Correlation femtoscopy study at NICA energies

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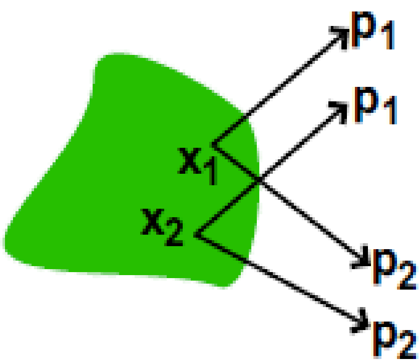
Introduction

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)



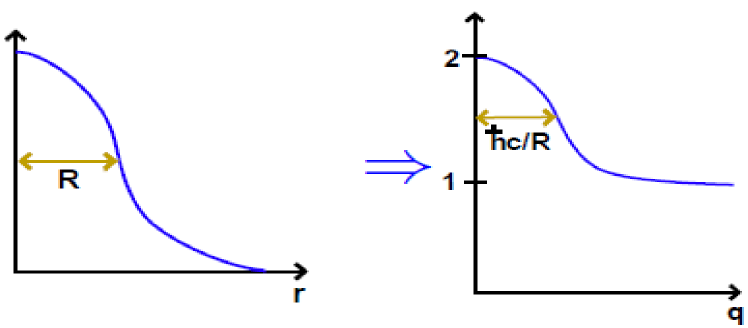
- Two particle Correlation Function (CF):

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

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

$S(q)$ – 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

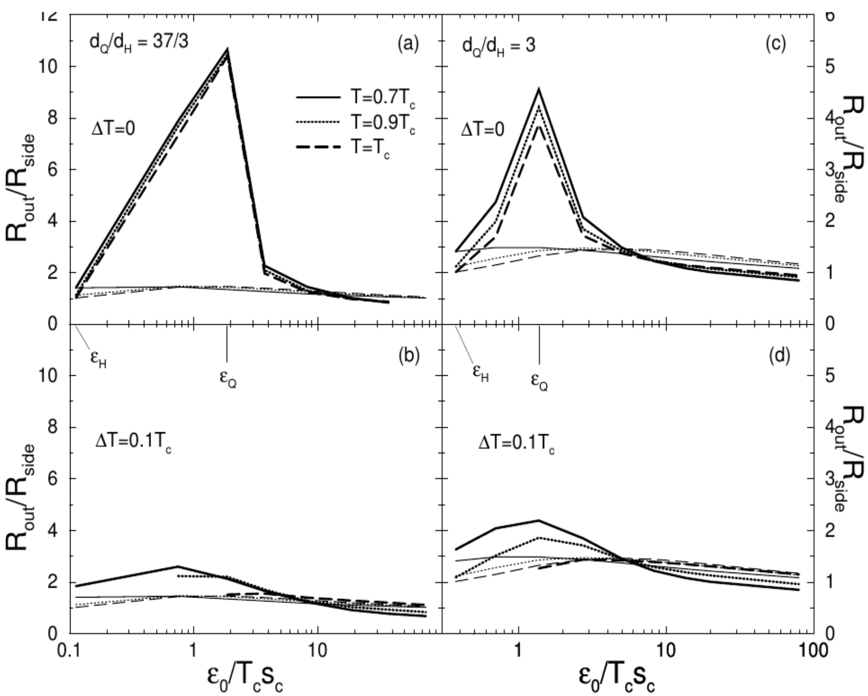
3D: $C(q_{out},q_{side},q_{long})=1+\lambda\exp(-R_{out}^2 q_{out}^2-R_{side}^2 q_{side}^2-R_{long}^2 q_{long}^2)$

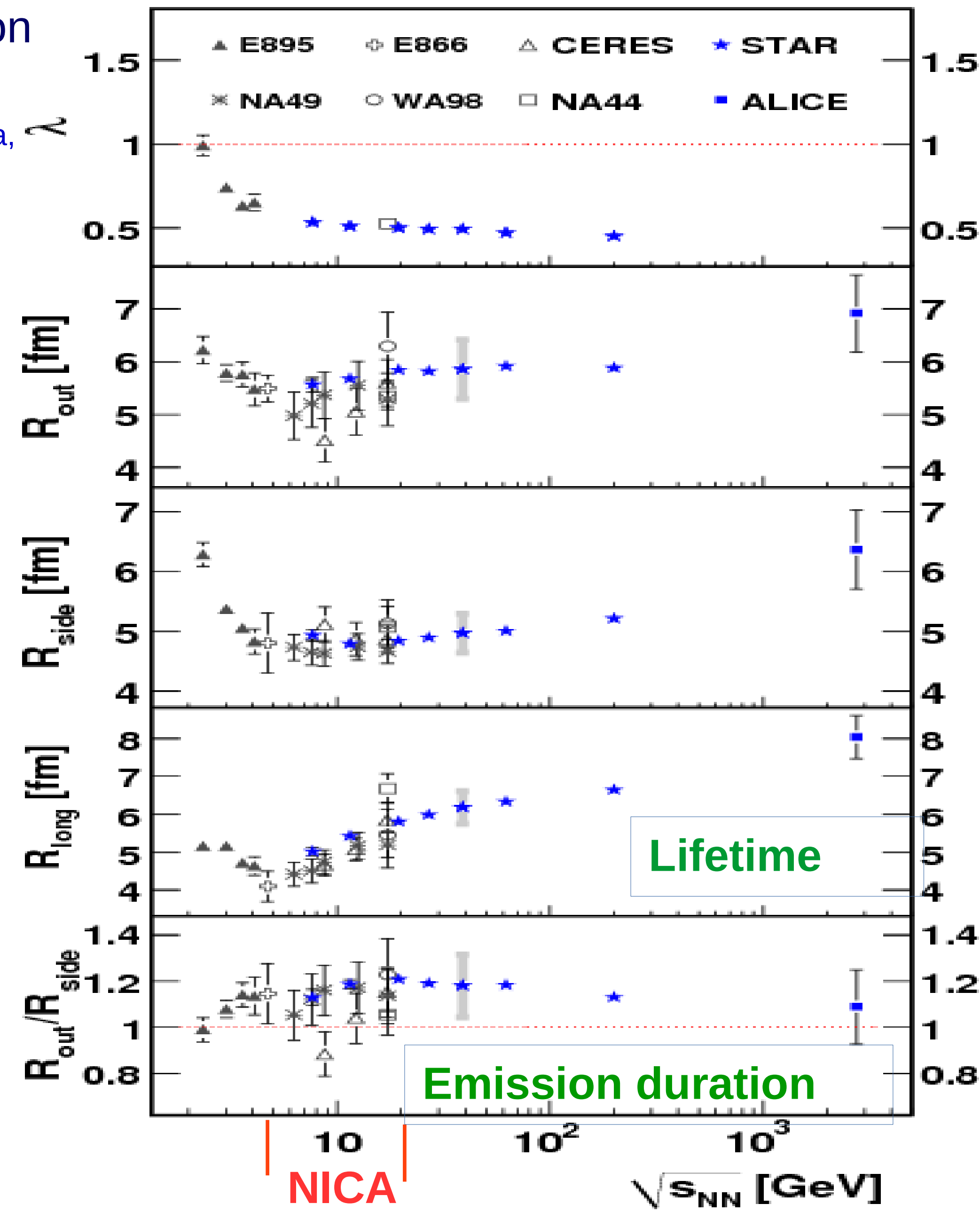
where both ***R*** and ***q*** are in Longitudinally Co-Moving Frame (**LCMS**)
long || beam; out || transverse pair velocity $\boldsymbol{v}_T$; side normal to out,long

Expected features of 1st order PT

- 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)

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



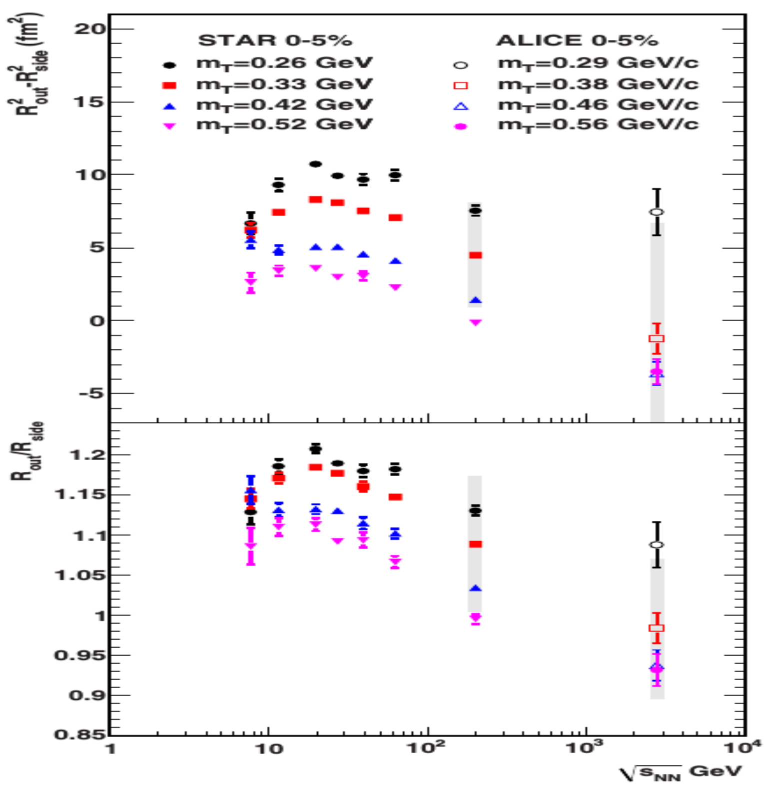


- But r-t correlations in expanding source reduce the observed R_{out} -> R_{out}/R_{side}

- What do the modern hydrodynamic (hybrid) models expect ?

Expected features of 1st order PT

- **Critical point ?**



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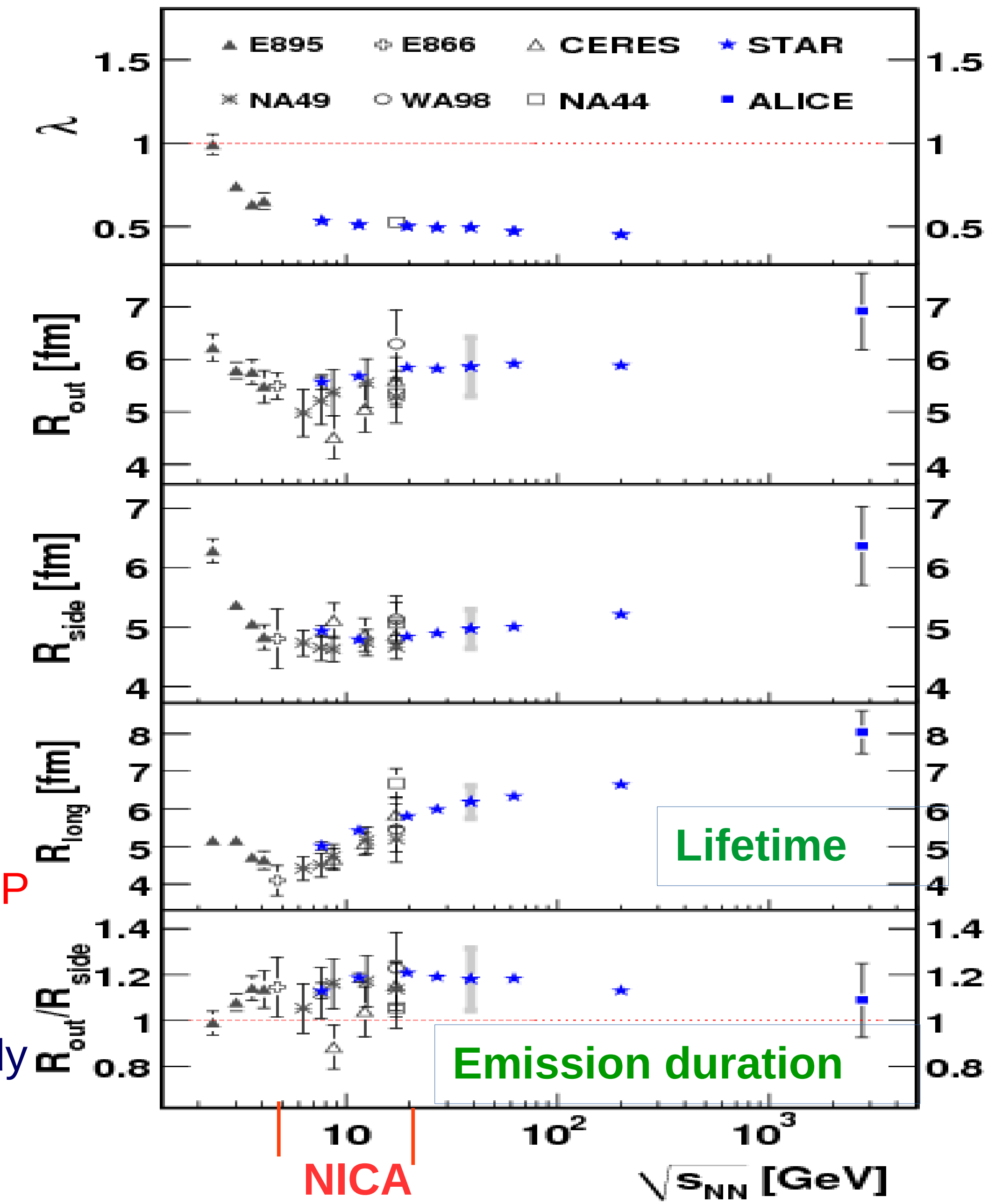

- A peak in R_{out}/R_{side} may not be related with CEP
- What do the modern hydrodynamic (hybrid) models expect ?
- VHLLE+UrQMD model was used for this study

ArXiv 1703.09628

Correlation femtoscopy study at NICA and STAR energies within the vHLLE+UrQMD model

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Correlation femtoscopy allows one to measure the space-time characteristics of particle production in relativistic heavy-ion collisions due to the effects of quantum statistics (QS) and final state interactions (FSI). The main features of the femtoscopy measurements at top RHIC and LHC energies are considered as a manifestation of strong collective flow and are well interpreted within hydrodynamic models employing equation of state (EoS) with a crossover type transition between Quark-Gluon Plasma (QGP) and hadron gas phases. The femtoscopy at lower energies was intensively studied at AGS and SPS accelerators and is being studied now in the Beam Energy Scan program (BES) at the BNL Relativistic Heavy Ion Collider in the context of exploration of the QCD phase diagram. In this article we present femtoscopic observables calculated for Au-Au collisions at $\sqrt{s_{NN}} = 7.7 - 62.4$ GeV in a viscous hydro + cascade model `vHLLE+UrQMD` and their dependence on the EoS of thermalized matter.

PACS numbers: 25.75.-q, 25.75.Gz
Keywords: relativistic heavy-ion collisions, hydrodynamics, collective phenomena, Monte Carlo simulations, vHLLE, UrQMD

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 τ0 is taken to be equal to the average time for the two colliding nuclei to completely pass through each other:

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

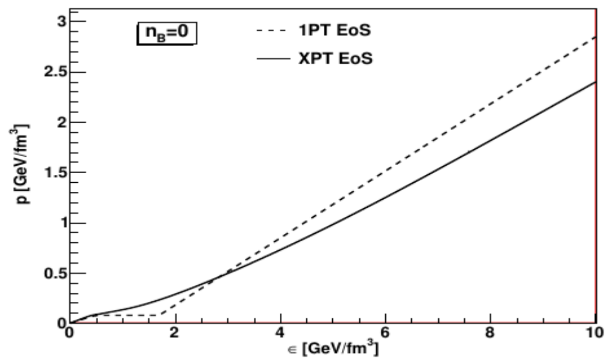
At τ = τ0 energy, momentum and baryon/electric charges of hadrons are distributed to fluid cells ijk around each hadron's position according to Gaussian profiles

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.

Model tuned by matching with the experimental data of SPS and BES RHIC.

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

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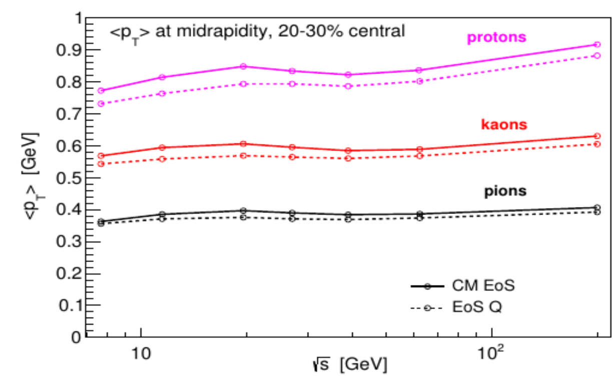
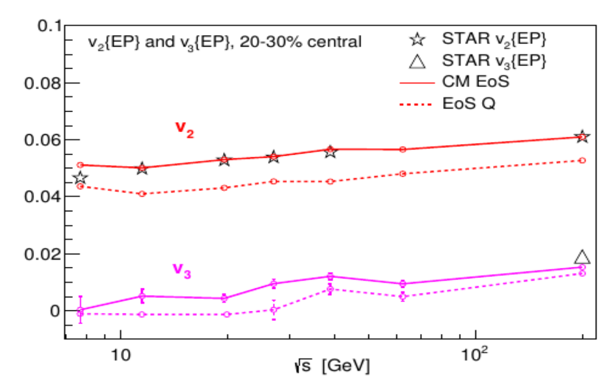
Model tuned by matching with the experimental data of SPS and BES RHIC.

Values of hydrodynamic starting time τ0 , initial state granularity R⊥ , Rη and shear viscosity over entropy ratio η/s adjusted for different collision energies in order to reproduce basic observables in the RHIC BES region. An asterisk marks the values of τ0 which are adjusted instead of being set directly from Eq. 1.

$\sqrt{s_{NN}}$ [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





vHLLE+UrQMD model

Pre-thermal phase → hydrodynamic phase → hadronic cascade

UrQMD | vHLLE (3+1)-D viscous hydrodynamics | UrQMD

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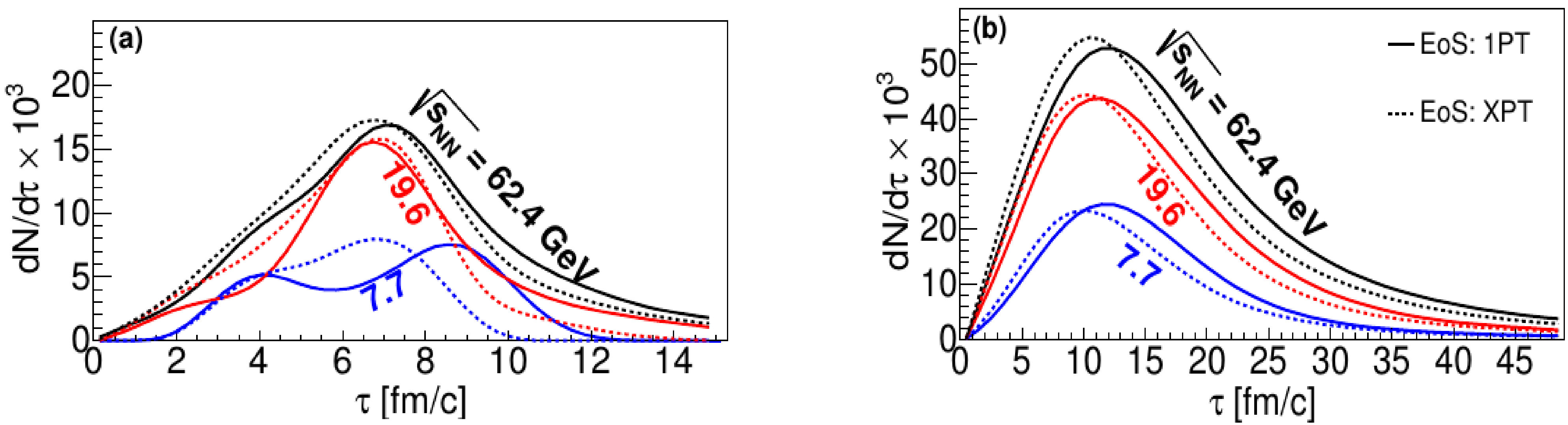
Pion emission times at the particlization surface and at the last interaction points

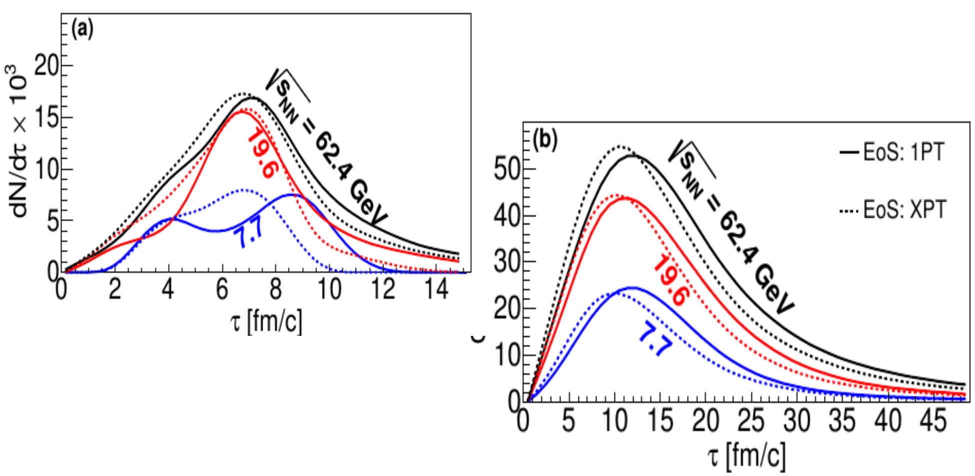


vHLLE+UrQMD model

Mean CMS times of pion emission at particlization and last interaction

$\sqrt{s_{NN}}$ [GeV]	EoS	particlization surface		last interactions	
		$\bar{t}$ [fm/c]	RMS [fm/c]	$\bar{t}$ [fm/c]	RMS [fm/c]
7.7	1PT	7.24	2.84	13.15	6.56
	XPT	6.16	2.01	11.61	6.26
11.5	1PT	7.33	2.31	13.09	6.92
	XPT	6.36	1.91	11.57	6.41
19.6	1PT	6.88	2.16	13.18	7.56
	XPT	6.41	2.15	11.93	6.93
27	1PT	6.85	2.37	13.38	8.07
	XPT	6.40	2.39	12.62	7.57
39	1PT	7.17	2.75	13.98	8.30
	XPT	6.64	2.58	13.05	7.85
62.4	1PT	7.00	2.82	14.11	8.50
	XPT	6.60	2.63	12.72	7.81

CMS times of pion emission at last interaction



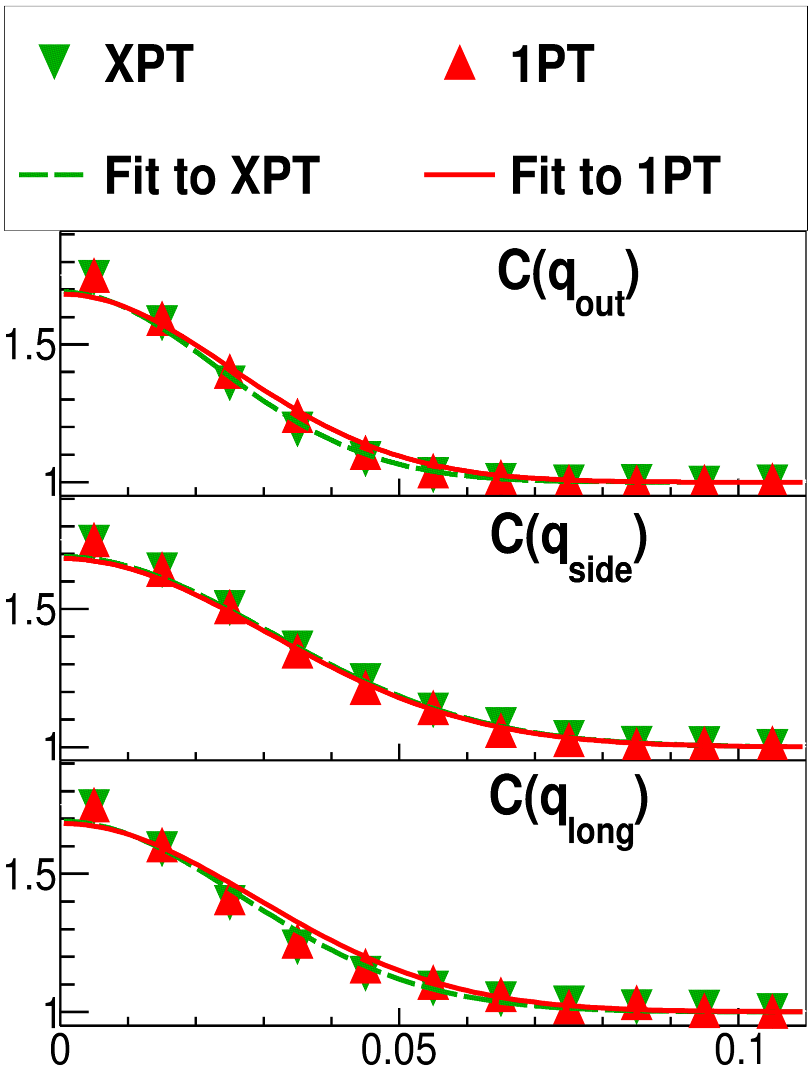
Emission times for 1st order phase transition are larger than for crossover.

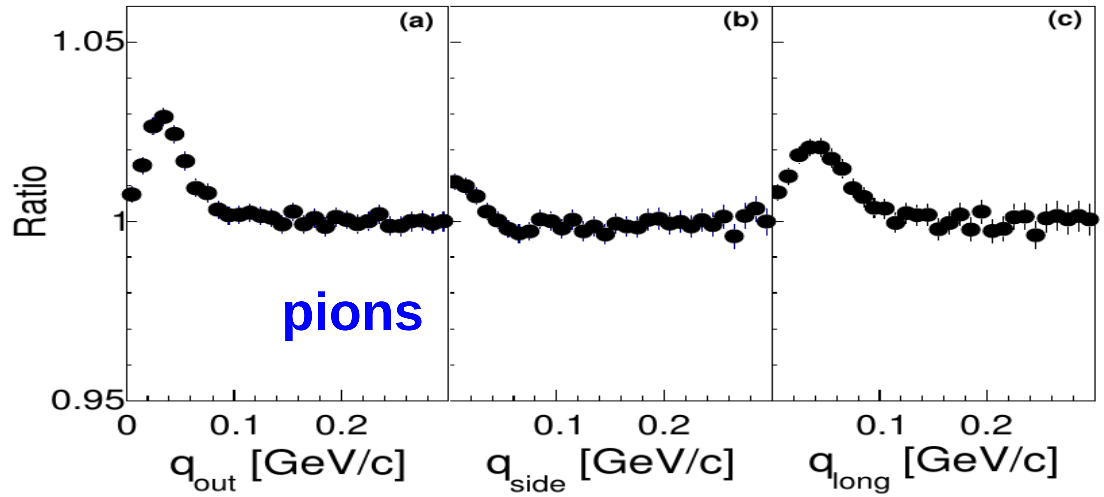
- Weak dependence of the average pion creation time on the collision energy. Maximal difference : ~1.5 fm. Interplay of longer pre- thermal and shorter hydrodynamic stage at lower collision energies
- On the other hand, the duration of hydro stage gets shorter as collision energy decreases because of lower initial energy density at the hydro starting time.
- The cascade smears the relative difference between the 1PT and XPT scenarios

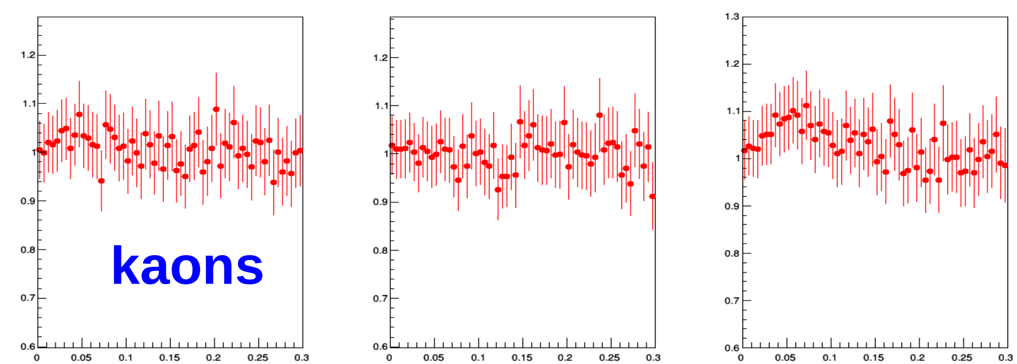
We are studying the possibilities to extract this difference experimentally at NICA/MPD using femtoscopy technique.

Correlation functions with vHLLE+UrQMD

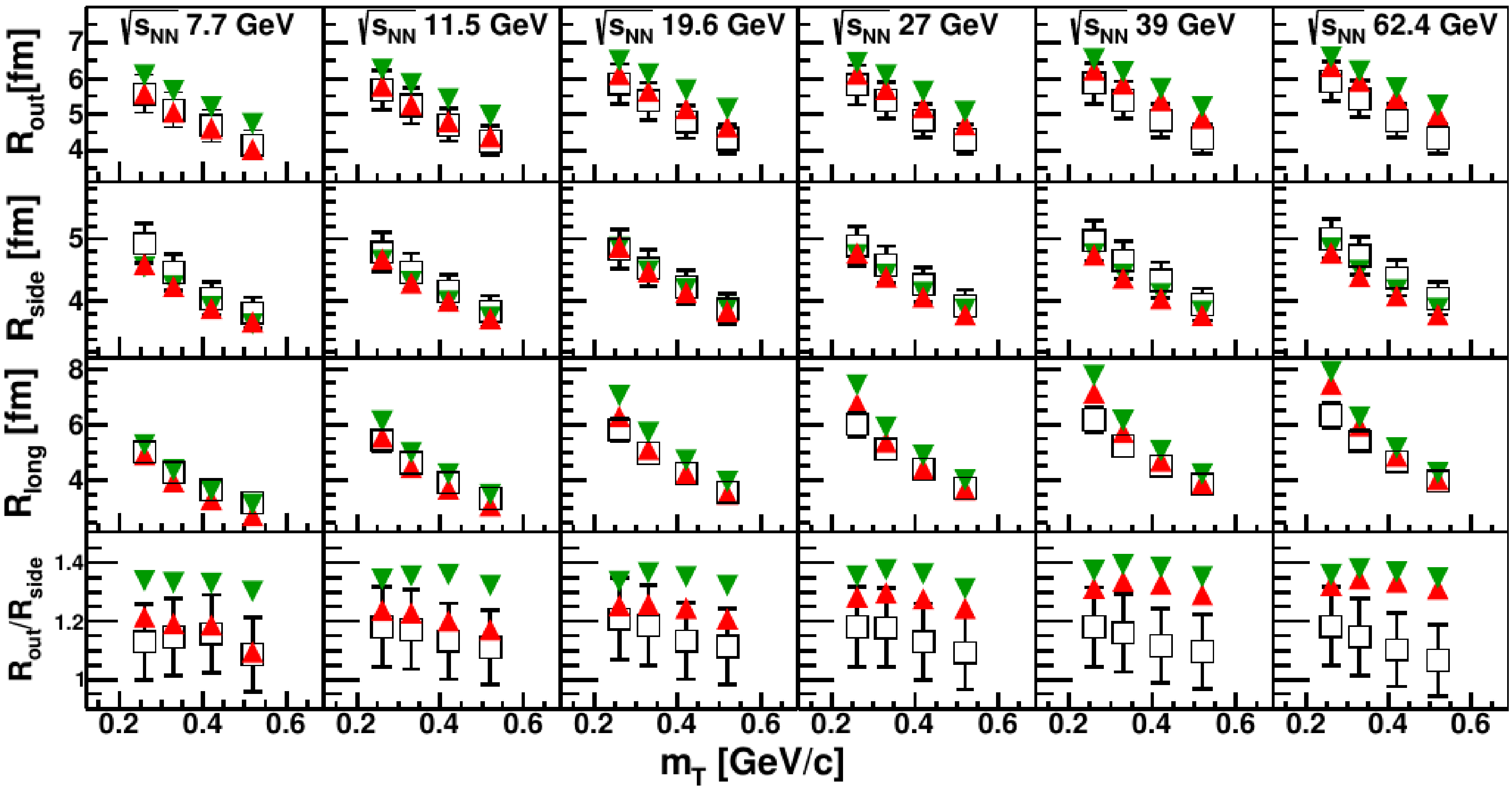
- The difference between pion CF for 1st order PT and crossover < 5%
- For kaons it is expected to be larger ~ 10%
- It is necessary to study different particle types. Importance of PID







3D Pion radii versus m_T with vHLLE+UrQMD model

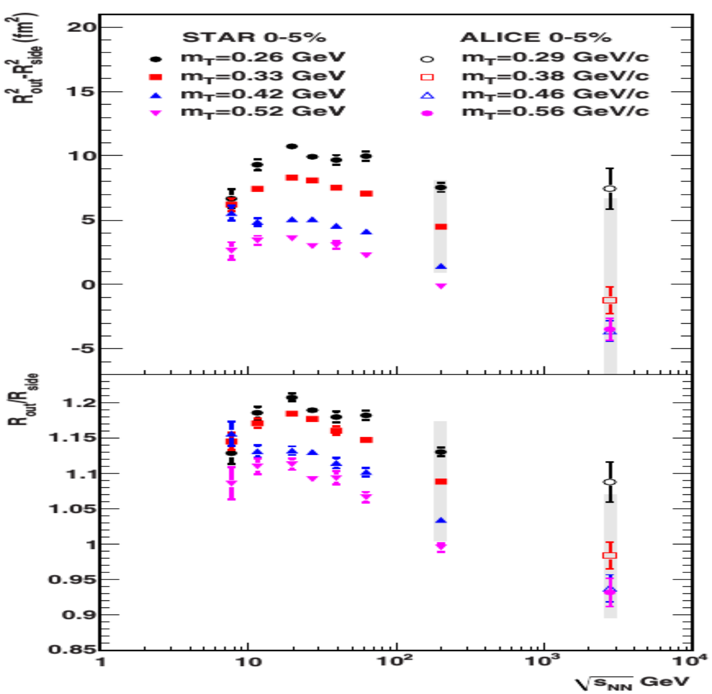


Green triangles - 1PT EoS, **Red triangles** - XPT EoS, **Open black squares** STAR data BES

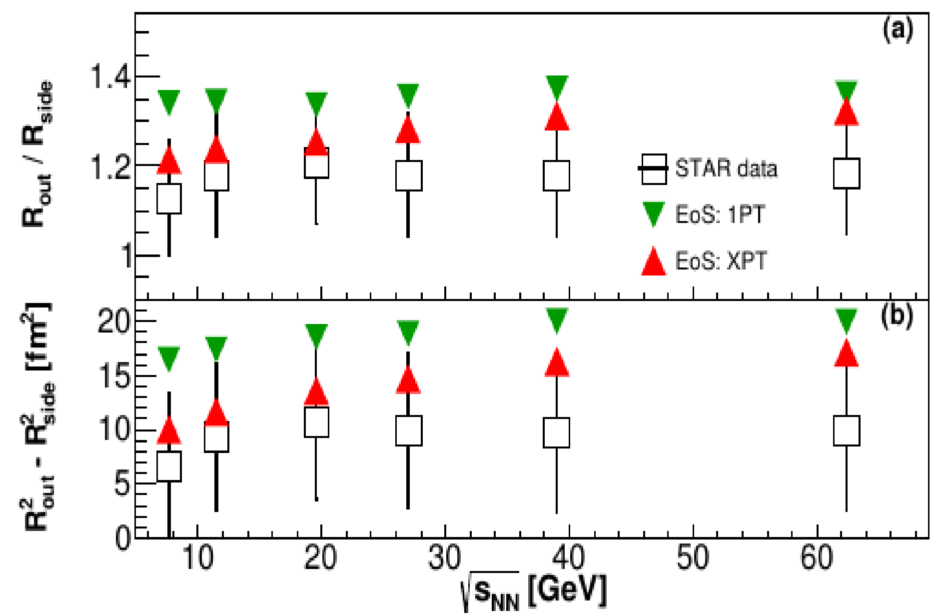
- R_{out}(XPT) at high energies and R_{out}(1PT) at all energies are slightly overestimated -> an indication of the need to reduce the emission time in the model
- R(1PT) > R(XPT) by ~ 1 fm for “out” and “long” radii

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

- R_{out} /R_{side} and R_{out} - R_{side} as a function of s_{NN} were studied at fixed m_T by the STAR Collaboration. A wide maximum near s_{NN} ~ 20 GeV/c in both excitation functions was observed.

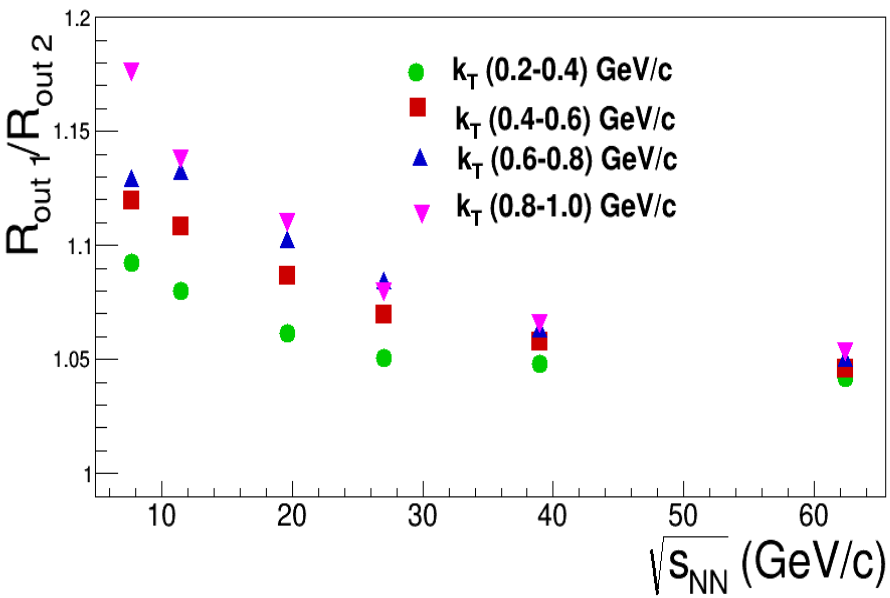


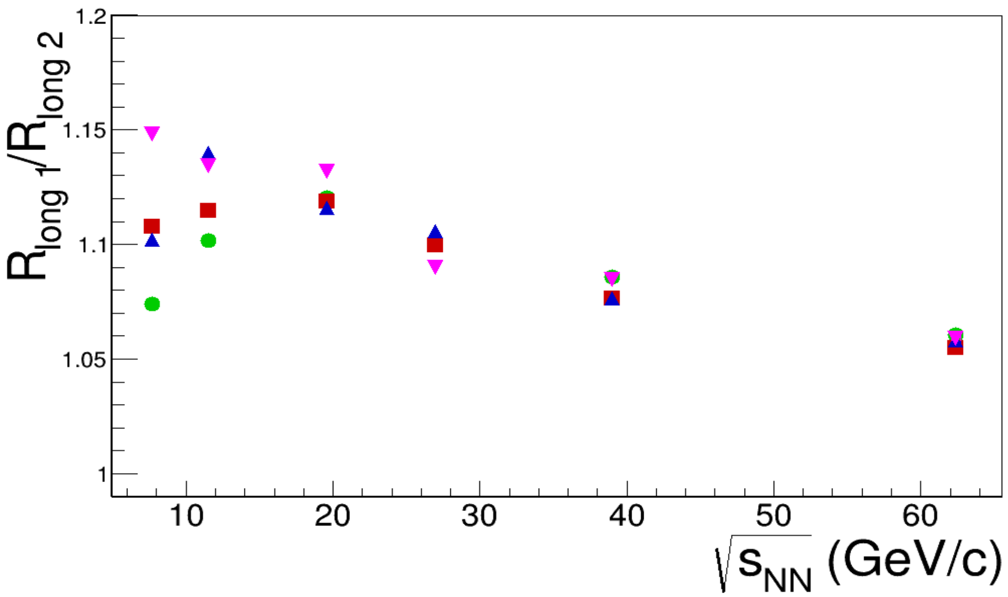
- R_{out} /R_{side}(XPT) agrees with almost all STAR data points within rather large systematic errors, while R_{out} /R_{side}(1PT) overshoots the data.

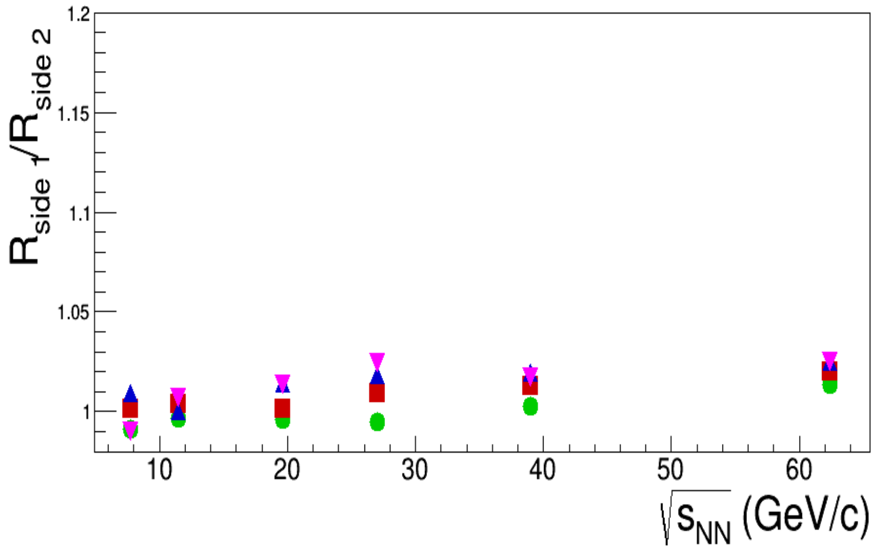


There is an indication in our study that optimal description of the femtoscopic radii requires about 1 fm shorter duration of pion emission with the present setup of the model, at all collision energies. It is an open question whether a new set of parameters can be found which accommodates the the femtoscopic radii.

Ratio R_{osl} 1PT/ R_{osl} XPT versus sqrt(s_{NN})







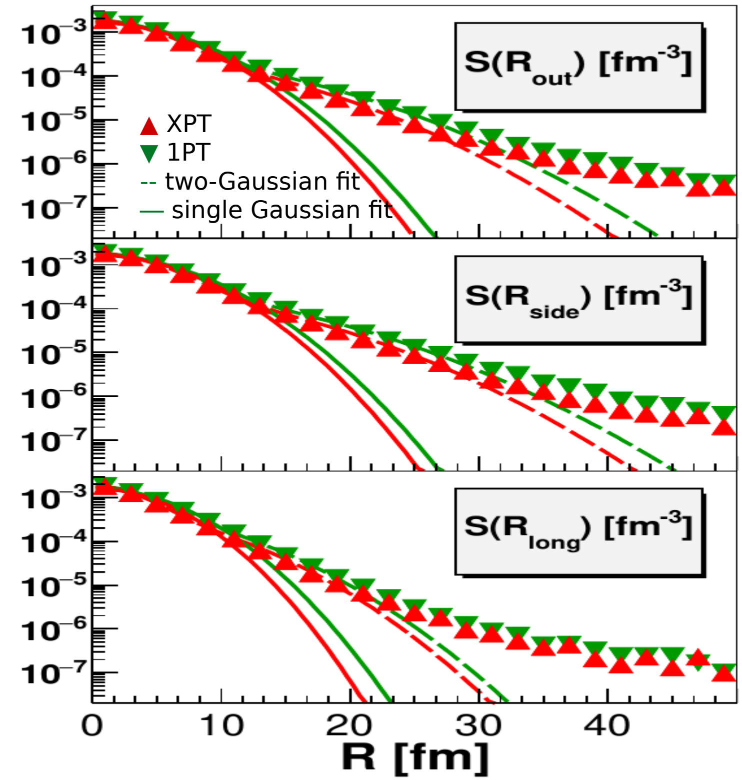
- R_{side} radii in the 1PT EoS and XPT EoS scenarios practically coincide;
- R_{out} (R_{long}) for 1PT EoS > XPT EoS, strong dependence on kT interval
- The difference comes from weaker transverse flow developed in the fluid phase with 1PT EoS as compared to XPT EoS & longer lifetime of the fluid phase in 1PT EoS

Source functions

The new Source Function technique was used.

SF for 1st order is wider than the one for crossover.

Main advantage of this technique is the possibility to use the Source Functions itself without any hypothesis about its shape.



$$C(\mathbf{k}^*, \mathbf{P}) = \int d^3\mathbf{r}^* S^{\alpha}(\mathbf{r}^*, \mathbf{P}) \left| \overline{\psi^{S,\alpha'\alpha}_{-\mathbf{k}^*}(\mathbf{r}^*)} \right|^2 ,$$

Different functions were tested to describe the shape of SF projections: single Gaussian

$$S(\vec{r^*}) \sim exp\left(-\frac{r^{*2}_{out}}{4R^{*2}_{out}} - \frac{r^{*2}_{side}}{4R^{*2}_{side}} - \frac{r^{*2}_{long}}{4R^{*2}_{long}} \right),$$

Gaussian + Gaussian;
Gaussian +Lorencian
Gaussian +Exp

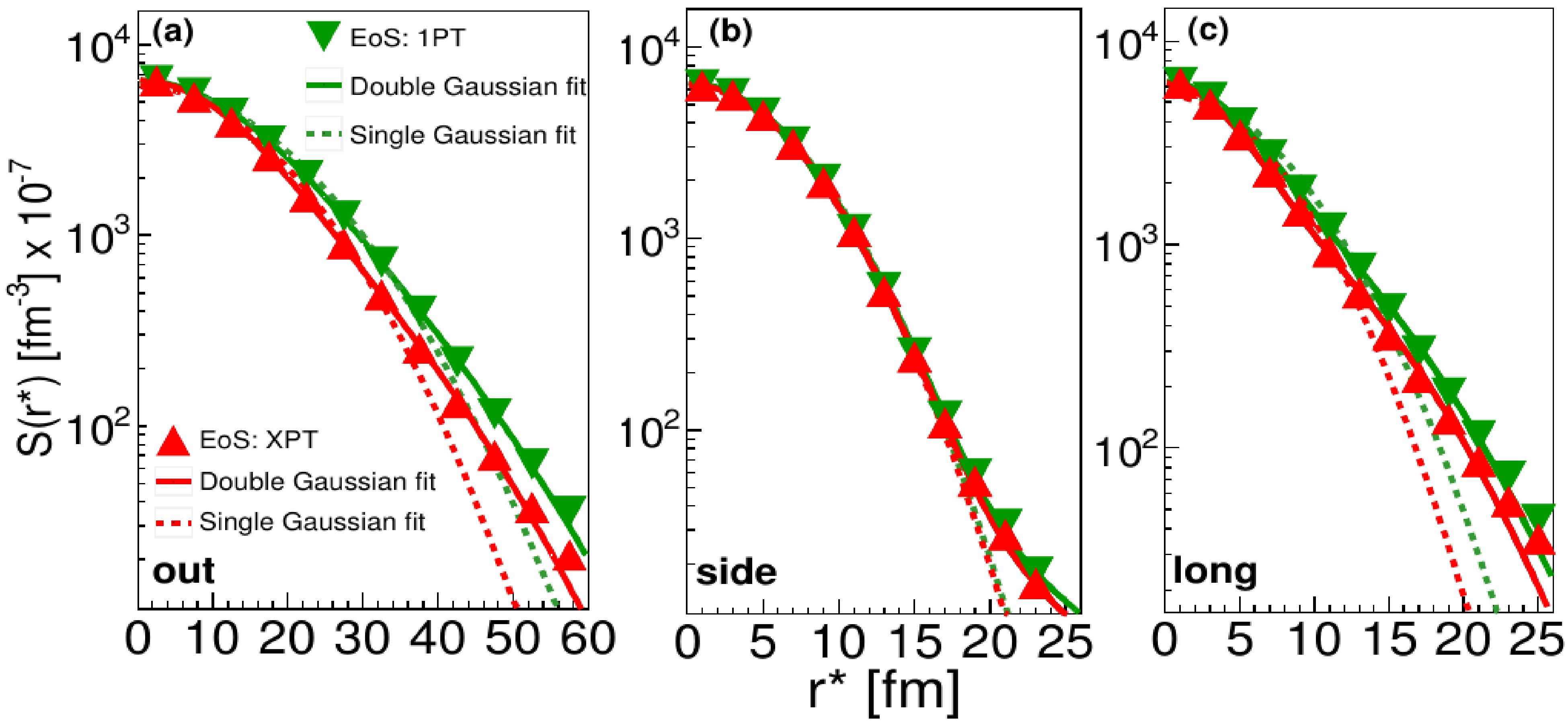
$$S^H(r_x, r_y, r_z) = \lambda \exp[-f_s(\frac{x^2}{4r^2_{xs}} + \frac{y^2}{4r^2_{ys}} + \frac{z^2}{4r^2_{zs}}) - f_l(\frac{x^2}{4r^2_{xl}} + \frac{y^2}{4r^2_{yl}} + \frac{z^2}{4r^2_{zl}})],$$

$$f_s = 1/[1 + (r/r_0)^2], \quad f_l = 1 - f_s$$

Hump-function

- The best description was obtained with Gaussian+Gaussian and Hump-function.
- Gaussian+Gaussian - simple interpretation (core-resonances) & more stable fitting procedure

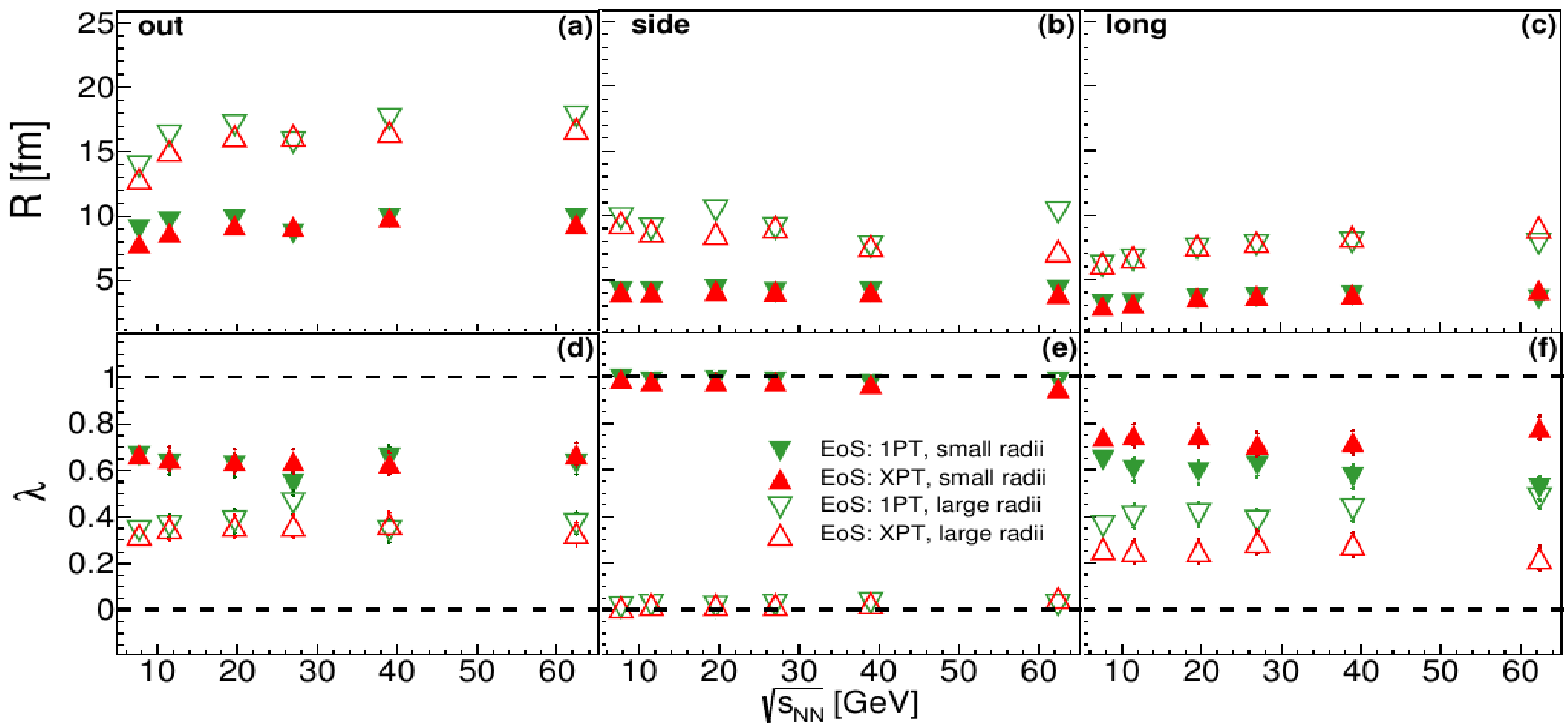
Source Function with vHLLE + UrQMD model



- Two-Gaussian fit describes reasonably SF till ~60 fm «out» and ~25 fm «side» and «long» directions.

- One-Gaussian fit gives large χ^2 / NdF, but the values of radii are equal to the ones of two Gaussian radii averaged according with relative contributions of small and large radii; That is why it reflects reasonably the main features of 2-Gaussian fit at small r*.

Pion Source Function with vHLLE + UrQMD



- "out" : $R_{out1,2}$ (1PT) > $R_{out1,2}$ (XPT); for the calculations with the first order phase transition and for the one with crossover phase transition decreases with increasing $\sqrt{s_{NN}}$;

  The relative contributions of small and large radii
  λ1 ~ 0.65 and λ2 ~ 0.35 do not depend on $\sqrt{s_{NN}}$ and on the type of EoS.
- The radii $R_{side1,2}$ and corresponding λ1,2 do not depend on $\sqrt{s_{NN}}$.
- "long": radii almost coincide for both types of EoS, The relative contribution of the large radii, λ2 increases with $\sqrt{s_{NN}}$, while λ1 decreases. λ2 (1PT) > λ2 (XPT)

Conclusions

- Possibility to distinguish between hybrid model source functions with 1st order phase transition and crossover was studied using vHLLE+UrQMD model
- Hydro phase lasts longer with 1st order PT.
- Hadronic cascade diminishes the difference between 1PT and XPT source functions,

  though there is still a possibility to distinguish them using the femtoscopy technique.
- vHLLE+UrQMD model with XPT describes RHIC femtoscopy radii at sqrt(s_{NN}) = 7.7-62.4 GeV
- There is an indication that optimal description of the femtoscopic radii requires about 1 fm

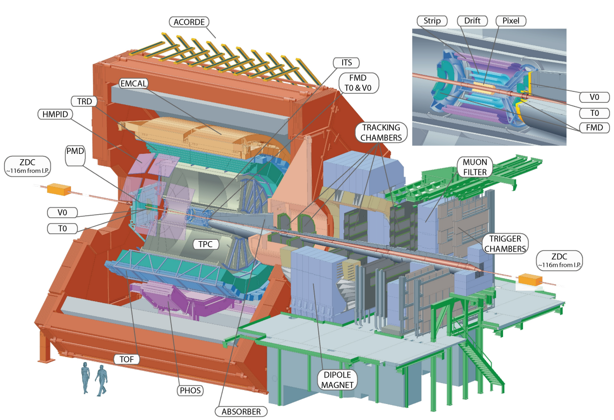
  shorter pion emission time with the present setup of the model, at all collision energies. - new tune of vHLLE+UrQMD model is needed.

  It'll be very interesting to try to use 3 phase hydro model (THESEUS) at low energies
- R_{out}(1PT) > R_{out}(XPT) & R_{long}(1PT) > R_{long}(XPT)
- --
- Source functions technique allows to get an additional information about differences between 1PT / XPT; Best parametrizations of SF : Gauss+Gauss and Hump
- The standard one-Gaussian parametrization of the 3D CF reflects correctly the behaviour of the SF at small r* and is sufficiently sensitive to EoS.
- It is very promising to make 3D CF analysis using heavier particles: K,p becuuse of more Gaussian shape of SF and less influence of resonances

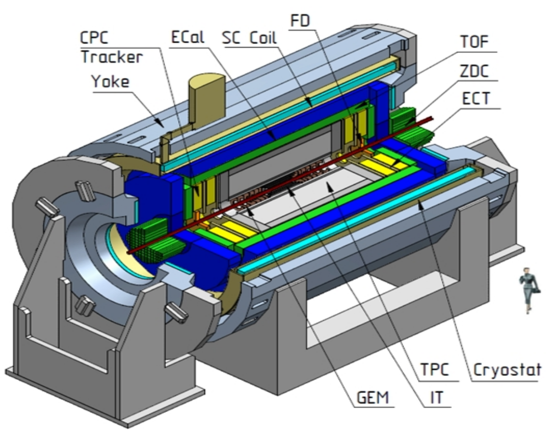
MPD detector has the same advantages as ALICE to study femtoscopy:

- It can be promising to make 3D CF analysis using heavier particles: K,p because of more Gaussian shape of SF and less influence of resonances
- Different particle pairs: πK, K+K-, πp, π Λ, ΛΛ .. can be studied -- different influence of cascade phase, emission assymetries..
- Az-sensitive femtoscopy is particularly sensitive to the evolution time (in addition to R_{long}) and to the expansion velocity.

ALICE	MPD
• Low momenum cut-off (p_T>100 MeV/c)	V
• Small material budget	V
• Excellent particle identification (PID) by: specific energy loss (dE/dx) & TOF	V
• Good primary and secondary vertex resolution	V



In femtoscopy context,
the remakable feature of collider experiments, compared with fixed target ones, is an excellent particle identification (not so important for correlations of identical pions, while quite important for other particle pairs) and a good two-track resolution.



Back Up

Imaging

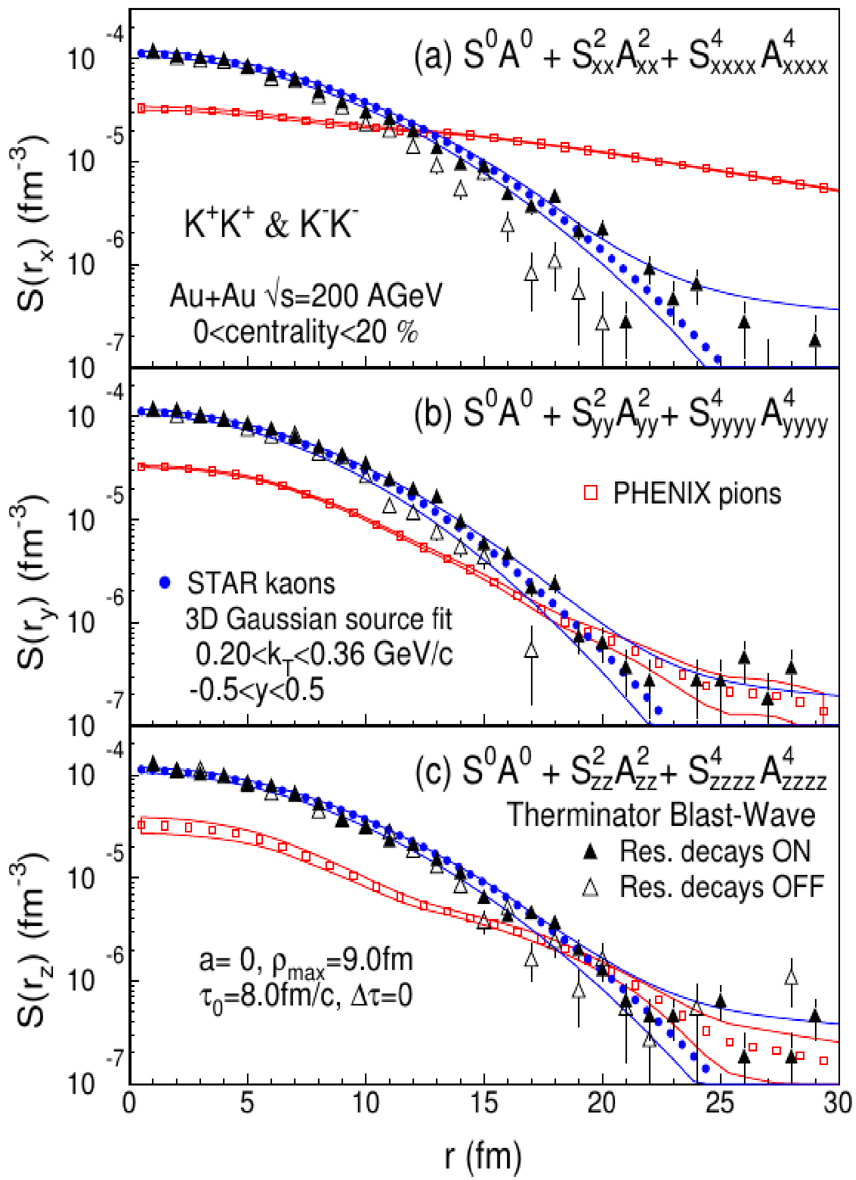
- PHENIX and STAR collaborations apply a new "imaging technique" to extract the S(r*)-source function, which represents time-integrated distribution of particle emission points separation r* in the pair rest frame (PRF).

$$C(\mathbf{q}) - 1 \equiv R(\mathbf{q}) = \int \left(|\phi(\mathbf{q},\mathbf{r})|^2 - 1 \right) S(\mathbf{r}) d\mathbf{r}.$$

- The method is suitable for extracting the S(r) directly from the data without any hypothesis about source shape; it seems to be very useful for comparison of the experimental data with the models with 1PT or Crossover EoS

- The good knowledge of all factors influencing the shape of correlation function is needed

STAR, Phys.Rev. C88 (2013) 3, 034906



UrQMD 3.4 model

Initial state → hydrodynamic phase → hadronic cascade

UrQMD | SHASTA (3+1)-D ideal hydrodynamics | UrQMD

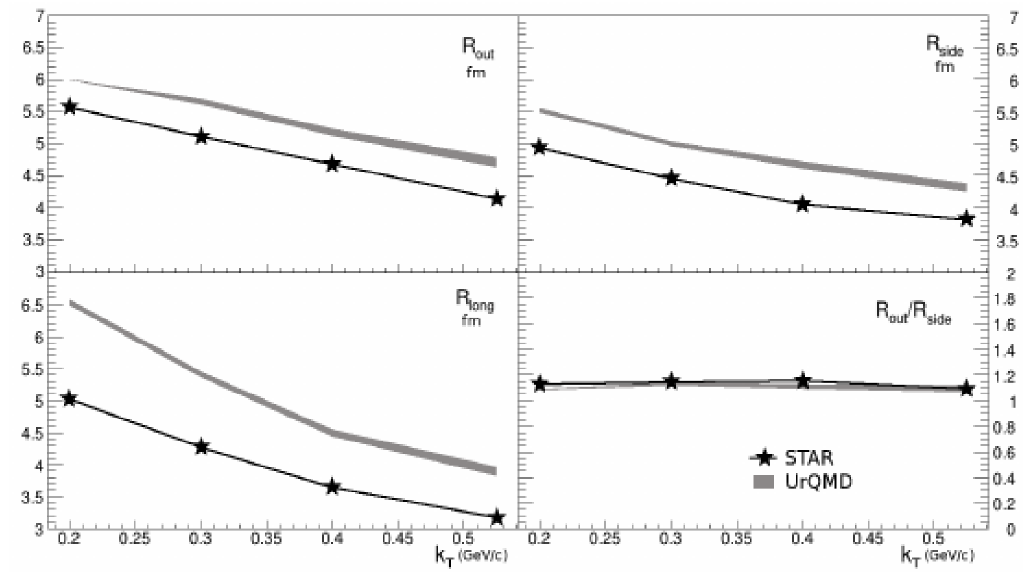
H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. St¨ocker, Phys. Rev. C 78 (2008) 044901.
UrQMD-3.4 code was taken from http://urqmd.org/
Many thanks to Hannah Petersen for the advises concerning parameters of simulations!

- Initial collisions and string fragmentations from the microscopic UrQMD model.
- (3+1)-dimensional ideal hydrodynamic evolution.
- hadronic cascade.

Chiral EoS - Crossover

Bag model EoS - 1st order

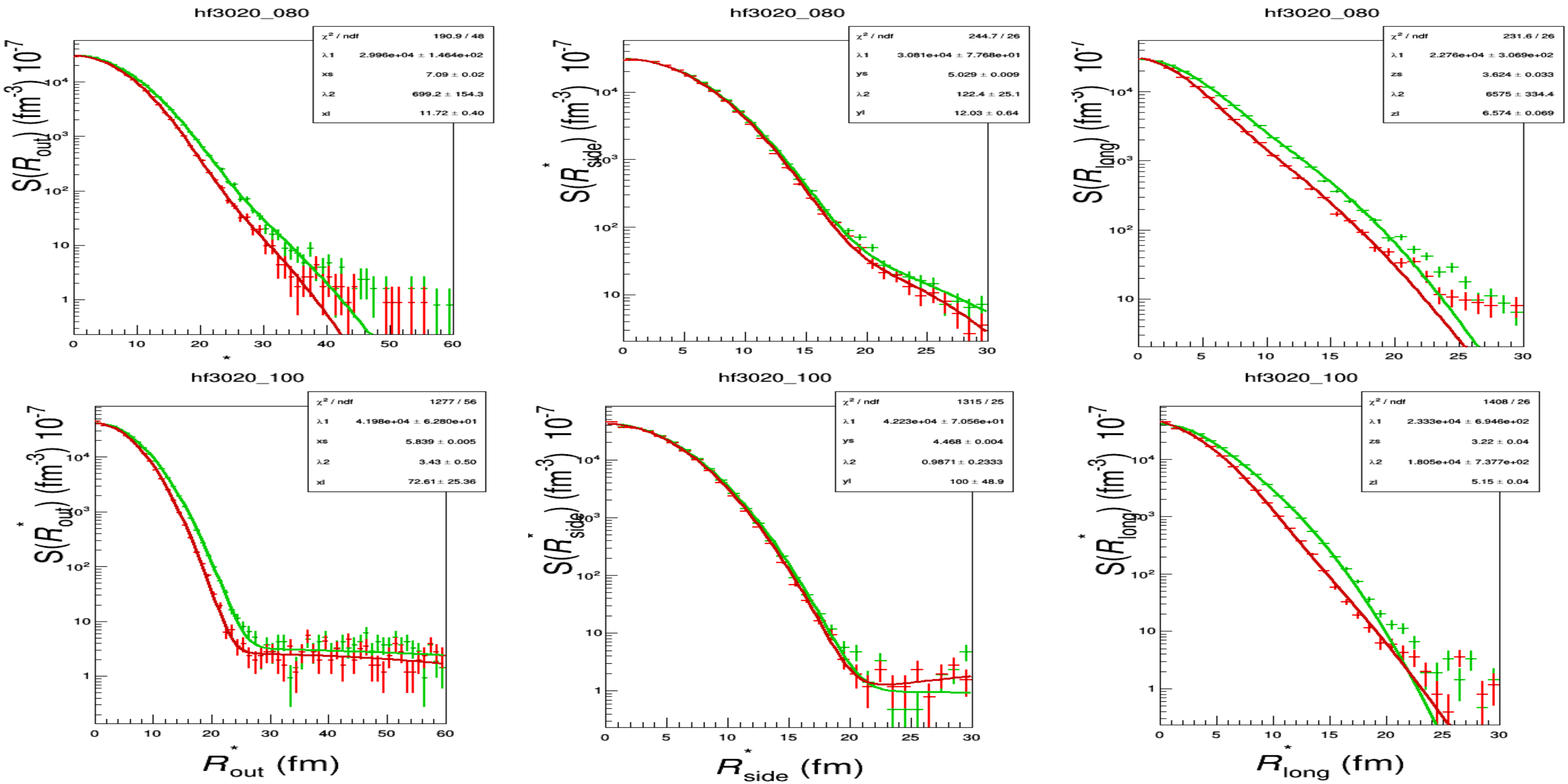
Hadron gas EoS



Both models describe the bulk data quite well, but the vHLLE+UrQMD seems to have a better description whereas UrQMD 3.4 tends to overestimate the femtoscopic radii.

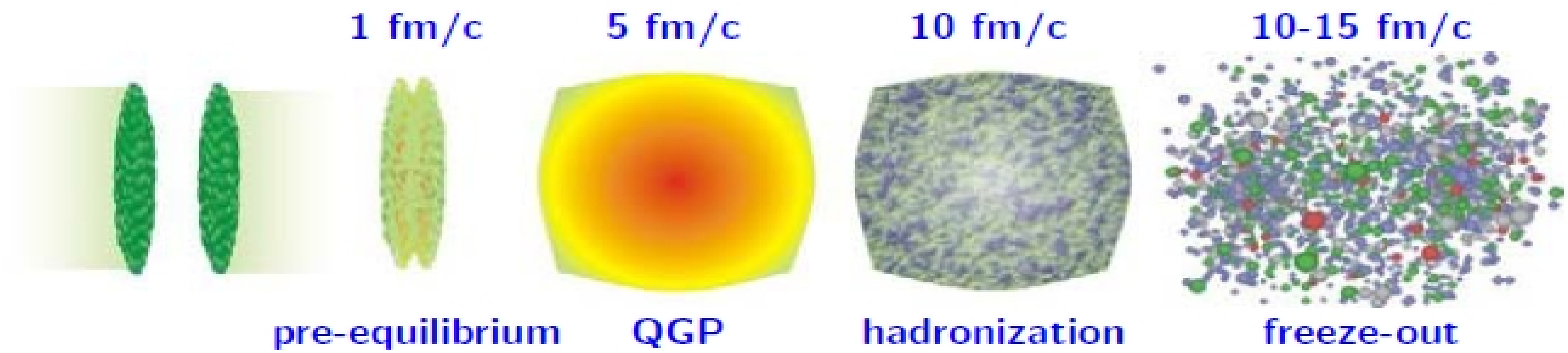
Kaon Source Function with vHLLE + UrQMD

Kaons 7.7 GeV/c Gauss+Gauss fit of 3D SF projections kT (0.2-0.8) GeV/c



- "out" : **for the same k_T range** the difference 1PT/XPT is smaller for heavier particles than for pions due to weaker influence of flow effects
- For kaons: more clear signal, less influence of resonances, --> more Guassian shape

Femtoscopy



Correlation femtoscopy : measurement of space-time characteristics R, $c\tau$ ~fm of particle production using particle correlations due to the effects of QS and FSI

G. Goldhaber, S. Goldhaber, W-Y Lee, A. Pais (Phys.Rev. 120 (1960) 300):
first showed the BE correlation of identical pions in pp^{-} collisions

G.I. Kopylov and M.I. Podgoretsky (1971-1975) (review: Phys.Part.Nucl. 20, iss. 3 (1989) 629, in Russian): elaborated basics of correlation femtoscopy

V.G. Grishin, G.I. Kopylov, and M.I. Podgoretsky showed analogy (Sov.J.Nucl.Phys. 13 (1971) 638) and difference (G.I. Kopylov and M.I. Podgoretsky, Sov. Physics JETP 42, 211 (1975)) between femtoscopy in particle physics and HBT effect in astronomy (R. Hanbury-Brown and R.Q. Twiss, Phil.Mag. 45 (1954) 633):
HBT effect is the dependence of the product of electric currents from two photo-detectors or antennas on their distance and a time delay, which allows one to measure the energy-momentum spread of the light quanta emitted by a distant object.

EoS vHLLE+UrQMD (Yurii's comments)

it's a bit more complex. The pressure from 1PT EoS is larger (compared to XPT) at high energy and smaller at low energy densities. This means that the core of the system accelerates a bit faster, whereas edges (around particlization surface) accelerate slower. Also, at the late stages of hydro evolution the core enters 'low density' regime, where the 1PT EoS has again lower pressure, and - also important - zero derivative of pressure as a function of energy density (which is speed of sound). So the region of epsilon<2 GeV is also important when one compares the EoS. The other thing is, Fig. 1 in 1601.0800 is p(e) at zero baryon density, whereas in the calculations it is never zero, and is significantly nonzero at lower collision energies. There, the picture is a bit shifted. I don't have a corresponding plot at hand, sorry.

crossover is a transition with no clearly separated phases. This means that in a certain temperature range there are fractions (contributions)of both hadron gas and quarks/gluons in the EoS. There is no latent heat, and no discontinuities of any order in thermodynamical functions.

Contrary to that, in **1PT EoS w**ith Maxwell construction the phase transition occurs at a certain value of temperature, where in mixed phase there are coexisting domains of hadron/QGP phases. Below the transition temperature, there is pure hadron phase, and above transition temperature there is pure QGP phase (free quarks/gluons in a bag).