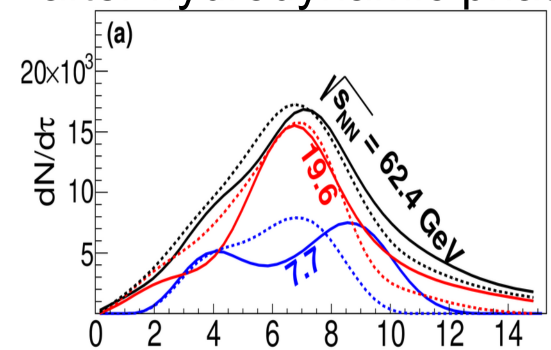
- Chiral EoS — crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model
  1st-order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

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

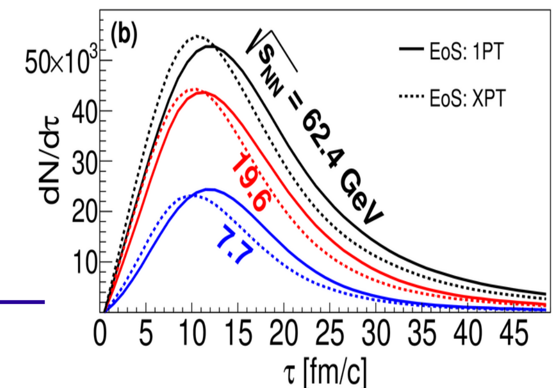
Fluid to particle transition at energy density = 0.5 GeV/fm^3

<u>Pion emission time</u>

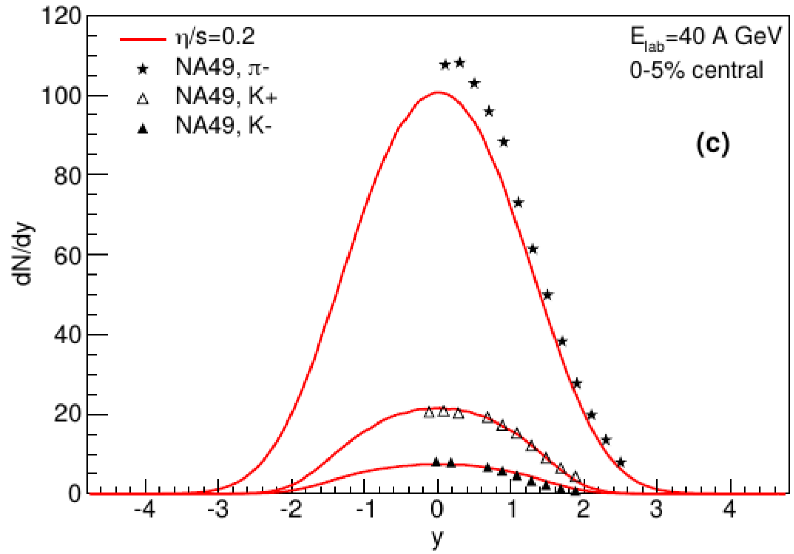
after hydrodynamic phase

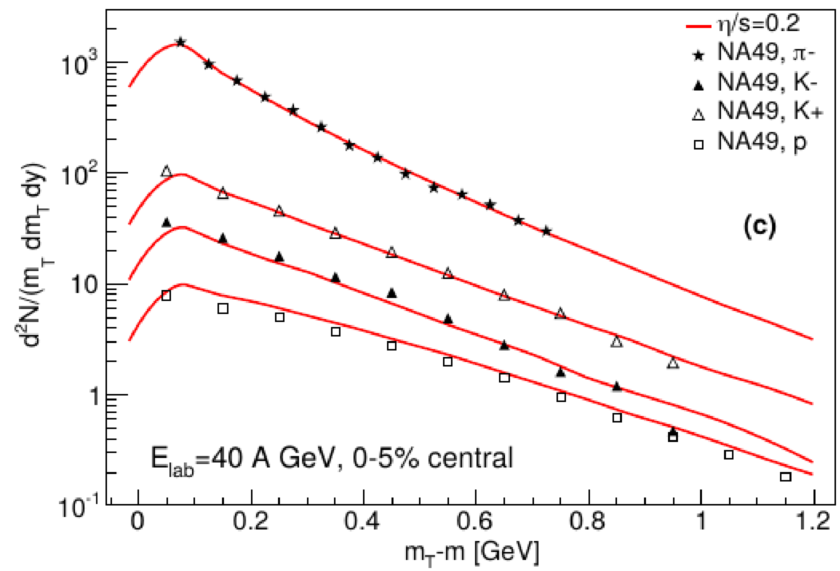


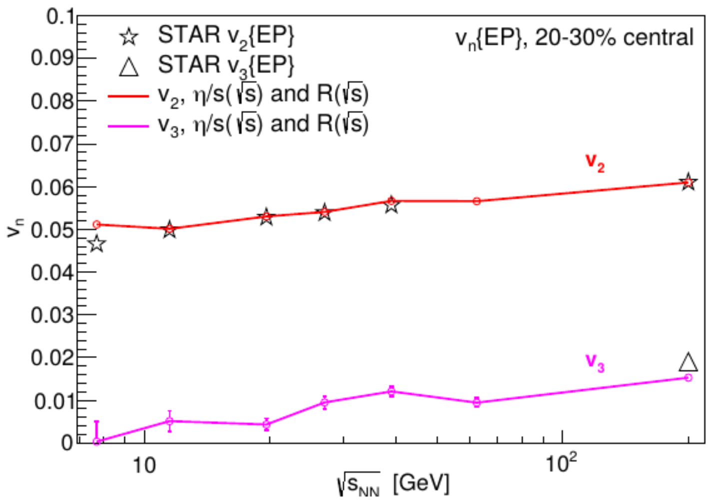
after cascade



Examples of vHLEE+UrQMD with XPT calculations for bulk observables



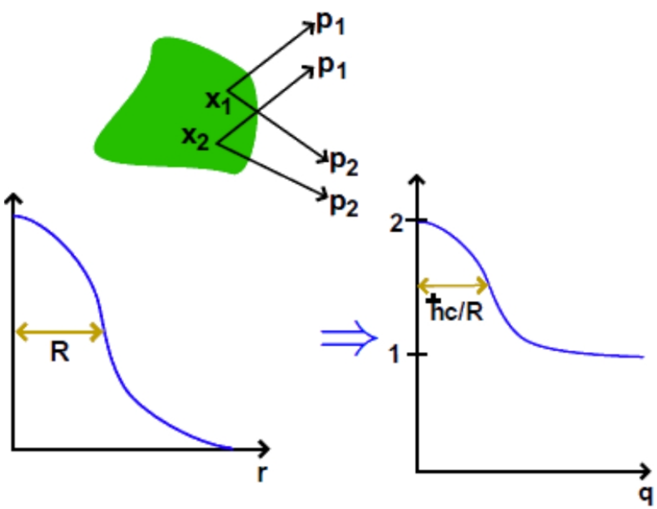




Adjustment to experimental data suggests
$\eta/s = 0.2 \rightarrow 0.08$ when
$\sqrt{s} = 7.7 \rightarrow 200$ GeV, modulo initial state (UrQMD) and EoS (Chiral model) used.

Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978,1509.3751 , talk QM2015

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

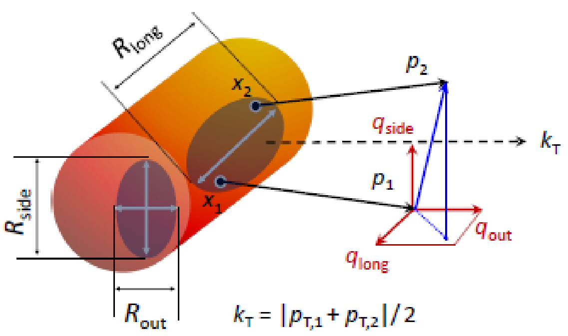
experiment: $$C(q)=\frac{S(q)}{B(q)},\ q=p_1-p_2$$

$S(q)$ – 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 analysis:

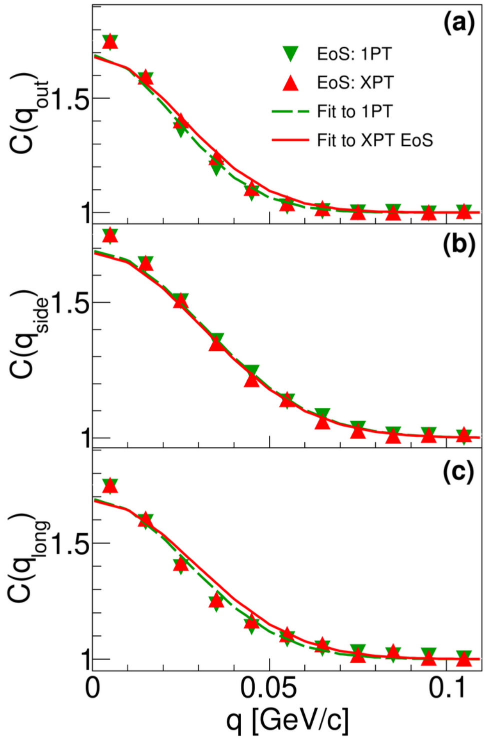
R_{side} sensitive to geometrical transverse size.
R_{long} sensitive to time of freeze-out.
R_{out} / R_{side} sensitive to emission duration.

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

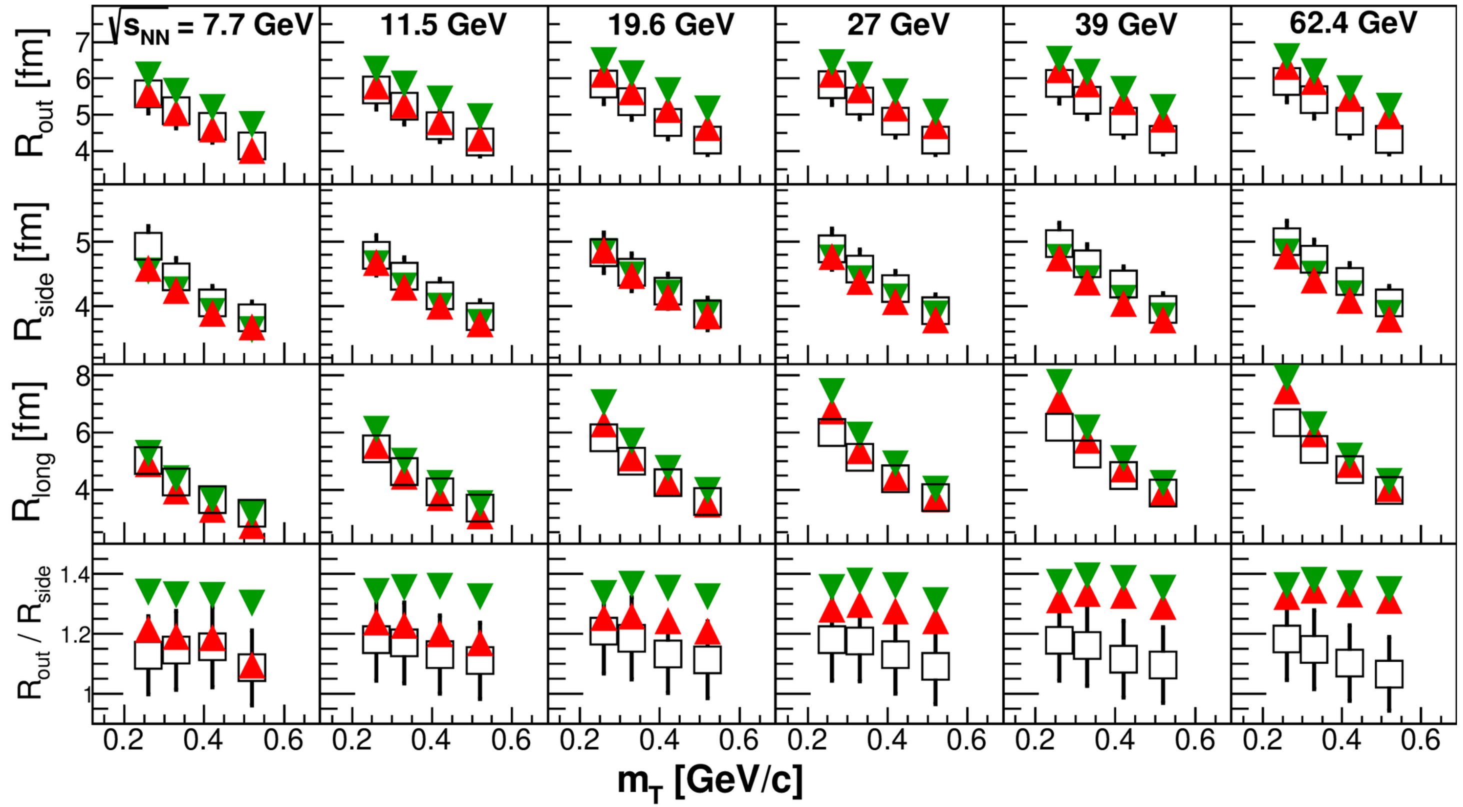
R and q are in Longitudinally Co-Moving Frame (**LCMS**)
long || beam; out || transverse pair velocity $\boldsymbol{v}_T$; side normal to out,long

3D Pion radii with vHLLE model

Projections of 3D Model CF



Phys.Rev. C96 (2017) no.2, 024911



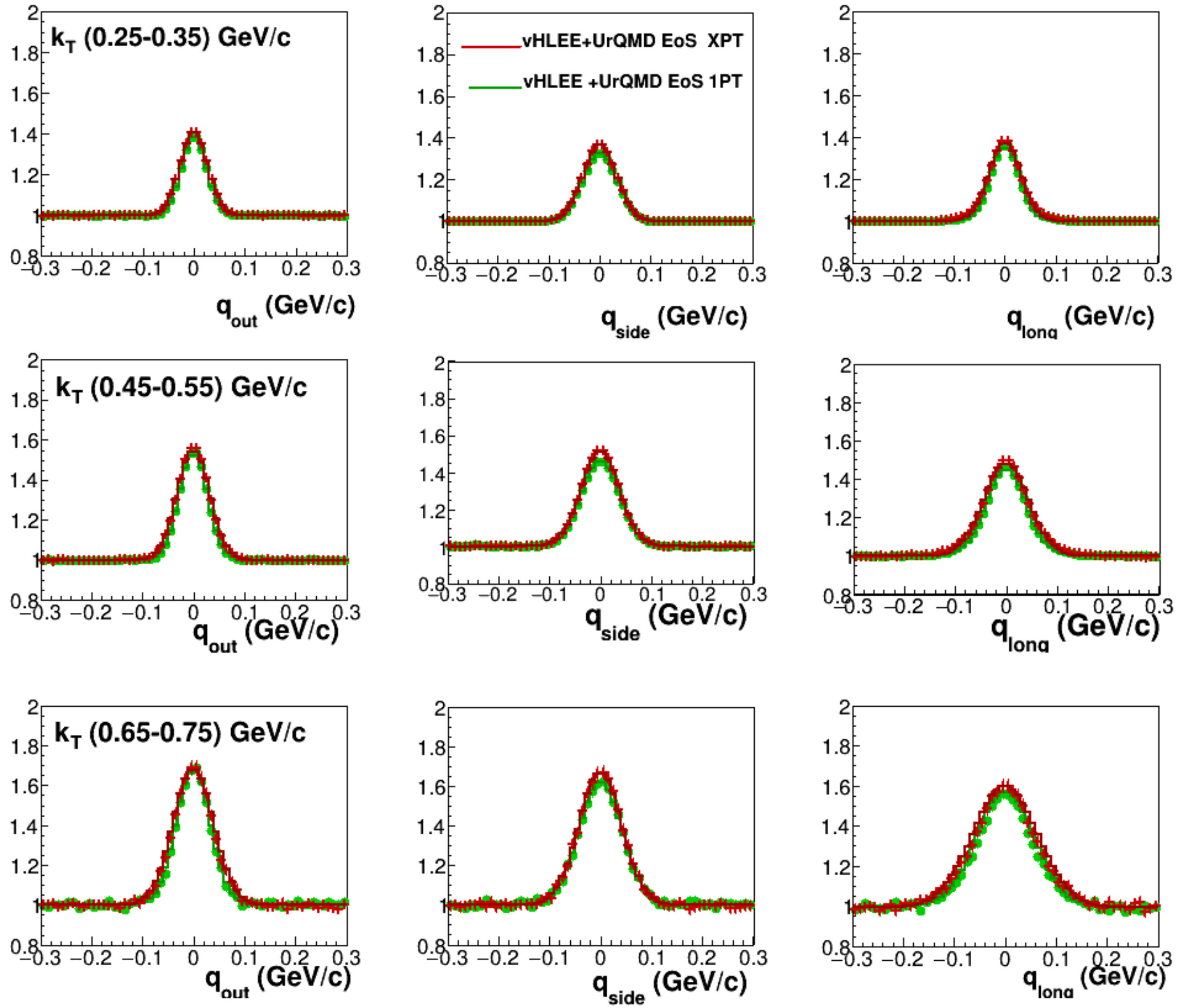
- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS describes better R(mT) dependencies
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT) by value of ~1-2 fm.**
- R_{out} /R_{side} (XPT) agrees with STAR data points at 7.7 and 11.5 GeV, but then increases with increasing collision energy while ratio in data is independent with collision energy; R_{out}/R_{side} for 1PT systematically overestimate data and is independent on collision energy.

3D Pion Correlation Functions with vHLLE model

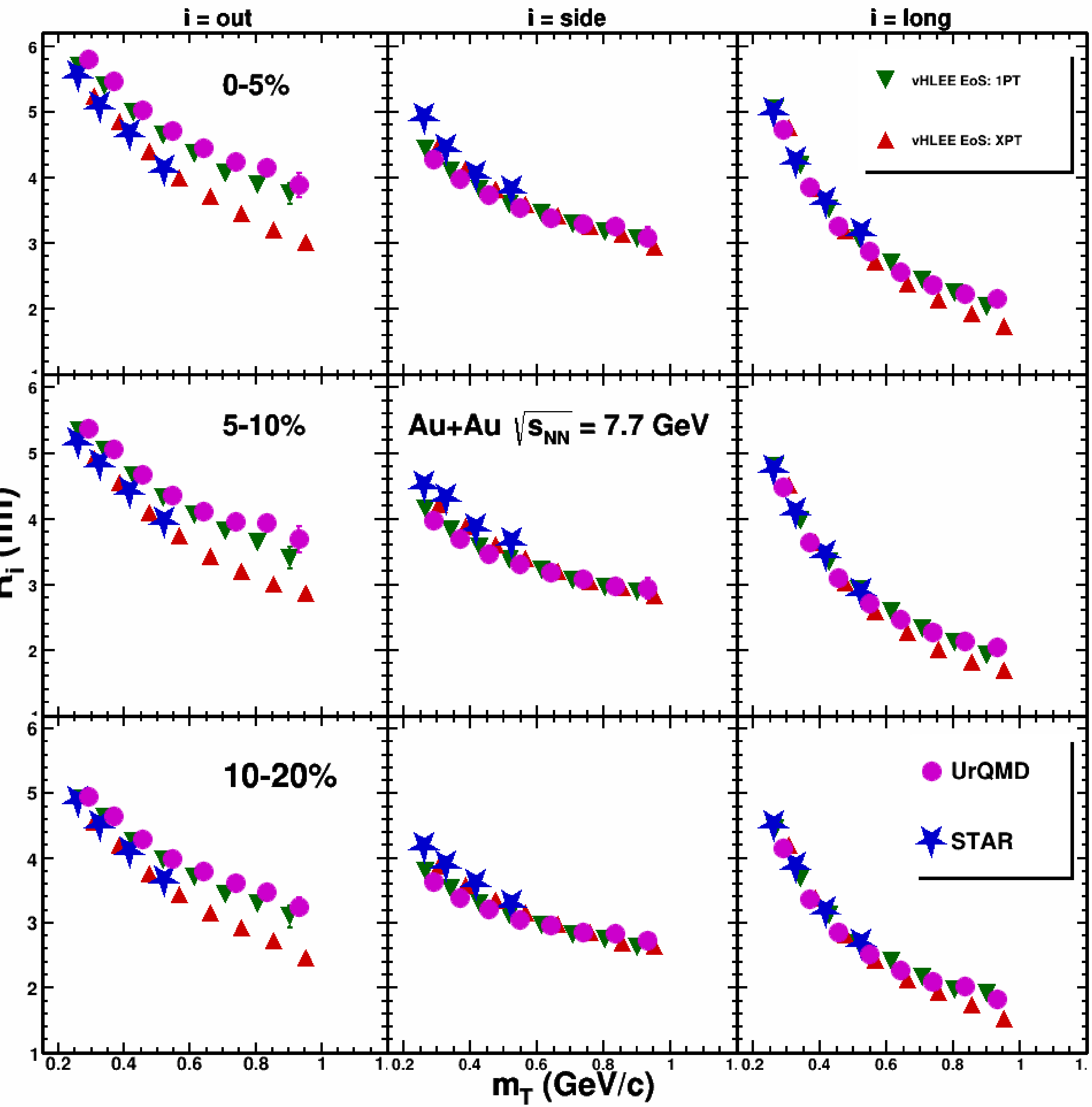
Analysis

- MDP femto package (see Grigory Nigmatkulov's talk)
- We performed analysis of pion and kaon correlations for vHLLE and UrQMD for different centrality ranges
- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV central events vHLLE
- Standard 3D Gaussian fit used
- Projections of 3D pion correlation functions on out-side-long
- XPT CF projections on long direction are wider than 1PT ones
- CF become wider with increasing k_T

1PT -green dots; XPT – red dots

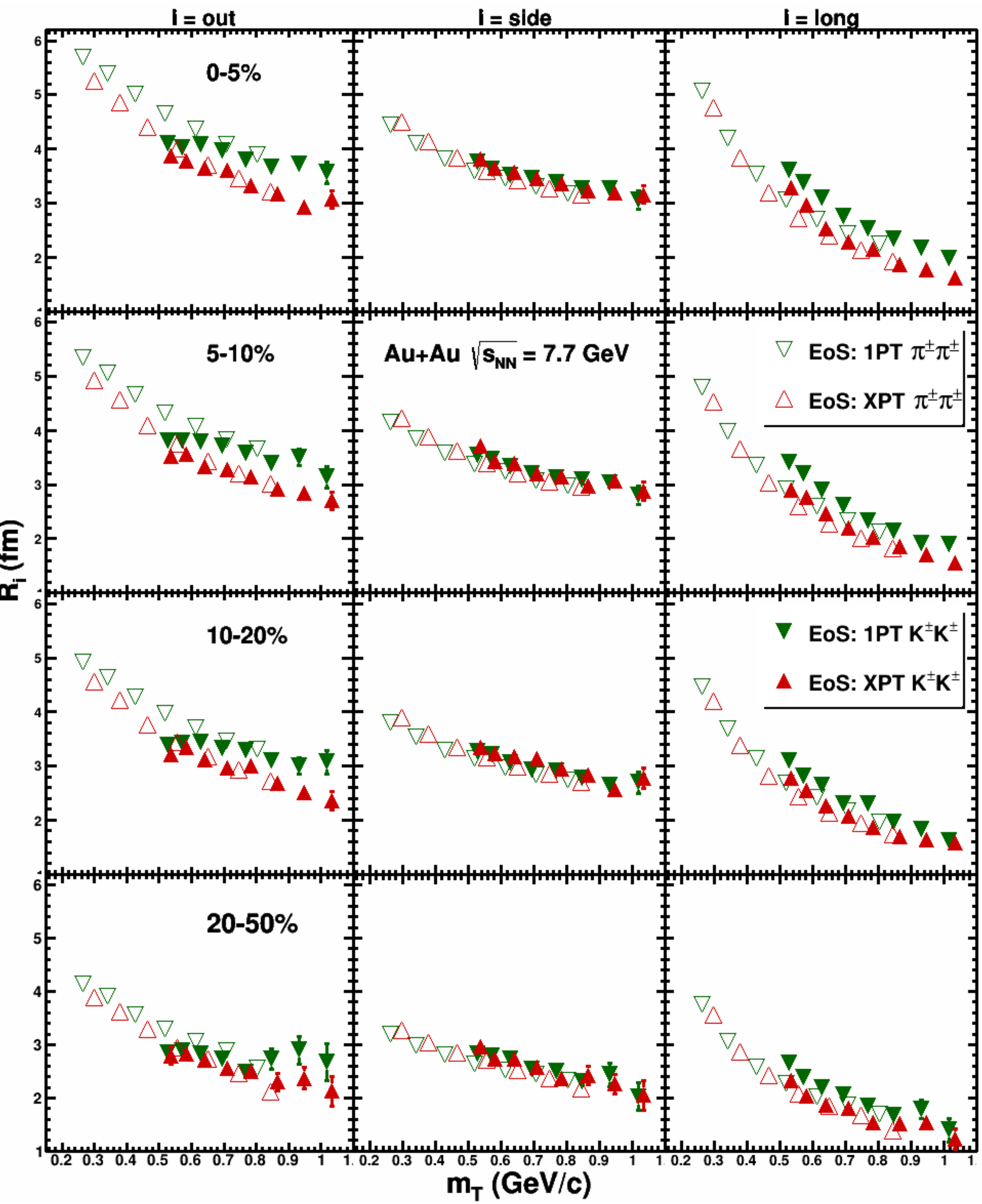


Pion radii with vHLLE and UrQMD models



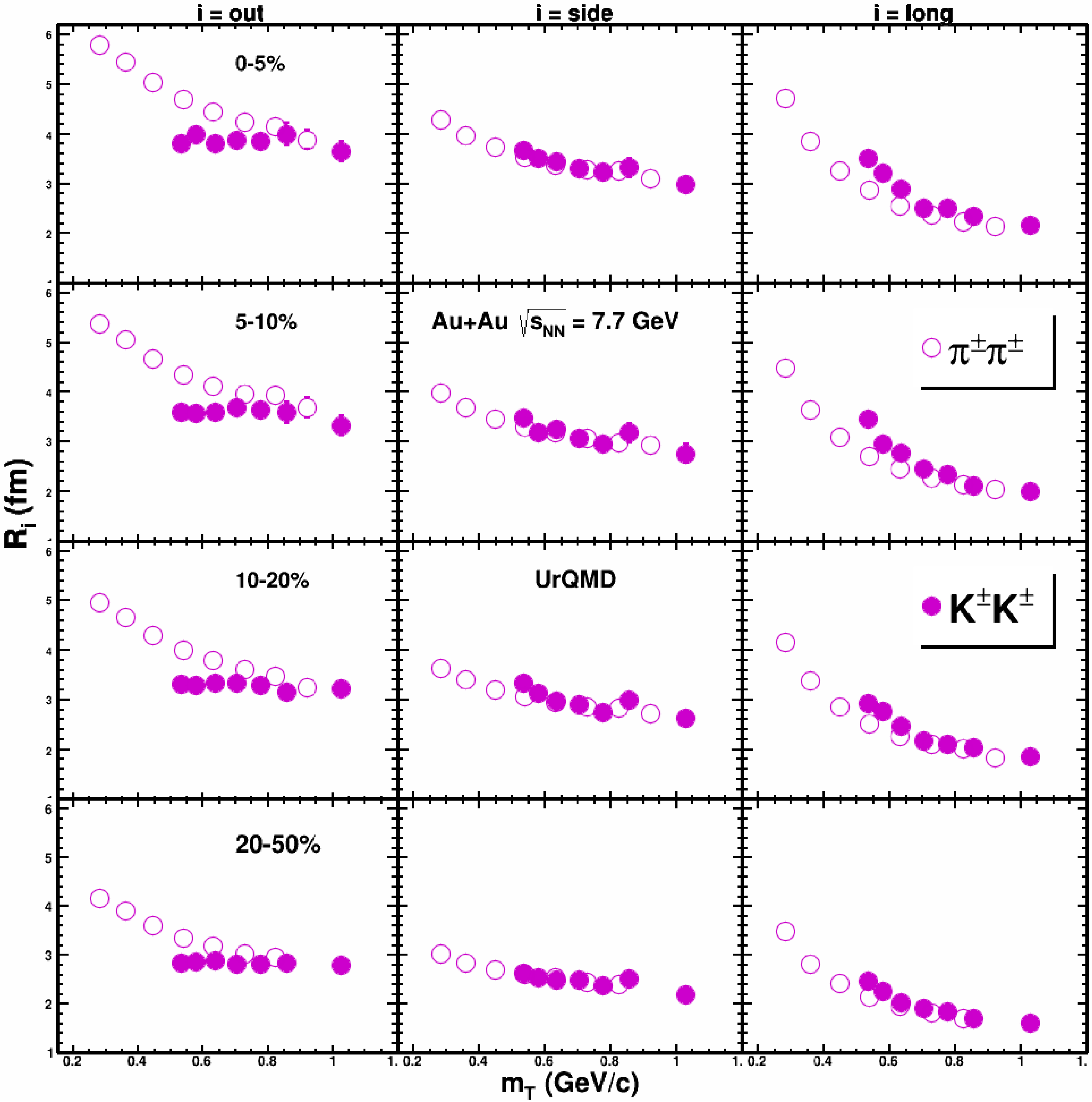
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- It is important to study k_T (m_T) dependence in larger interval than STAR
- Radii decrease with m_T → radial flow
- Increase size with increasing centrality →simple geometric picture of the collisions.
- Crossover EoS describes better $R_{out}(m_T)$
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT)**
- **UrQMD is closed to 1PT**
- The similar trends is observed for AuAu 11.5 GeV

Pion and kaon radii with vHLLE model



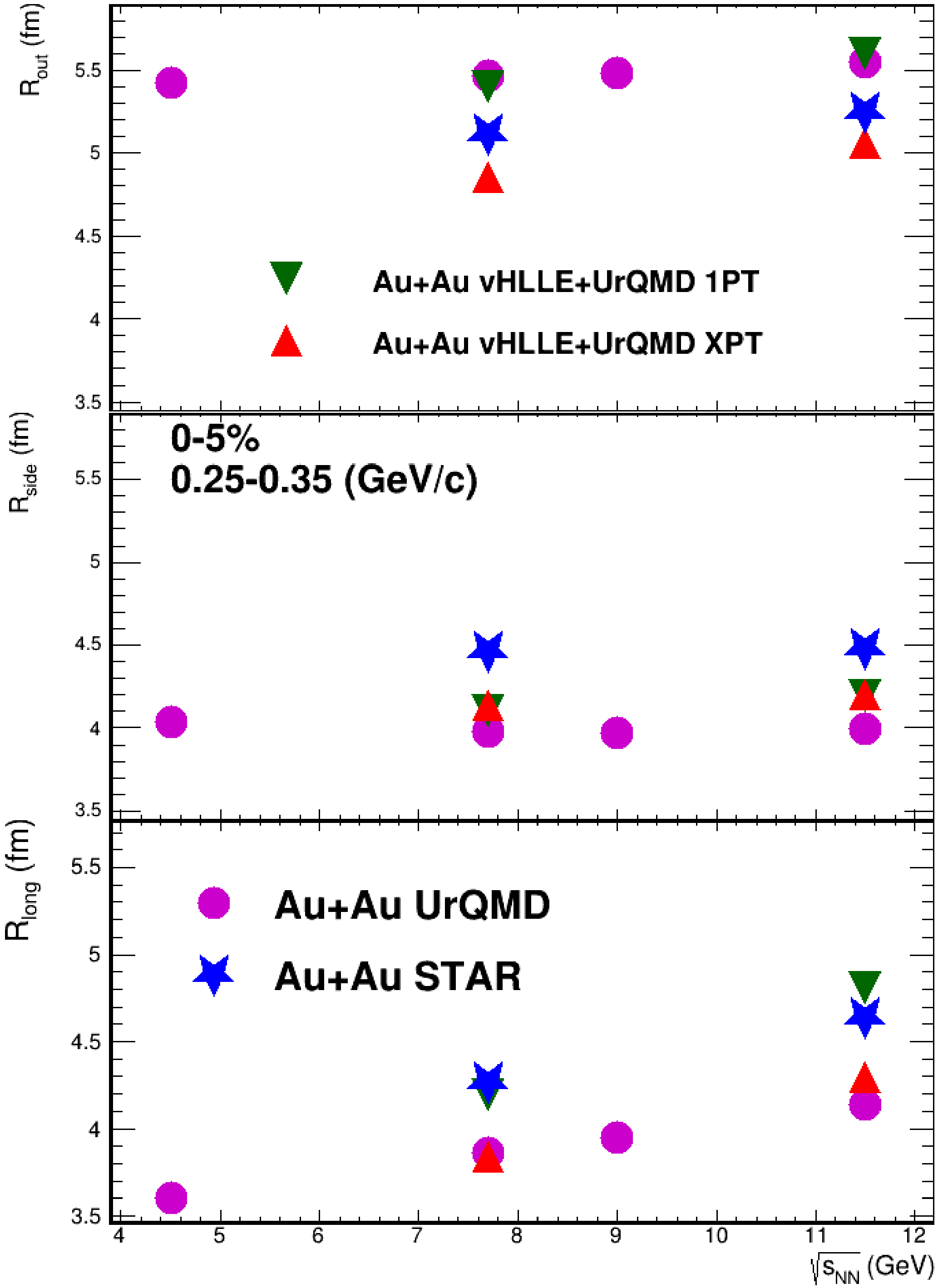
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- Approximate m_T scaling for R_{side}
- Similarly to pions : kaon radii decrease with m_T → radial flow ;
- **for 1PT EoS almost flat dependence R_{out} (m_T) is observed → weaker flow**
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT)**
- R_{long} kaon radii for XPT > R_{long} pion similarly to experiment (LHC & RHIC)
- Very different predictions of vHLLE model for different EoS → importance to study heavier than pions particles → kaons
- The similar trend is observed for AuAu 11.5 GeV

Pion and kaon radii with UrQMD model



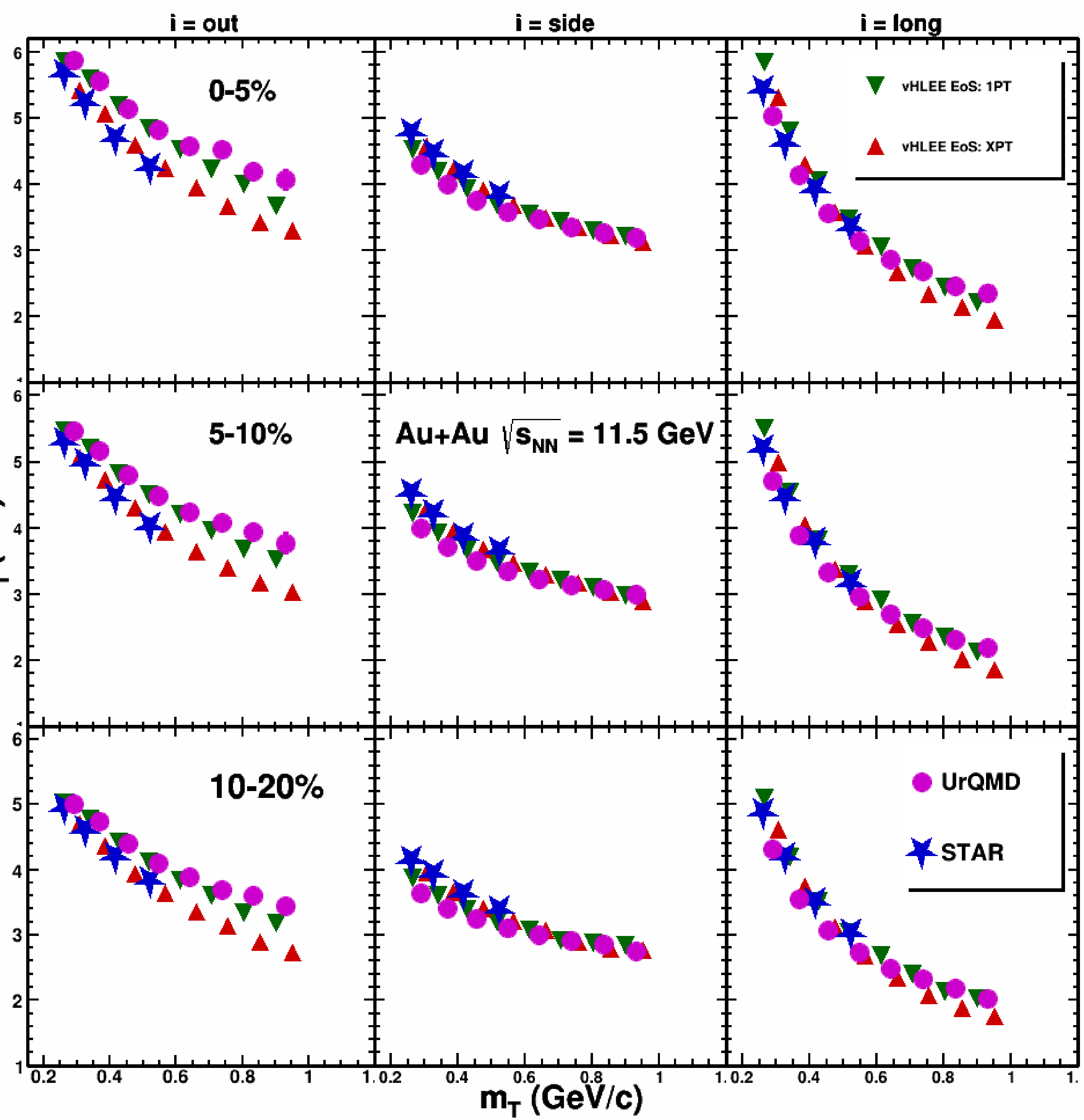
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- **kaon radii demonstrate almost flat behavior similarly to vHLEE with the 1PT EoS →weak flow**
- R_{long} kaon radii are larger than pion ones similarly to experiment (LHC & RHIC)
- The similar trend is observed for AuAu 11.5 GeV

Energy dependence of pion radii



- NICA energy range: $\sqrt{s_{NN}} = 4 – 11$ GeV
- We performed femtoscopic analysis of pions in this energy range using vHLEE and UrQMD models
- There is a lack of systematical high accuracy and high statistics studies of QGP phase transition for this region in the world !

Pion radii with vHLLE and UrQMD models



- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- It is important to study k_T (m_T) dependence in larger interval than STAR
- Radii decrease with m_T → radial flow
- Increase size with increasing centrality →simple geometric picture of the collisions.
- Crossover EoS describes better $R_{out}(m_T)$
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT)**
- **URQMD is closed to 1PT**
- The similar trends is observed for AuAu 11.5 GeV

Introduction: Factorial Moments (intermittency)

Factorial Moments
(see Olga Kodolova's talk)

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

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

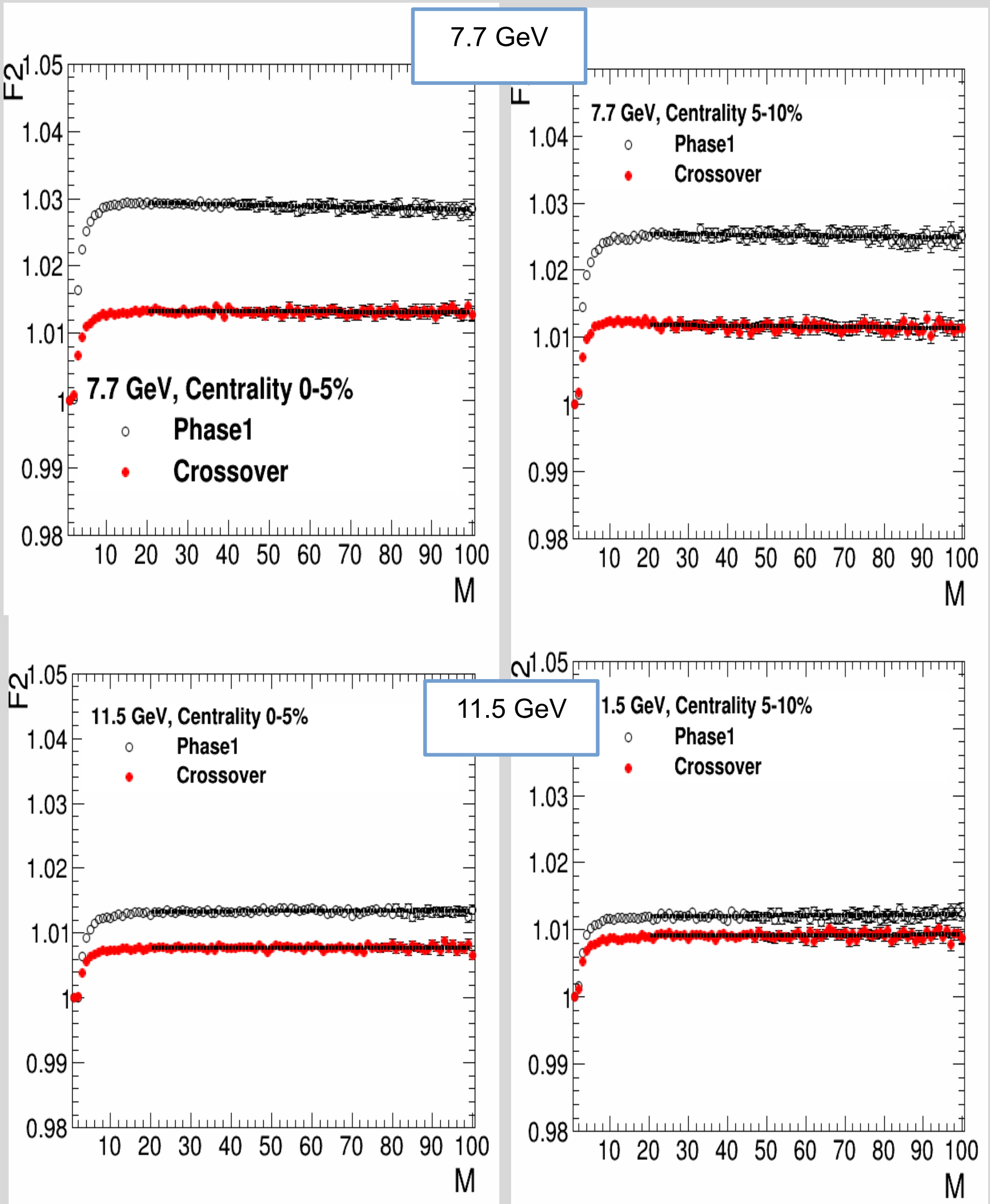
Note: there is a set of definitions of moments and cumulants.

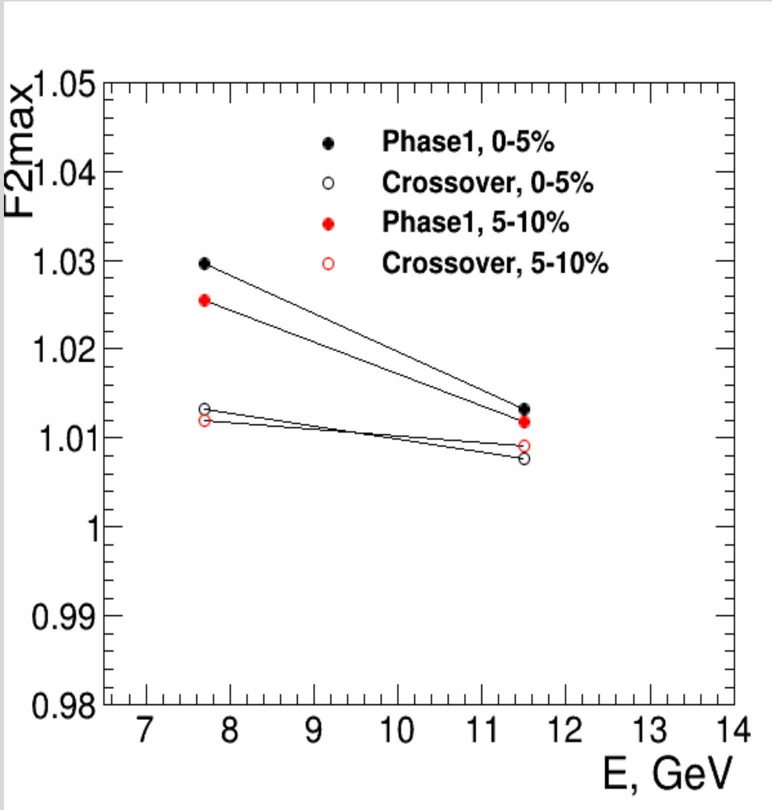
of the rapidity distribution on the size δy (*Δ*y/M, M is the number of bins, *Δ*y is the size of the mid rapidity window):

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.

Au-Au, UrQMD+vHLLE





- Different energy dependence is expected for Crossover and 1st order phase transition
- There is a mild dependence on centrality for 1st order phase transition