Femtoscopy: the way back on the energy scale from ALICE to NICA.

Part-I

P. Batyuk, Yu.Karpenko, L. Malinina, K. Mikhaylov, R. Lednicky, O. Rogachevsky, D. Wielanek

Outline

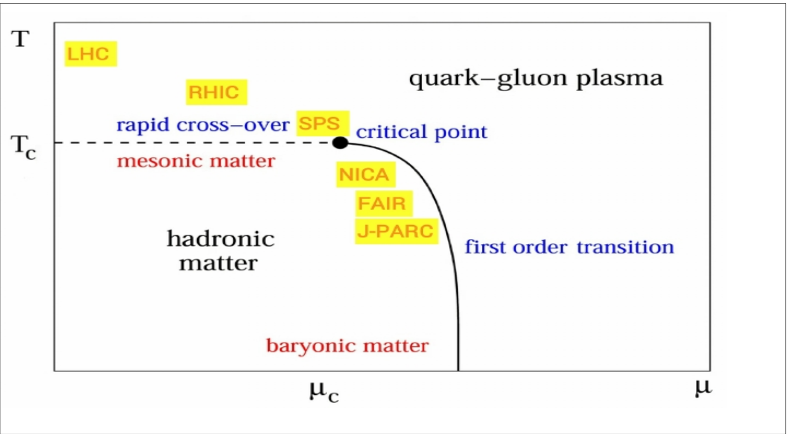
I part: I will discuss what we are studying and why.

II part: Daniel Wielanek will discuss the first studies performed with the new FEMTO-NICA software.

- Introduction
- Main lessons of femtoscopy at high energies
- 1st order Phase Transition criteria for femtoscopy
- UrQMD 3.4 model
- vHLLE+UrQMD model
- Source functions obtained with the models used
- Summary

Introduction

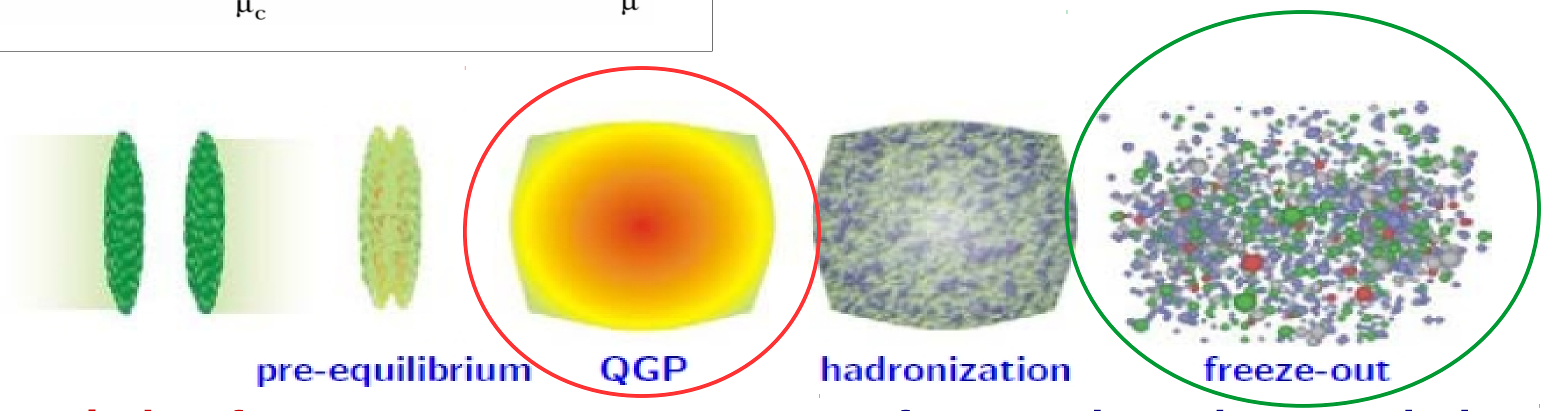
- Crossover transition to QGP occurs at RHIC & LHC



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

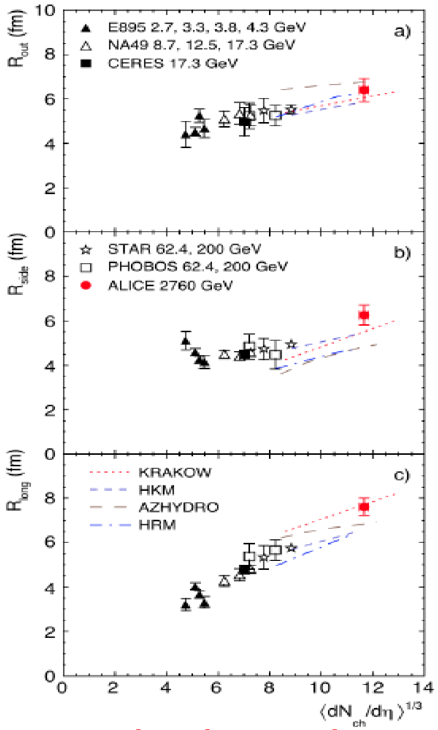
- At what energies do hydro models with 1st order PT describe femtoscopy observables better than those with crossover PT ?

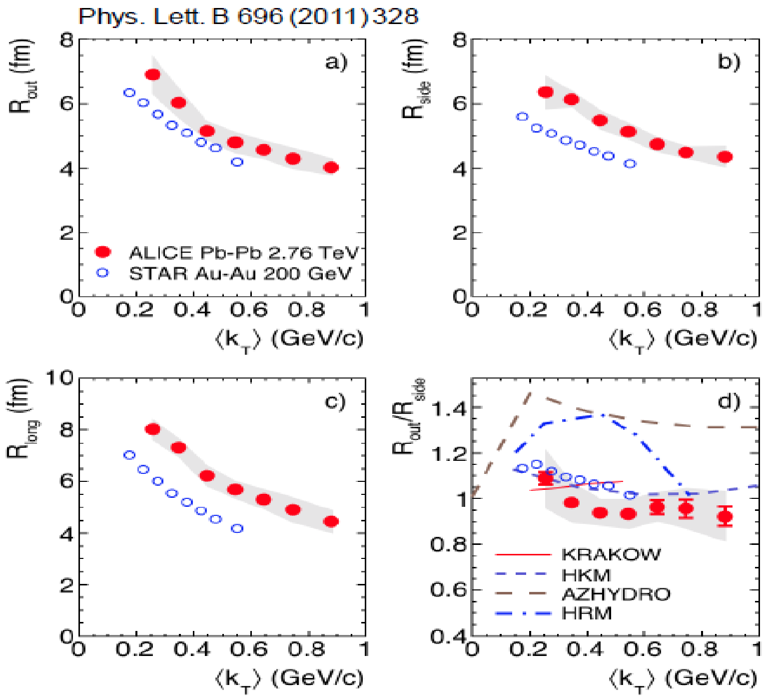
- Which femtoscopy observables are most sensitive to this difference ?



Correlation femtoscopy : measurement of space-time characteristics R, cτ ~fm of particle production using particle correlations due to effects of QS and FSI

Main ALICE femtoscopy results





- Homogeneity volume 2 times larger than at RHIC
- τ ~ 40% larger than at RHIC (extracted from Rlong vs. mT)
- Scaling of the radii with(dNch/dη)$^{1/3}$
- Strong k_T dependence of radii -> strong transverse flow
- R_{out}/R_{side} smaller than at RHIC -> stronger r-t correlations

- Hydrodynamic models describe well the whole set of femtoscopy observables at RHIC & LHC energies.
- Importance of: pre-thermal transverse flow, crossover transition between quark-gluon and hadron medium, non-hydrodynamic behavior of the hadron gas at the latest stage -- cascade.

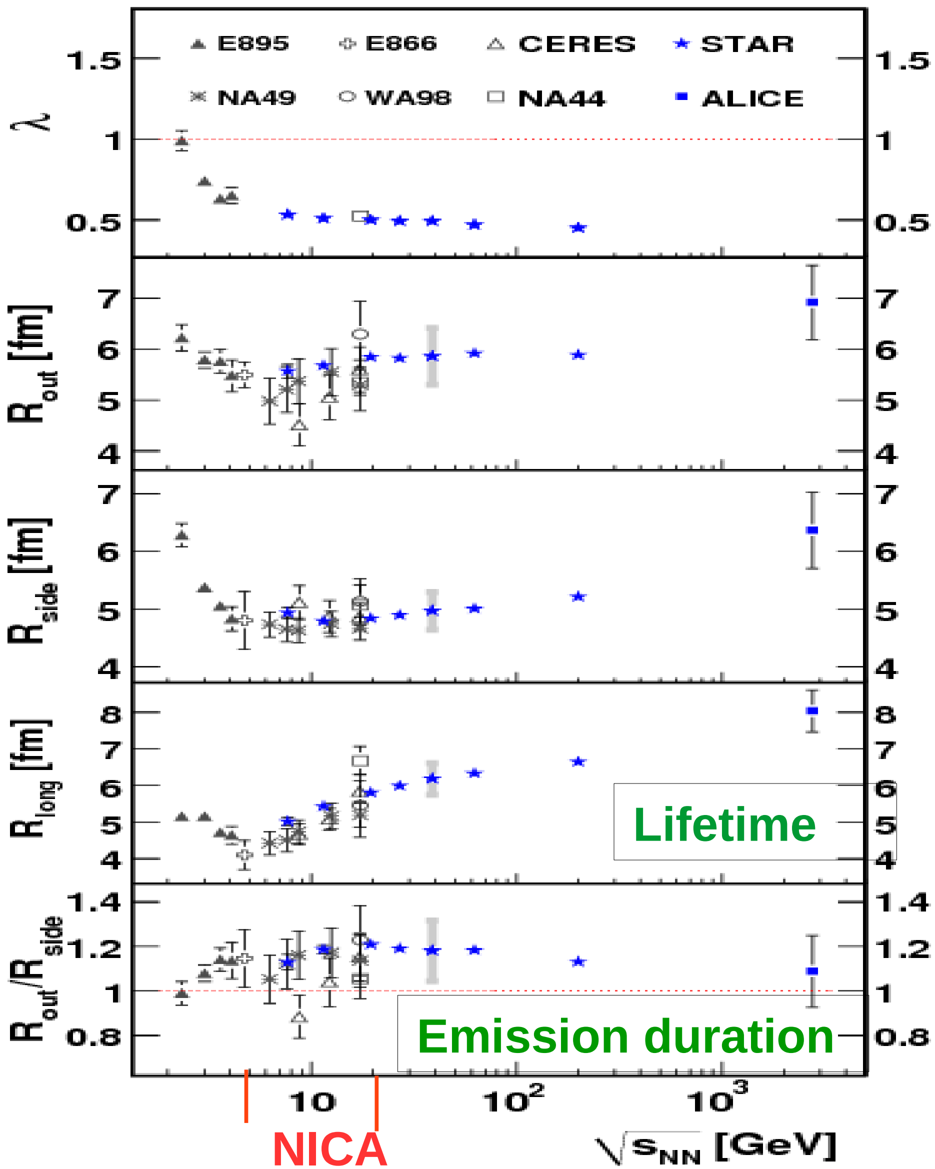
Expected features of 1st order PT

- LHC Pb-Pb : sqrt(s_{NN}) ~ 2.76 TeV
  RHIC sqrt(s_{NN}) ~ 62.4 to 200 GeV
  large T & small μ_B

- RHIC Beam Energy Scan program (BES)
  sqrt(s_{NN}) = 7.7, 11.5, 19.6, 27, 39 GeV
  small T & large μ_B

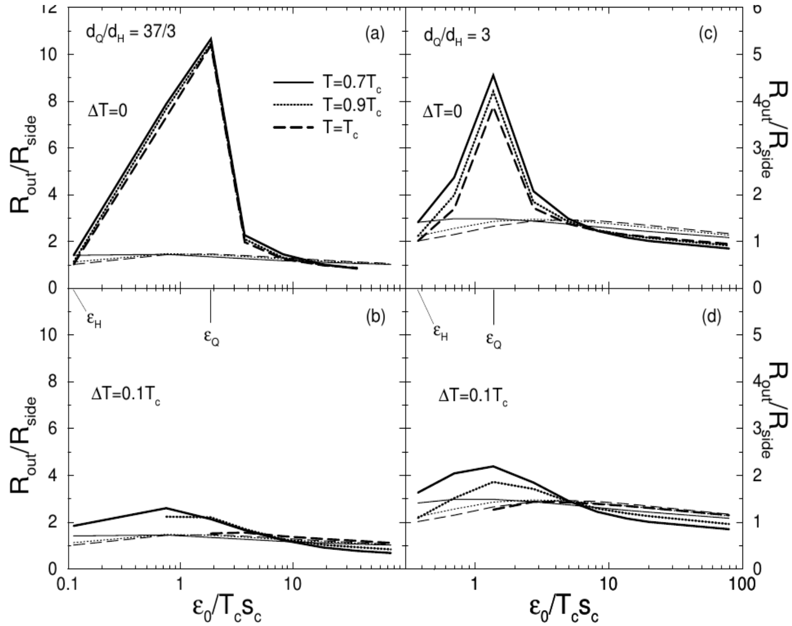
- NICA Expected beams
  sqrt(s_{NN}) = 4 - 11 GeV
  small T & large μ_B

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

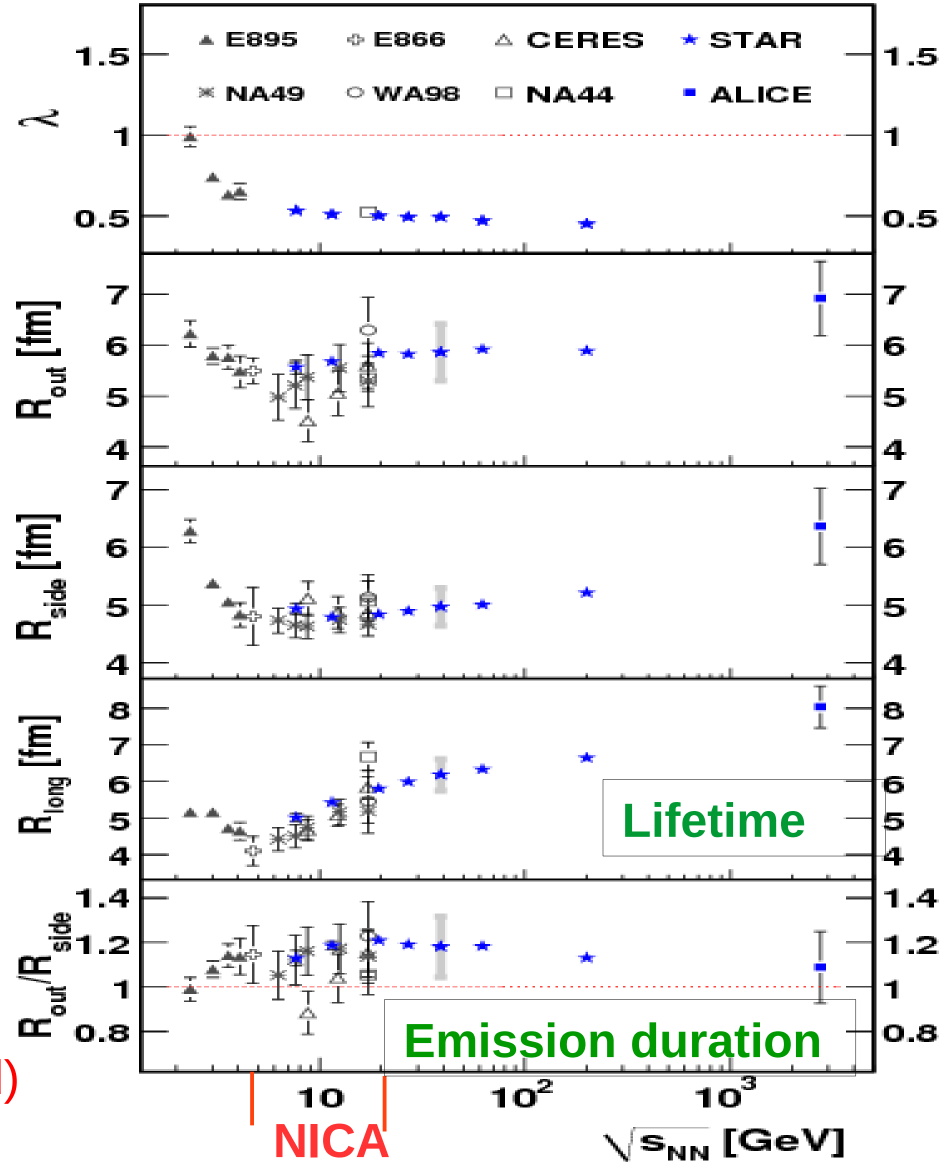


Expected features of 1st order PT

- It was predicted that for 1st order phase transition $R_{out}/R_{side} \gg 1$ & 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 ?

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!

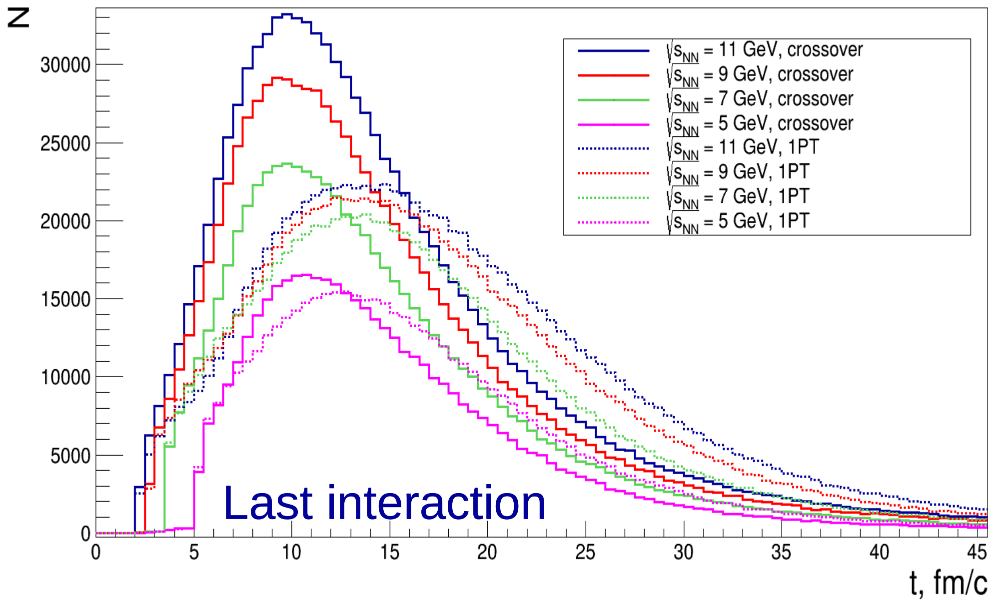
- Initial collisions and string fragmentations from the microscopic UrQMD model.
- (3+1)-dimensional ideal hydrodynamic evolution.
- hadronic cascade.

Chiral EoS - Crossover

Bag model EoS - 1st order

Hadron gas EoS

- Hydro phase lasts longer with 1^{st} order PT



vHLLE+UrQMD model

Pre-thermal phase → hydrodynamic phase → hadronic cascade

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

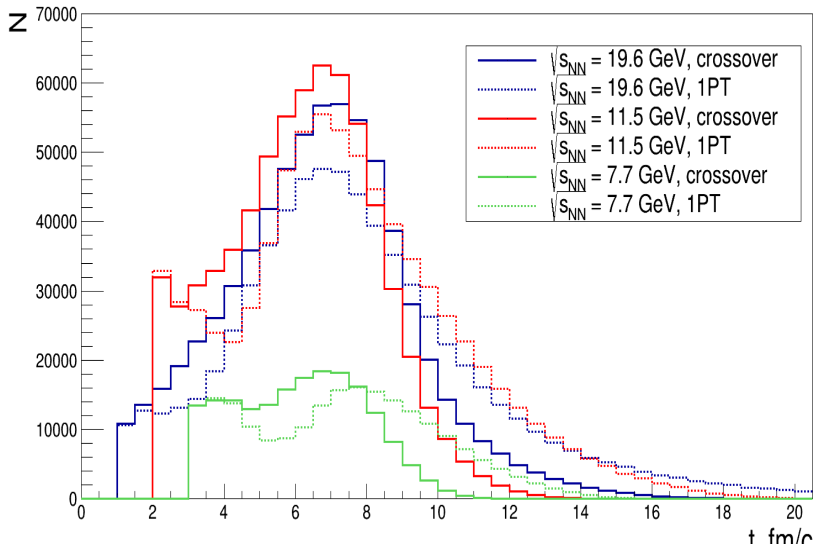
Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978,1509.3751 , talk QM2015
vHLLE code: free and open source, https://github.com/yukarpenko/vhlle, Comput. Phys. Commun. 185 (2014), 3016

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

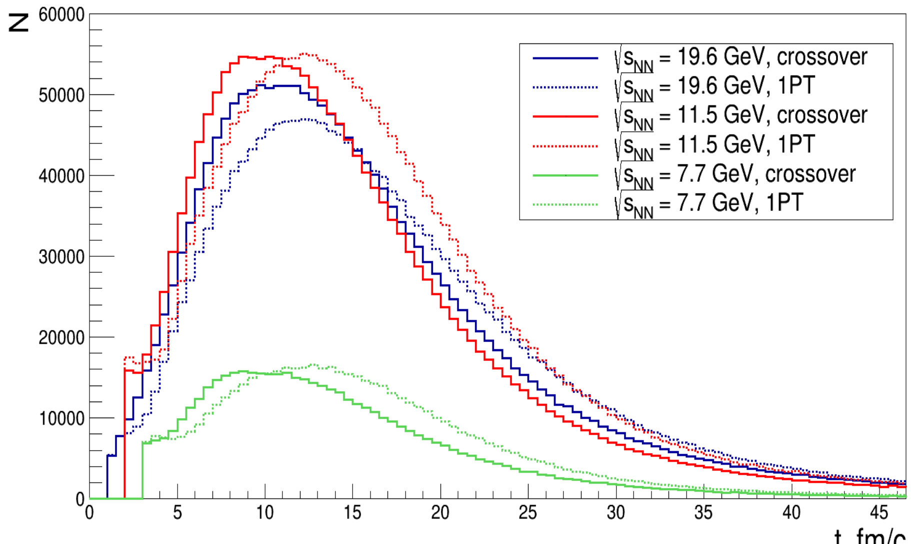
Chiral EoS -crossover phase transition
J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

HadronGas + Bag Model – 1st order PT
P.F. Kolb, et al, Phys.Rev. C 62, 054909 (2000)

vHLLE



vHLLE+UrQMD



vHLLE+UrQMD model

Pre-thermal phase → hydrodynamic phase → hadronic cascade

UrQMD vHLLE UrQMD

Iu. Karpenko, P. Huc ... 509.3751 , talk QM2015
vHLLE code: free a... 2014), 3016

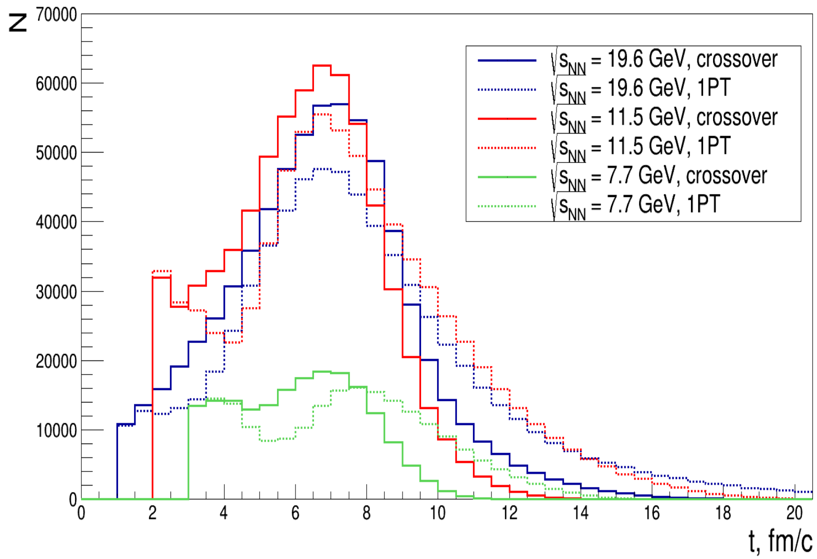
Model tuned ... RHIC.

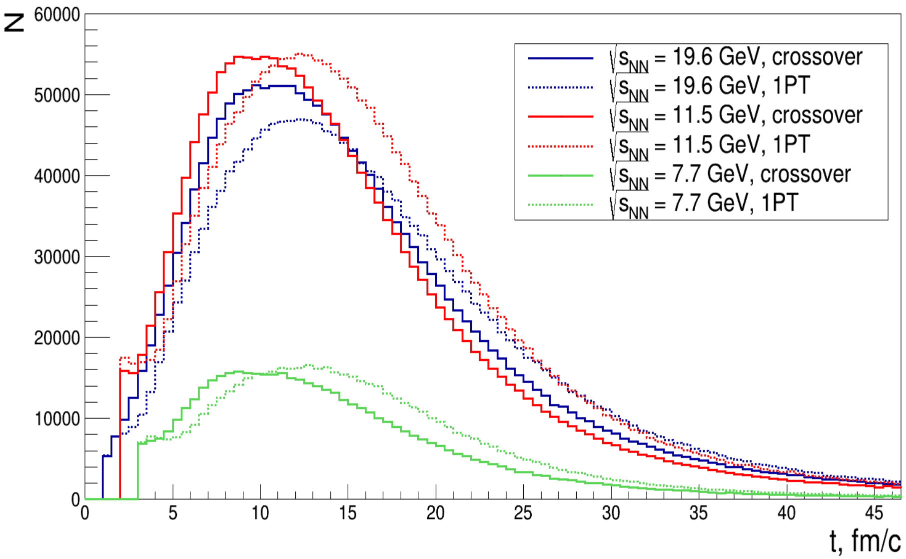
Chiral EoS -... – 1st order PT
J. Steinheimer, ... 054909 (2000)

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

Is it possible to see it using Femtoscopy technique ?

v... vHLLE+UrQMD

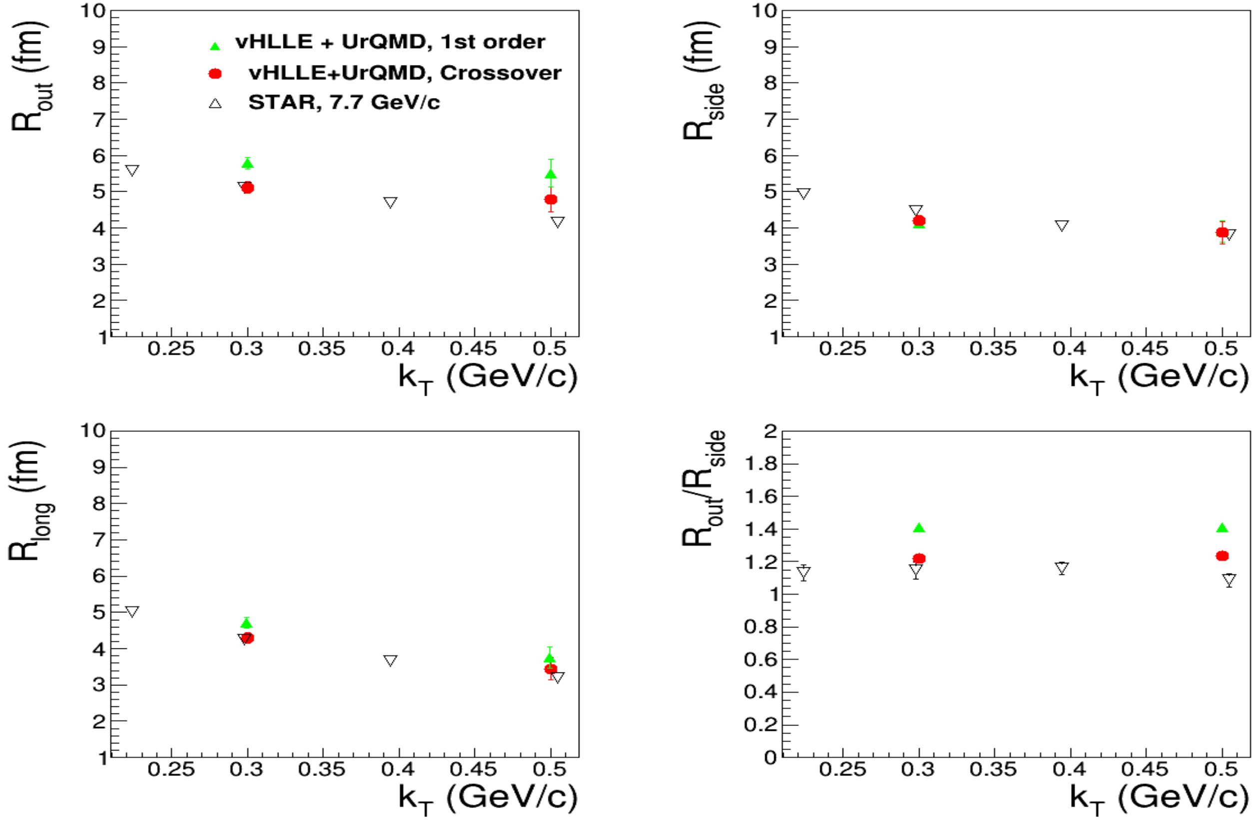




Radii versus k_T with vHLLE+UrQMD model

- **Very first test** with ~5000 vHLLE+UrQMD events

$\pi\pi$ AuAu , sqrt(sNN)= 7.7 GeV/c

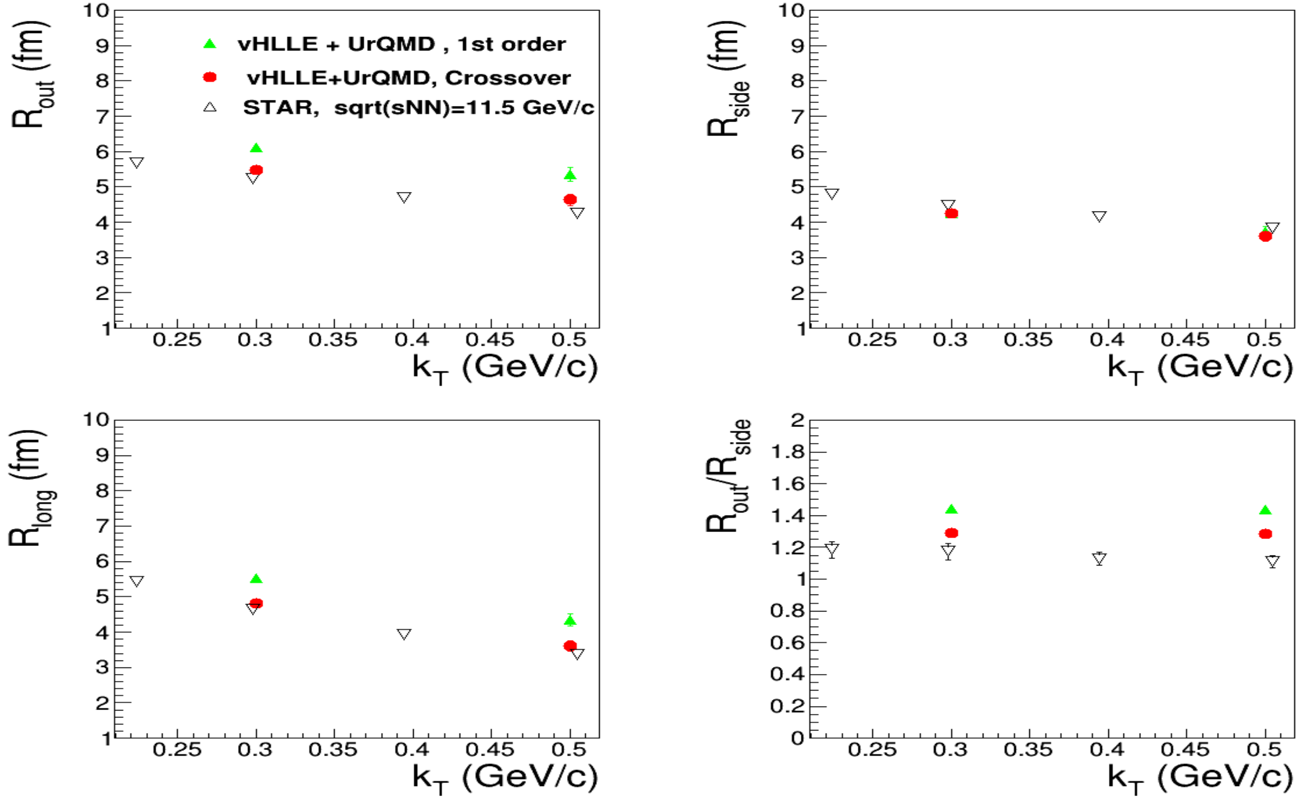


- R_{long} 1st order > R_{long} Crossover, difference < 0.5 fm
- R_{out}/R_{side} 1st order > R_{out}/R_{side} Crossover
- It looks like vHLLE+UrQMD model with Crossover describes STAR data better than the one with 1st order PT, but more detailed study is needed

Radii versus k_T with vHLLE+UrQMD model

- **Very first test** with ~20000 vHLLE+UrQMD events

$\pi\pi$ AuAu , sqrt(s_{NN})= 11.5 GeV/c



- R_{long} 1st order > R_{long} Crossover, difference ~ 0.5 fm
- R_{out}/R_{side} 1st order > R_{out}/R_{side} Crossover
- model with Crossover PT describes STAR data better than with 1st order PT

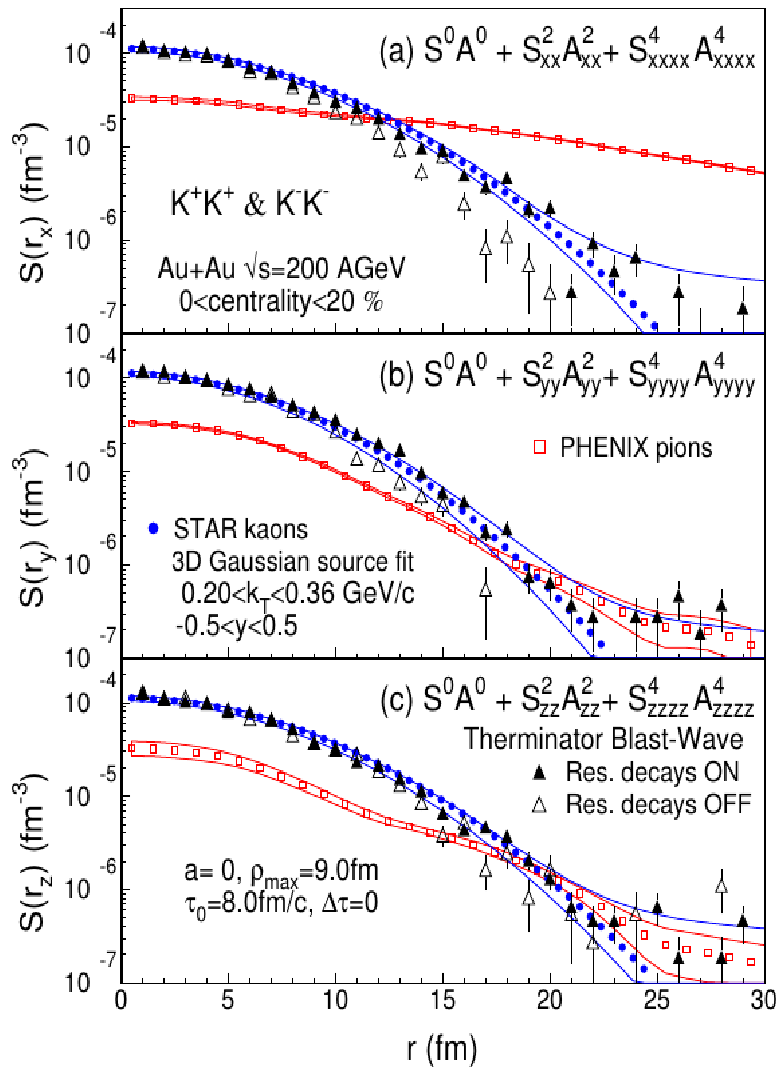
Imaging

- 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.

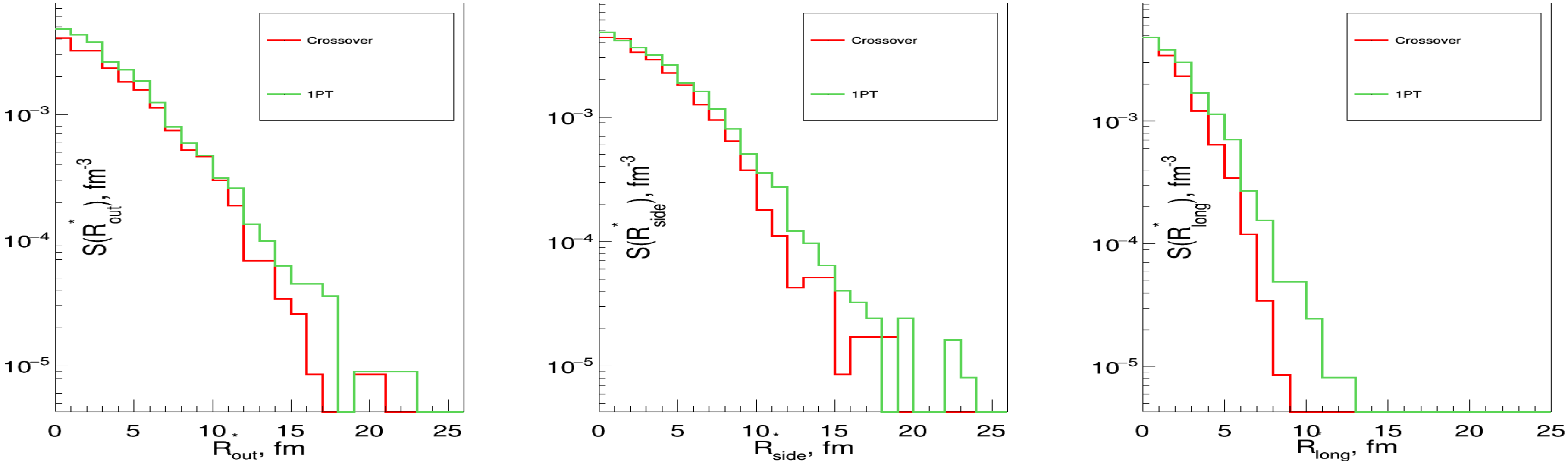
STAR, Phys.Rev. C88 (2013) 3, 034906



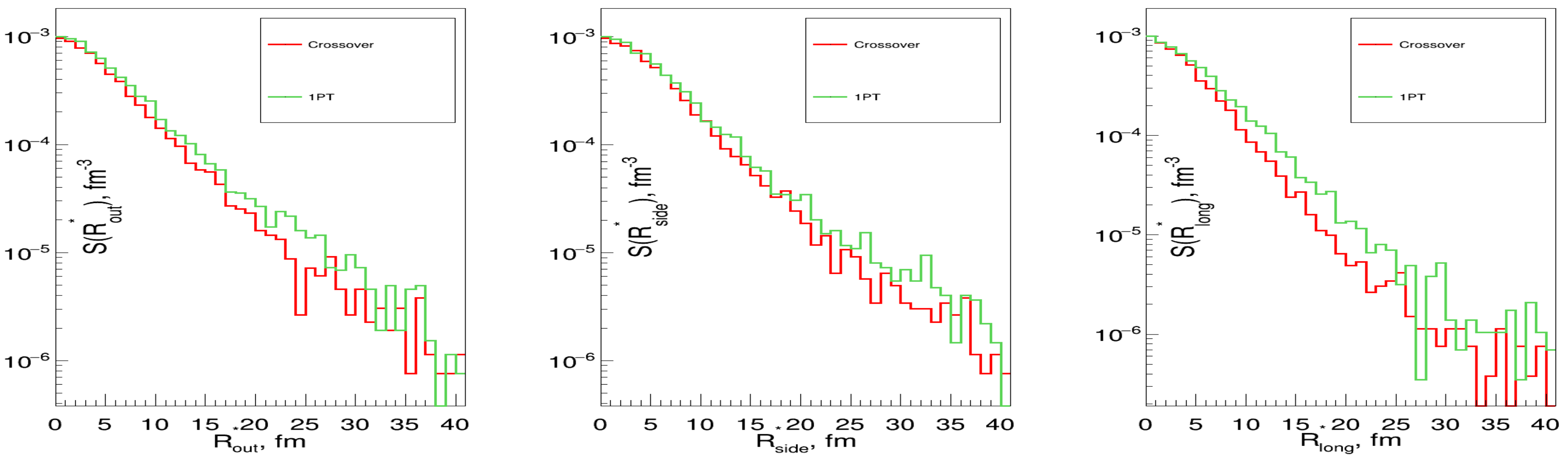
Source Function with vHLLE + UrQMD model

VHLLE

sqrt(sNN) =7.7 GeV : **S(r) for ππ**



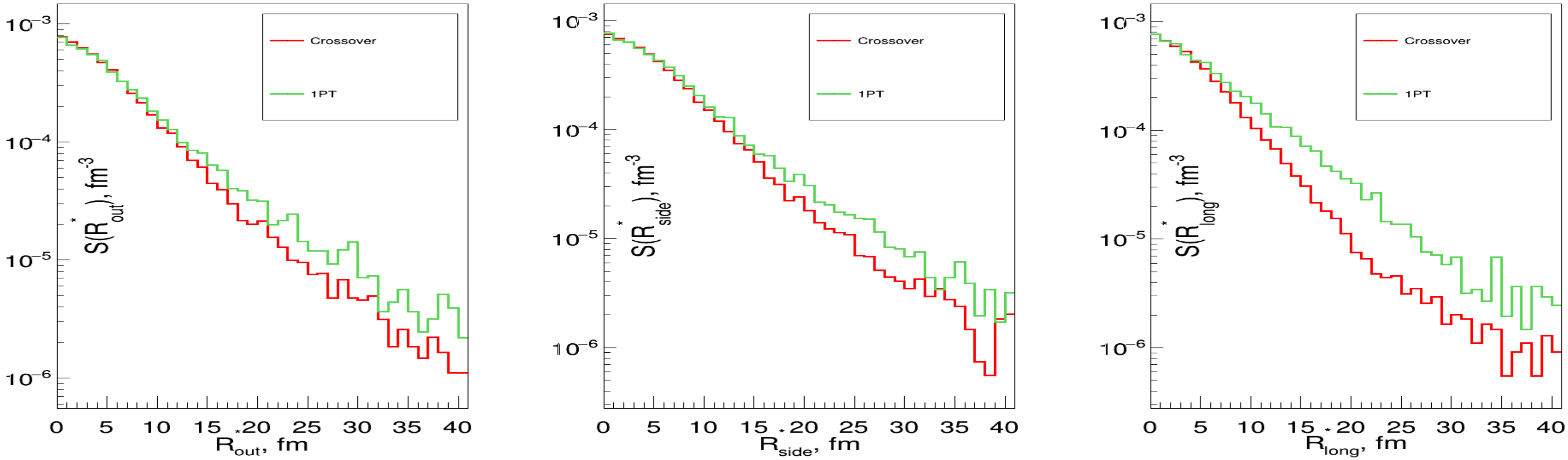
VHLLE + UrQMD



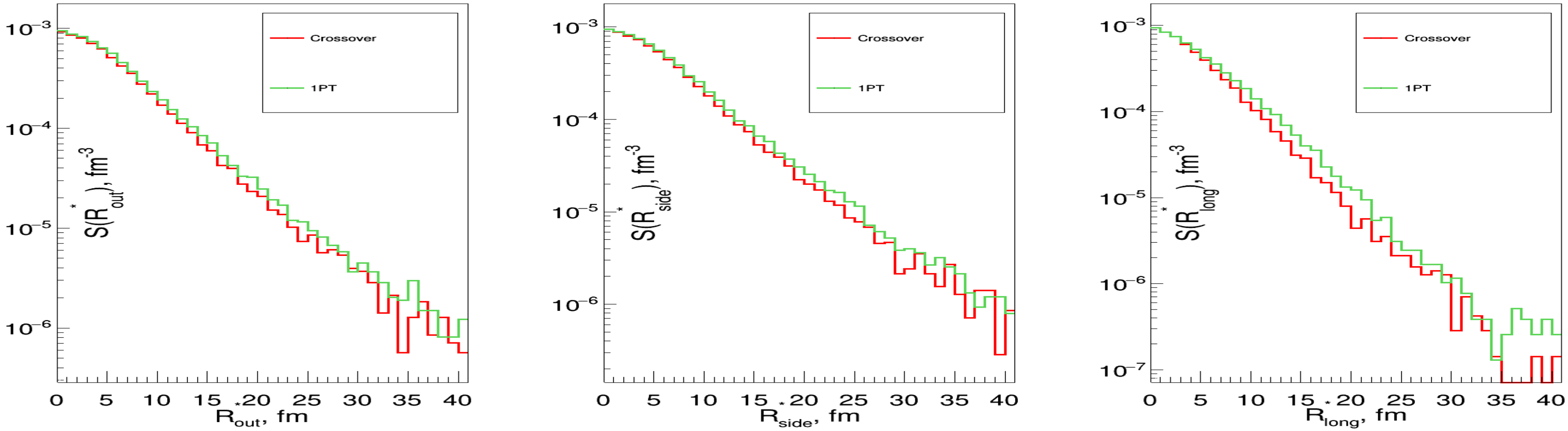
Source Function with vHLLE + UrQMD model

VHLLE

sqrt(sNN) =11.5 GeV : **S(r) for ππ**

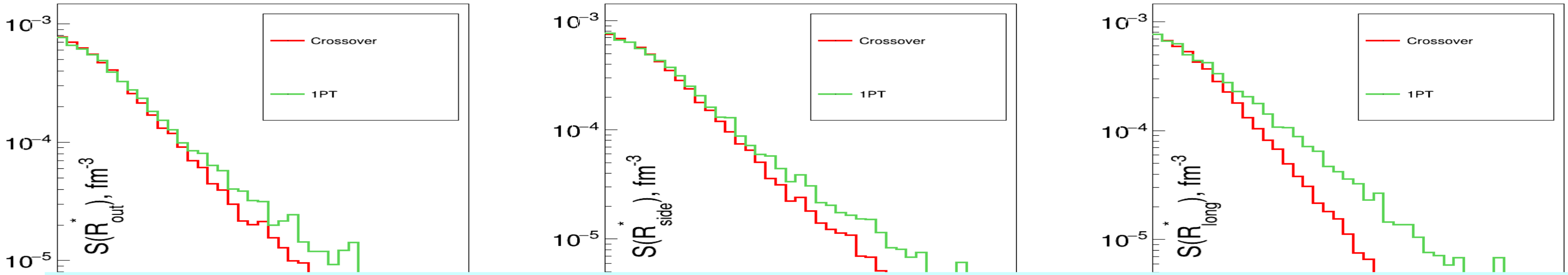


VHLLE + UrQMD

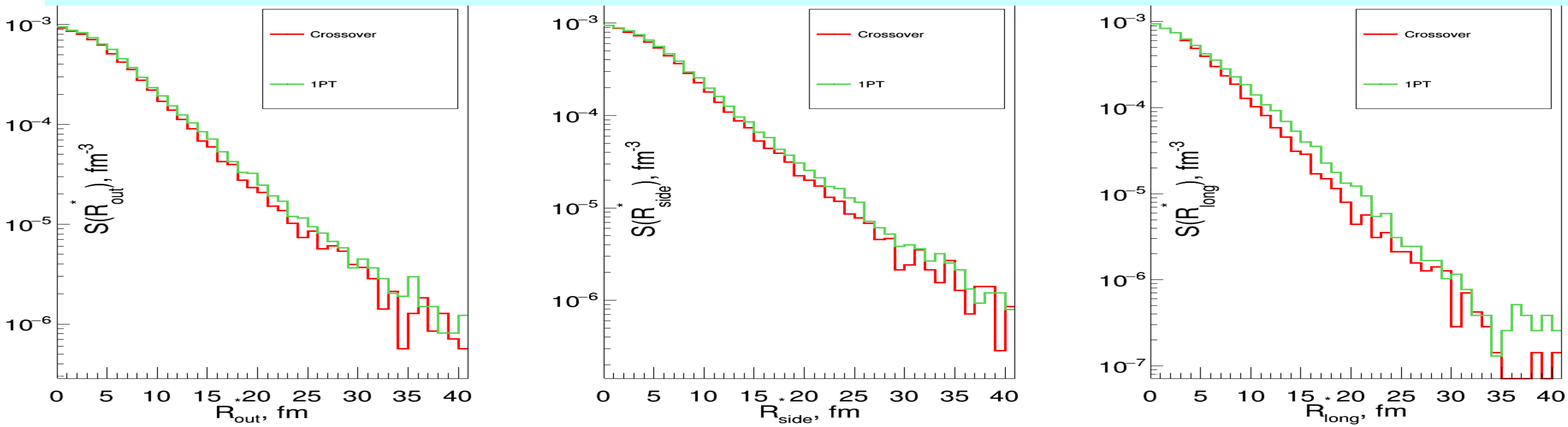


Source Function with vHLLE + UrQMD model

VHLLE sqrt(sNN) =11.5 GeV : **S(r) for ππ**

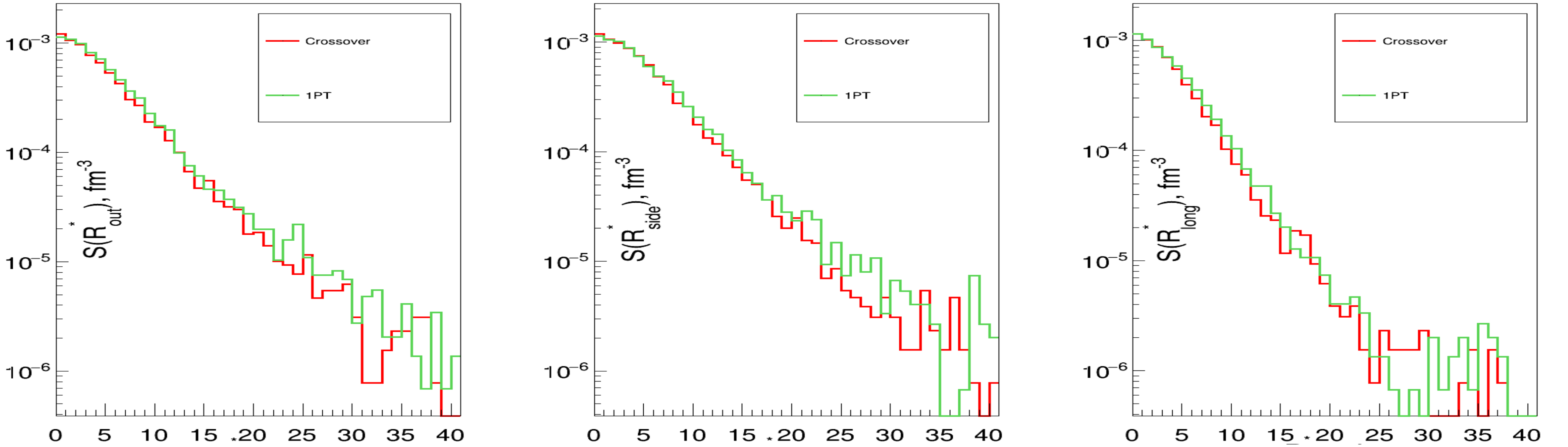


For the calculations with pure hydro vHLLE with 1[st] order PT the tails of source functions are longer than those obtained with crossover PT.
For the calculations with cascade the difference is smeared but also seen.
The largest difference is observed for R_{long}

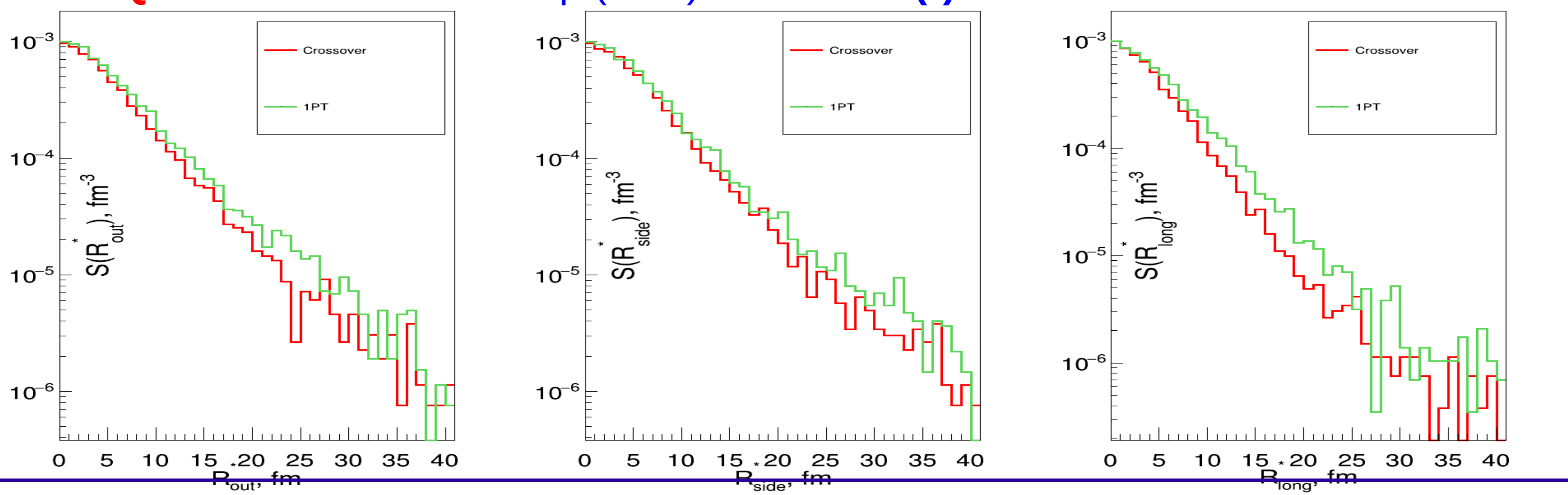


Source Function with UrQMD 3.4 model

UrQMD-3.4 sqrt(sNN) =5 GeV : **S(r) for ππ**

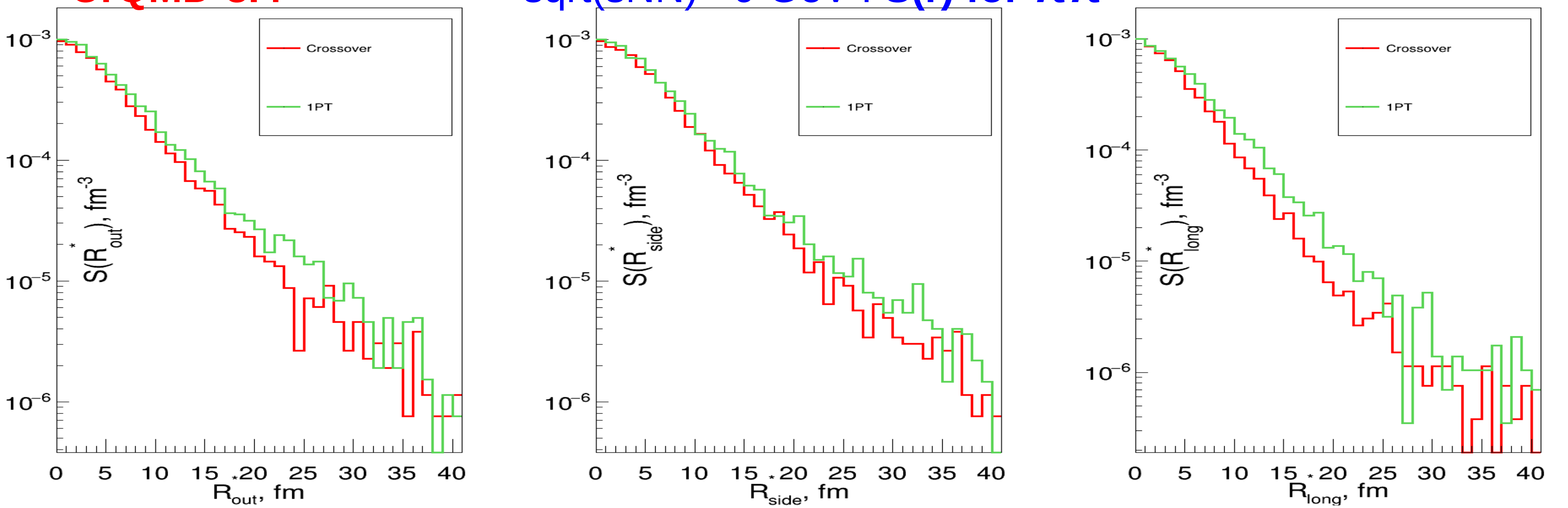


UrQMD-3.4 sqrt(sNN) =7 GeV : **S(r) for ππ**

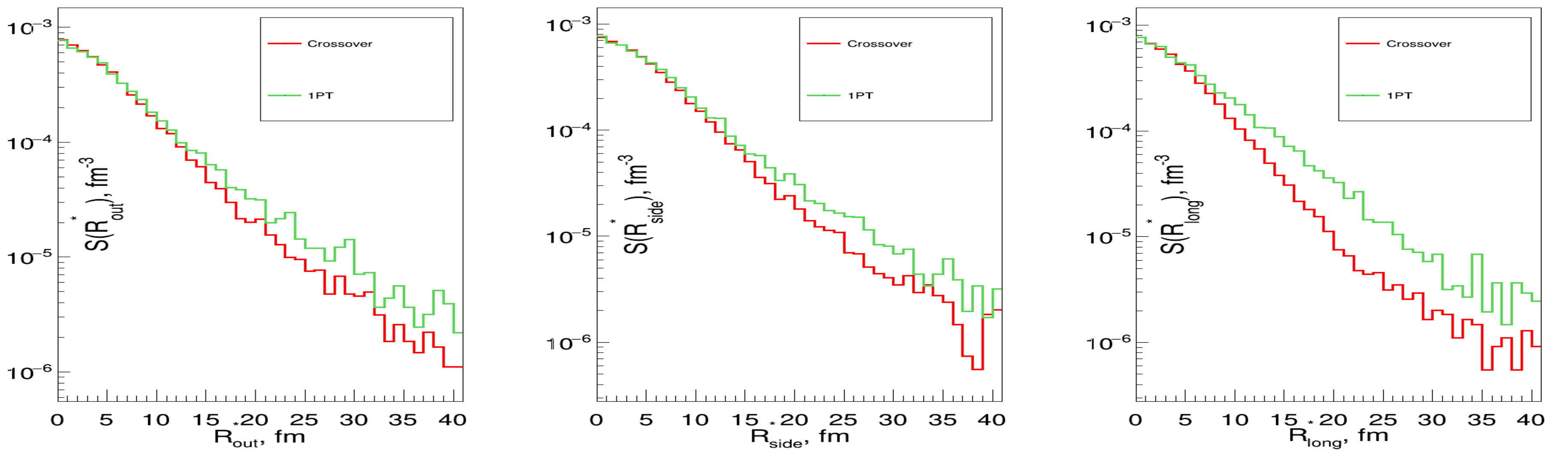


Source Function with UrQMD 3.4 model

UrQMD-3.4 sqrt(sNN) =9 GeV : **S(r) for ππ**

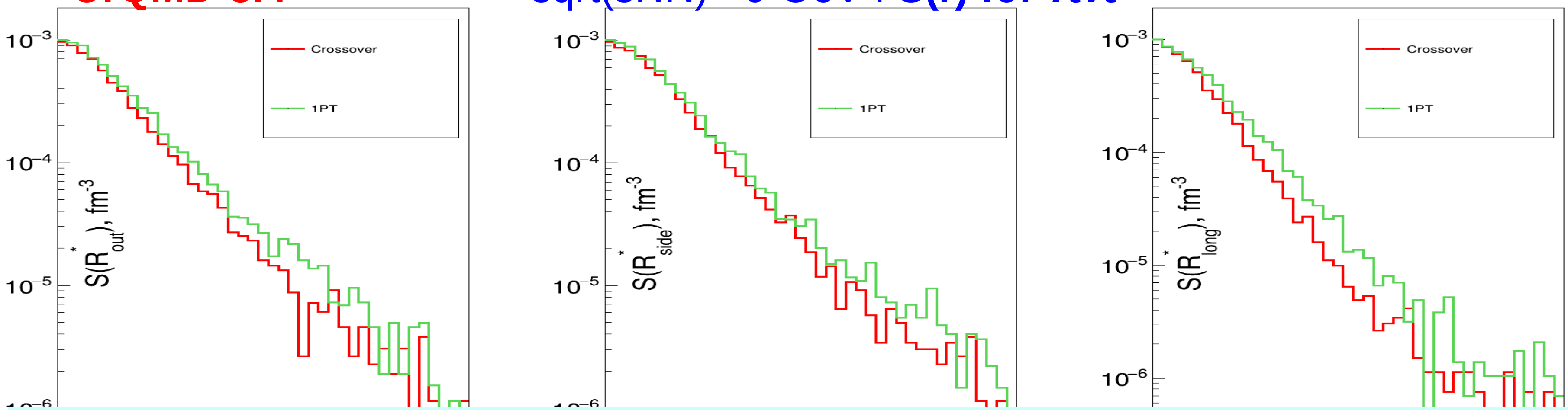


UrQMD-3.4 sqrt(sNN) =11 GeV : **S(r) for ππ**



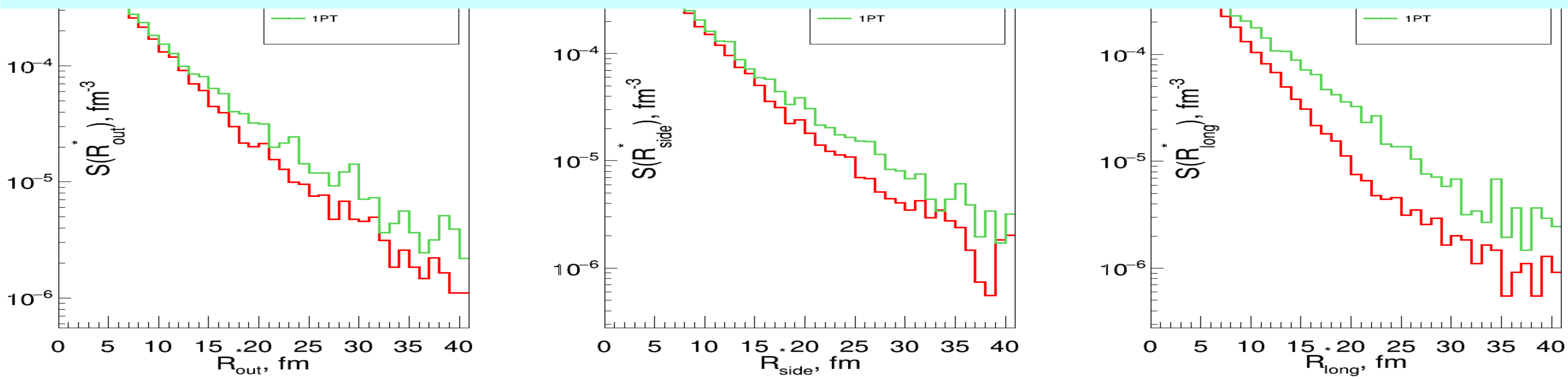
Source Function with UrQMD 3.4 model

UrQMD-3.4 sqrt(sNN) =9 GeV : **S(r) for ππ**



For the calculations with 1st order PT the tails of source functions are longer than those obtained with crossover PT.

The largest difference is observed for R_{long}



Summary & Plans

- Possibility to distinguish between hybrid model source functions

  with 1st order phase transition and crossover was studied using vHLLE+UrQMD and UrQMD34 models.
- Hydro phase lasts longer with 1st order PT.
- Hadronic cascade strongly affects the source functions, but there is still a possibility to distinguish between 1st order and Crossover using this technique.
- We are planning to continue these studies with larger statistics for pions and kaons

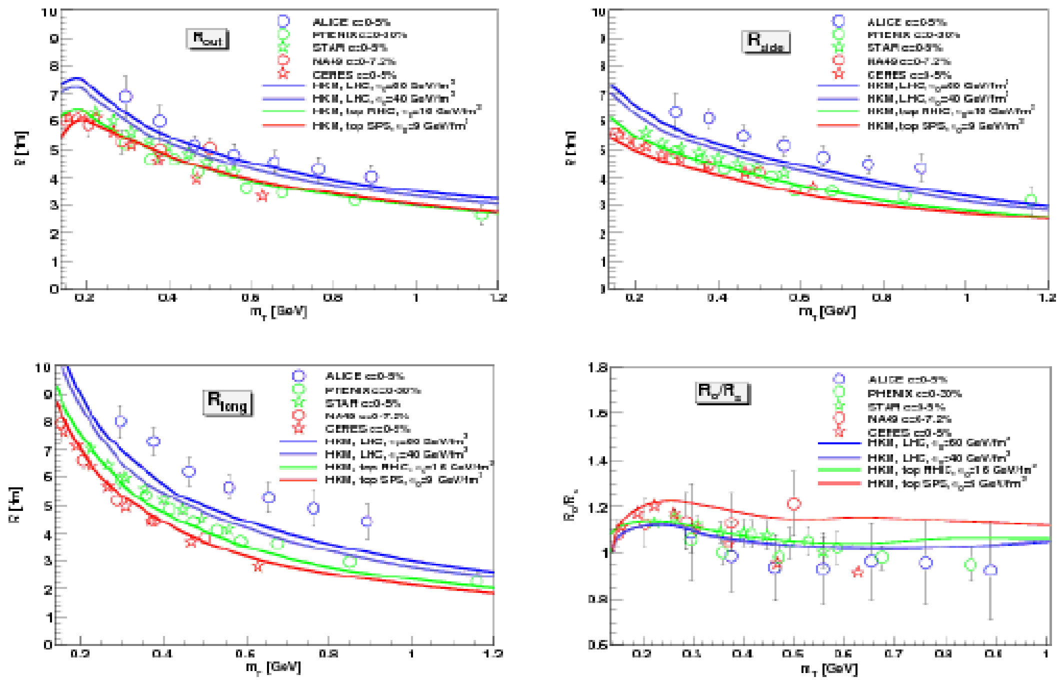
- vHLLE+UrQMD model with Crossover describes RHIC femtoscopy radii

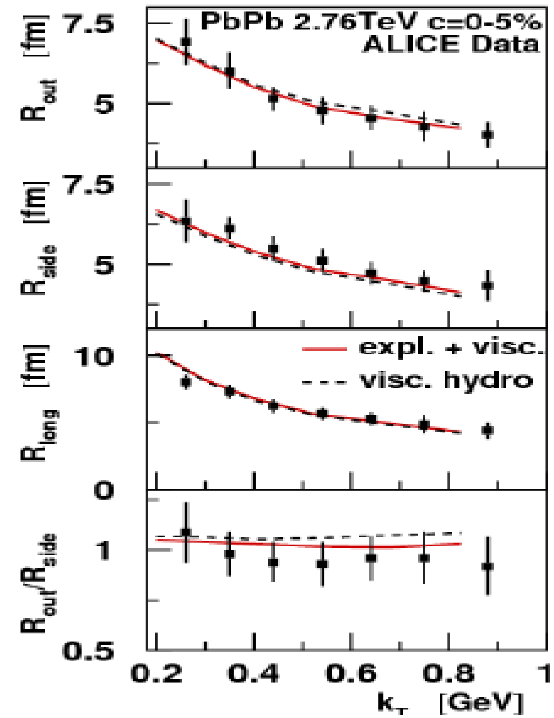
  at sqrt(s_{NN}) =7.7-11.5 GeV better than with 1st order PT
- R_{long} radii for 1st order > R_{long} Crossover, difference is rather small for low energies
- R_{out}/R_{side} for 1st order > R_{out}/R_{side} Crossover, difference is rather small for low energies
- We are planning to study the non-Gaussian tails of CF using different parametrizations:

  e.g Hump or Edgeworth parametrizations.

Additional slides

Theoretical interpretations for LHC





Yu. Karpenko, Yu. Sinyukov, Phys.Lett. B688 (2010) 50-54

Hydro-Kinetic Model: **the same hydrokinetic basis as that used for RHIC** supplemented with hadronic cascade model at the latest stage of the evolution:.**The following factors are important**: presence of pre-thermal transverse flow, crossover transition between quark-gluon and hadron medium, non-hydrodynamic behavior of the hadron gas at the latest stage, and correct matching of hydrodynamic and non-hydrodynamic stages.

P. Bożek,Phys.Rev. C83 (2011) 044910

3D relativistic viscous hydrodynamics.

Glauber model initial conditions

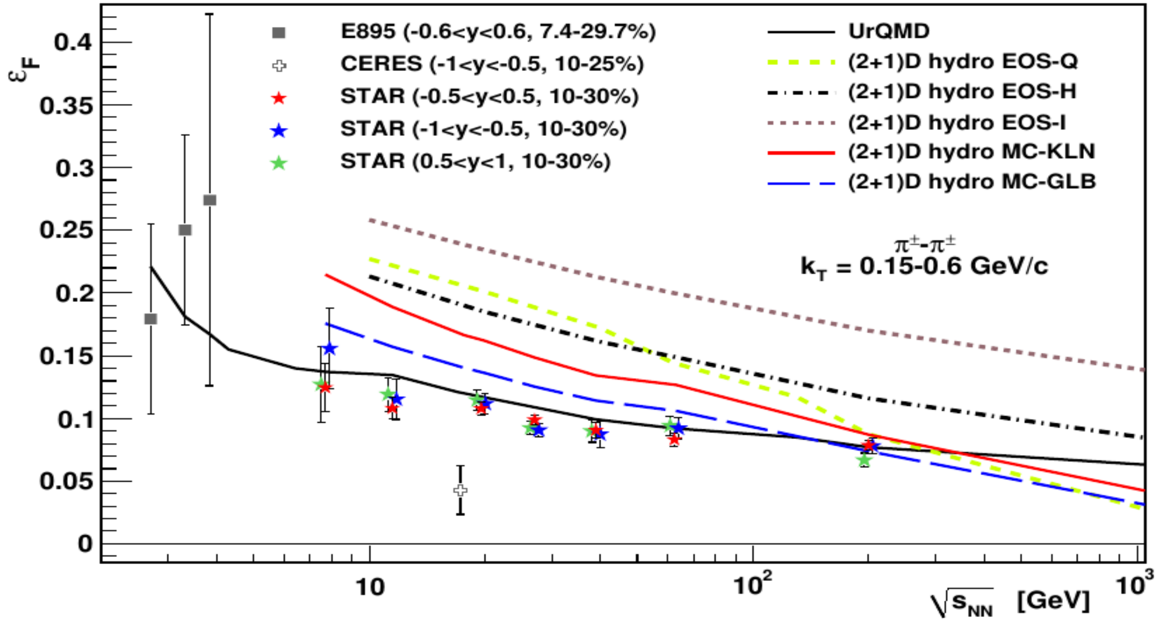
EoS based on lattice results and hadron-gas model - crossover.

The viscosity and the EoS are the same as those used for RHIC energies.

Az-femtoscopy

STAR arxiv 1403.4972 [hep-exp]

Dependence of the kinetic freeze-out eccentricity for pions on collision energy



$$\varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

From: F. Reti`ere and M. A. Lisa, Phys. Rev. C 70, 044907 (2004)

$\sigma_x^2 = \{x^2\} - \{x\}^2$ in-plane

$\sigma_y^2 = \{y^2\} - \{y\}^2$ out-of-plane

The prediction of the Boltzmann transport model, UrQMD matches most closely the freeze-out shape at all energies. UrQMD does not require assumptions about how freeze-out occurs; the model is 3D and does not require boost-invariance, therefore, it is equally applicable at all the studied energies.