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Feasibility of femtoscopy studies at the NICA energies

P. Batyuk, L. Malinina, D. Wielanek

`pavel.batyuk@jinr.ru`
VBLHEP, JINR

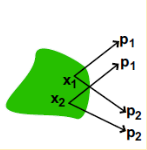
Section 1: High energy physics

March 16, 2016

Outline

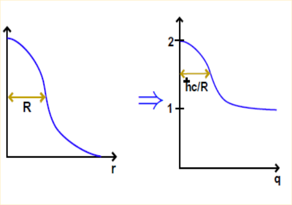
- **Introduction**
- **Femtoscopy at different energies: from STAR to NICA**
- **Source function technique**
- **Conclusion**

Introduction



Correlation femtoscopy:

Measurement of space-time characteristics R, c_τ (fm) of particle production using particle correlations due to the effects of quantum statistics (QS) and final state interactions (FSI)



Two-particle correlation function:

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

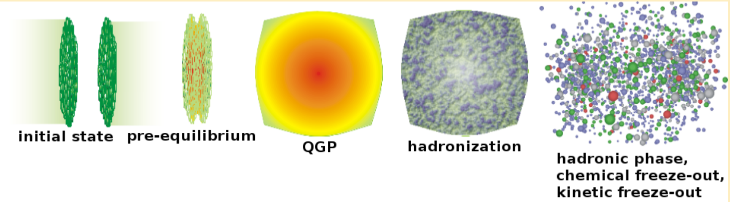
$$\textbf{experiment: } C(q) = \frac{S(q)}{B(q)},\ q = p_1 - p_2$$

S(q) is a distribution of pair momentum difference of particles from the same event

B(q) is a reference distribution built by mixing of particles from different events

Introduction

The main goal of experiments with heavy ion collisions is to study the new forms of matter which can be created under the extreme conditions at the early stage of the evolution.



- Information on the space-time evolution can only be extracted by study the femtoscopy correlations.
- The correlations depend on the space-time distance separating emission points and on the particle relative momentum.
- The space-time relative distances are measured at the points where the particles stop to interact, then they are set free (kinetic freeze-out). This moment occurs at very late stage of collisions after the QGP was created and disappeared.
- The available signals (geometric growth of the reaction zone, the specific features of the collective flow generated by the QGP pressure gradients) are revealed in the final state as very specific space-momentum correlations influencing particle spectra and correlation radii.

Femtoscopy: parametrizations used

$$C(q) = 1 + \lambda e^{-R_{inv}^2 q_{inv}^2}$$

λ is a correlation strength,

R_{inv} assumes a Gaussian radius in the Pair Reference Frame (PRF)

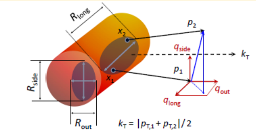
1d-analysis is sensitive only to the system size averaged over all directions.

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

R, q are defined in the Longitudinally Co-Moving Frame (LCMS)

3d-analysis gives an access to the three system sizes in three directions separately.

Definition of femtoscopic radii:



3D-analysis:

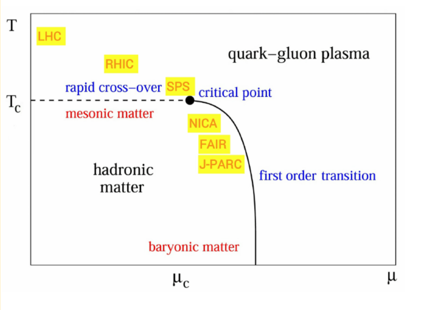
R_{side} is sensitive to **geometrical transverse size**

R_{long} is sensitive to **time of freeze-out**

R_{out}/R_{side} is sensitive to **emission duration**

Introduction

Crossover transition to QGP occurs at RHIC & LHC



The Questions arisen:

- At what energies do the hydro models with the 1st order phase transition (1PT) describe femtoscopy observables better than those with crossover?
- What femtoscopy observables are the most sensitive to this difference?

Femtoscopy: Energy Scan

RHIC: $\sqrt{s_{NN}} = 62$ to 200 GeV

large T & small μ_B

Smooth, rapid crossover

BES @ RHIC: $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39$ GeV

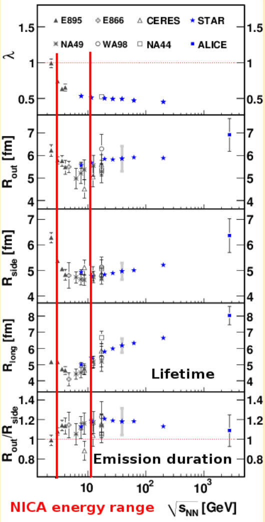
small T & large μ_B

search for "critical point"

NICA: $\sqrt{s_{NN}} = 4$ to 11 GeV

small T & large μ_B

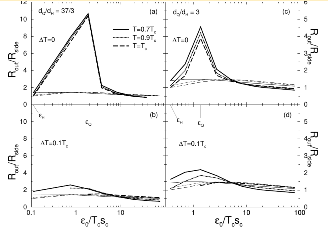
STAR, Phys.Rev. C92 (2015) 1, 014904



Expected features of the 1st order PT

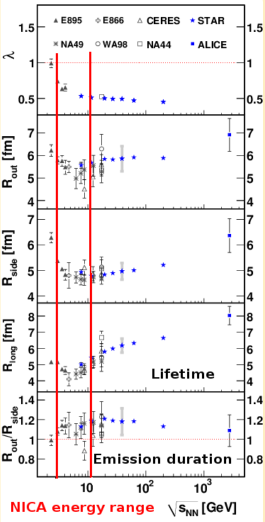
1PT: $R_{out}/R_{side} >> 1$ **& large** R_{long} **due to emission stalling during PT**

D. H. Rischke and M. Gyulassy, Nucl. Phys. A608, 479 (1996)



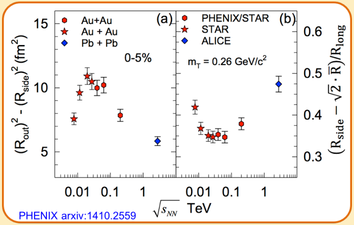
What do the modern hydrodynamic (hybrid) models expect?

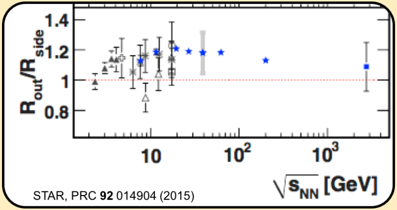
STAR, Phys.Rev. C92 (2015) 1, 014904



Search for critical point location

Softening? Critical point?





Mike Lisa, QM 2015:

This is precisely the sort of thing we've been seeking, & it's happening in "interesting" BES energies. It requires and deserves serious theory / modeling.

vHLLE + UrQMD model

Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015)
vHLLE code: free and open source, https://github.com/yukarpenko/vhlle

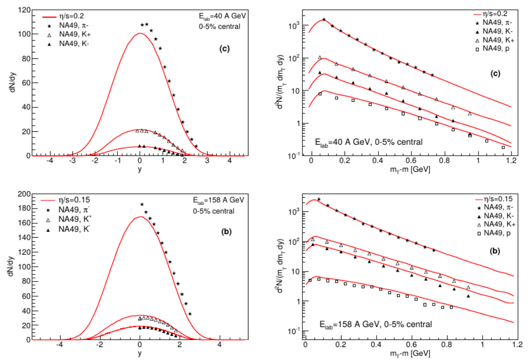
Pre-thermal phase → hydrodynamic phase → hadronic cascade

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

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

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

40 + 158 A GeV PbPb SPS ($\sqrt{s} = 8.8$ and 17.3 GeV)



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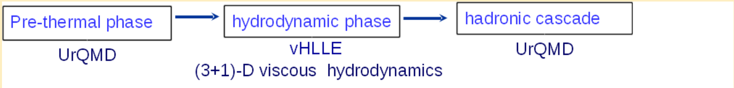
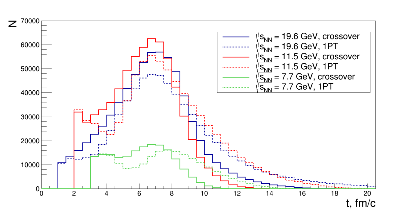
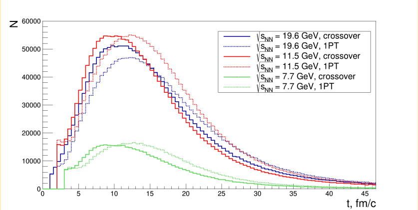


vHLLE



vHLLE + UrQMD



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

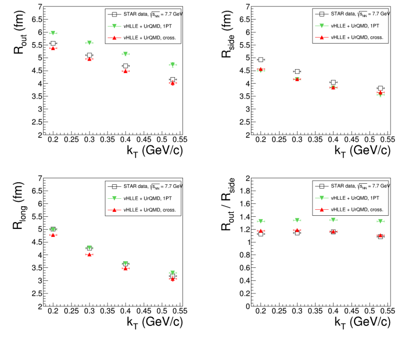
Is it possible to see this time difference using the femtoscopy techniques?

Radii versus k_T with the vHLLE + UrQMD model

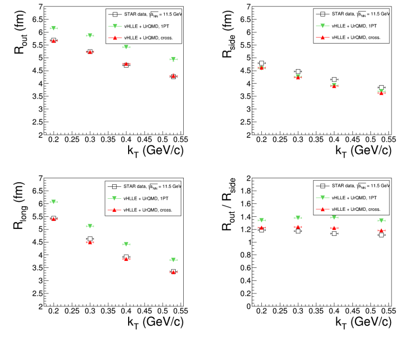
Details of analysis

vHLLE + UrQMD: $\sim$ **100 000 events,** $\pi^+\pi^+$ **pairs,** $0.15 < p_T < 0.8$ **GeV/c,** $|\eta| < 1$, k_T **bins (in GeV/c):** $[0.15, 0.25]$, $[0.25, 0.35]$, $[0.35, 0.45]$, $[0.45, 0.60]$

AuAu @ $\sqrt{s_{NN}} = 7.7$ GeV



AuAu @ $\sqrt{s_{NN}} = 11.5$ GeV



- R_{long} **(1PT)** $>$ R_{long} **(crossover), difference** $\sim$ **0.5 fm**
- R_{out}/R_{side} **(1PT)** $>$ R_{out}/R_{side} **(crossover)**

A more detailed study is required ...

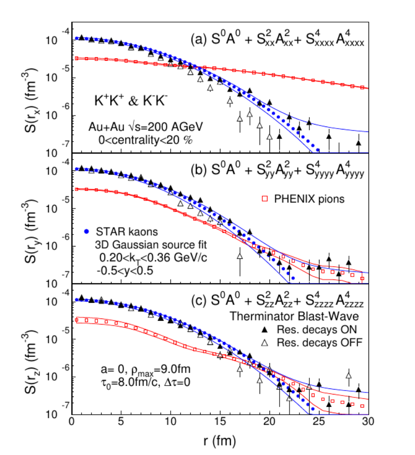
Source Function Technique

$S(r^*)$ is a **source function**, which represents time-integrated distribution of particle emission points separation r^* in the PRF.

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

The method is suitable for extracting the $S(r^*)$ directly from the data **without any hypothesis about source shape**.

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



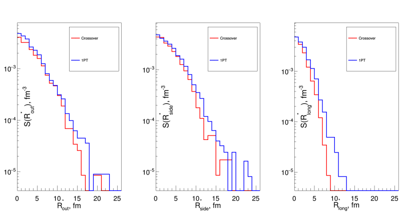
Source Function Technique

Details of analysis

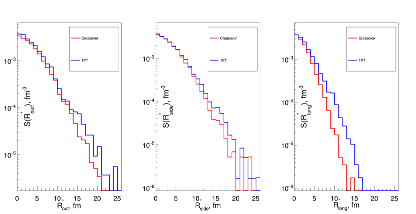
vHLLE + UrQMD: a very first test.

$\pi^+\pi^+$ **pairs, 0.15** $< p_T <$ **0.8 GeV/c,** $|\eta| < 0.5$, k_T **bins (in GeV/c):** $[0.2, 0.4]$

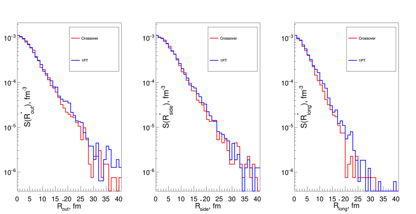
$\sqrt{s_{NN}} = 7.7$ **GeV, vHLLE**



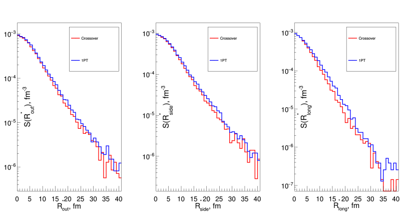
$\sqrt{s_{NN}} = 11.5$ **GeV, vHLLE**



$\sqrt{s_{NN}} = 7.7$ **GeV, vHLLE + UrQMD**



$\sqrt{s_{NN}} = 11.5$ **GeV, vHLLE + UrQMD**



Conclusion, Part 1

- **Despite hadronic cascade affects strongly the observed source functions, it seems to be possible to distinguish them within the vHLLE + UrQMD hybrid model.**
- **Hydro phase lasts longer with the 1PT.**
- **We plan to continue these studies with larger statistics for π- and K-mesons.**
- **The vHLLE + UrQMD model with crossover describes the RHIC femtoscopy radii at $\sqrt{s_{NN}} = 7.7$, 11.5 GeV better than with the 1PT.**
- R_{long} **(1PT)** $>$ R_{long} **(crossover), the observed difference is rather small for low energies.**
- R_{out}/R_{side} **(1PT)** $>$ R_{out}/R_{side} **(crossover), the observed difference is rather small for low energies.**
- **We plan to study the non-Gaussian tails of CFs using different parametrizations: e.g. Hump or Edgeworth parametrizations.**

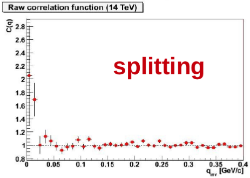
Thank you for your attention!

BACKUP SLIDES

Splitting and Merging effects

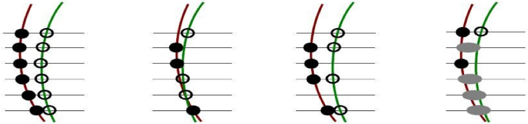
Example of correlation function

- An example of the raw correlation function from PDC06 data obtained via AliFemto code



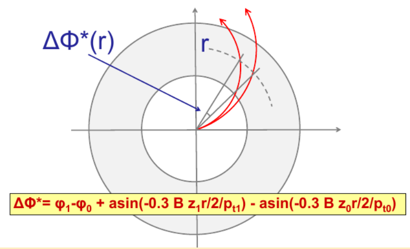
Quality cut

$$q_i = \begin{cases} -1 \text{ if both tracks have a hit in padrow} \\ \ \ 0 \text{ if none of the tracks have a hit in padrow} \\ +1 \text{ if only one track has a hit in padrow} \end{cases} \qquad Quality = \frac{\sum_{padrows} q_i}{\# \, hits \text{ in } the \ pair}$$



Separate tracks	Probably a split track	Probably separate tracks	Probably a split track
Quality = -0.5	Quality = 1.0	Quality = -0.125	Quality = -0.36
GOOD	GOOD	GOOD	BAD

Anti-merging cut (The ALICE collaboration)

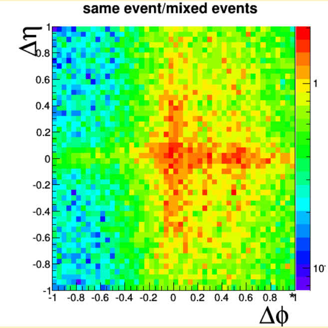


$$\Delta\Phi^*(R) = \phi_1 - \phi_0 + \arcsin\left(-\frac{0.3 B_z Z_1 R}{2 P_{T1}}\right) - \arcsin\left(-\frac{0.3 B_z Z_0 R}{2 P_{T0}}\right)$$

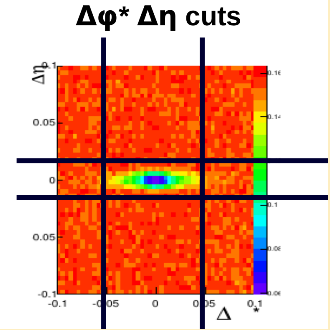
ϕ_1 and ϕ_0 are azimuthal angles of the tracks at the vertex.
P_{T1} and P_{T0} are their transverse momenta.
B_z indicates the magnetic field in z-direction.
Z_1 and Z_0 are charges of particles forming the track.

$\Delta\phi^*\Delta\eta$ distribution

How it looks:



How it should look:



The merging is not visible due to a very strong splitting.
Firstly, we need to suppress the splitting!