

## Further development of the hydrokinetic model and description of the RHIC and LHC A+A femtoscopic data

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A study of the energy behavior of the interferometry radii is carried out for the RHIC and LHC energies within the hydrokinetic model (HKM). For the purpose of this study, different approaches for hadron interactions at post (chemical) freeze-out stage of evolution are considered: pure hydro-kinetic approach or combined algorithm using also UrQMD code. In the latter case hydrodynamic and hadronic cascade stages of evolution are matched smoothly via intermediate hydro-kinetic stage, forming the hybrid hydrokinetic model (hHKM). The model predictions for the HBT radii at LHC energies are compared with the recent results of the ALICE Collaboration. The role of non-equilibrium and non-hydrodynamic stage of the matter evolution in formation of the femtoscopic scales at the LHC energies is analyzed.

*The Seventh Workshop on Particle Correlations and Femtoscopy*

*September 20 - 24 2011*

*University of Tokyo, Japan*

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## 1. Introduction

Experiments at RHIC brought an unexpected results on the correlation femtoscopy of identical pion pairs, commonly referred to as “RHIC HBT puzzle”, which was not solved in hydrodynamic (or hybrid) models of A+A collisions. Much later, the factors which allow one to describe simultaneously the spectra and femtoscopic scales at RHIC energy in hydrodynamic approach, become understood. The factors are [1, 2, 3, 4, 5, 6]: a relatively hard equation of state because of crossover transition (instead of the 1st order one) between quark-gluon and hadron phases and due to nonequilibrium composition of hadronic matter, presence of prethermal transverse flows and their anisotropy developed to thermalization time, an “additional portion” of the transverse flows owing to the shear viscosity effect and fluctuation of initial conditions. These ideas allowed us to reach a simultaneous description of kaon and pion femtoscopy together with their momentum spectra at top RHIC energy [7].

Recently, the first LHC results of the femtoscopy analysis in Pb+Pb collisions at  $\sqrt{s} = 2.76$  TeV has been published by the ALICE Collaboration [8]. The principal question is whether an understanding of the space-time matter evolution in Au+Au collisions at RHIC can be extrapolated to the LHC energies. Here we present the quantitative predictions given for LHC within hydrokinetic model (HKM) earlier [9], compare them with the recent ALICE LHC results and make the corresponding inference based on the first results of new hybrid hydrokinetic model (hHKM).

## 2. Hydrokinetic approach to A+A collisions

Hydrokinetic model incorporates hydrodynamical expansion of the systems formed in A+A collisions and their dynamical continuous decoupling described by the escape probabilities in a way consistent with the kinetic equations in the relaxation-time approximation for emission functions. For detailed description of the model we refer the reader to Refs. [2, 10]. The HKM is also the correct basis to switch over a hydrodynamic evolution of continuous medium to an evolution of particles within cascade model like UrQMD [7]. The model which matches the hydrokinetic model and UrQMD we call hybrid HKM (hHKM).

Our results are all related to the central rapidity slice where we use the boost-invariant Bjorken-like initial condition. We suppose the proper time of thermalization of quark-gluon matter, to be  $\tau_0 = 1$  fm/c. The initial energy density in the transverse plane is supposed to be Glauber-like [11] with zero impact parameter. The maximal initial energy density -  $\varepsilon(r=0) = \varepsilon_0$  is the fitting parameter. From the analysis of particle multiplicities we choose it for the top RHIC energy to be  $\varepsilon_0 = 15$  GeV/fm<sup>3</sup>. For the LHC energy  $\sqrt{s} = 2.76$  TeV the corresponding value is  $\varepsilon_0 = 40$  GeV/fm<sup>3</sup> that in hydrokinetic model corresponds to multiplicity of charged particles at mid-rapidity  $dN_{ch}/d\eta \approx 1500$ . The pre-thermal transverse flow which the system already has at  $\tau_0 = 1$  fm/c [1] is supposed to be linear in radius  $r_T$ :  $y_T = \alpha r_T/R_T$  where  $\alpha$  is the second fitting parameter and  $R_T = \sqrt{\langle r_T^2 \rangle}$ . From the best fit of the pion transverse spectra at the RHIC energy we take  $\alpha = 0.28$  in HKM and  $\alpha = 0.18$  for hHKM and the same value we keep for the LHC energy. Note that the fitting parameter  $\alpha$  absorbs also a positive correction for underestimated resulting transverse flow especially in HKM where we do not account for the the viscosity effects [12] (in

hHKM these effects are effectively included at the hadronic stage, therefore  $\alpha$  is essentially less than in HKM).

Following to Ref. [2] we use at high temperatures the EoS [13] adjusted to the QCD lattice data. We suppose the chemical freeze-out for the hadron gas at  $T_{ch} = 165$  MeV [14] for top RHIC energy. Based on collision energy dependence of chemical freeze-out parameters known from the above-mentioned statistical model, we keep the same value of  $T_{ch}$  for LHC case. Below  $T_{ch}$  a composition of the hadron gas is changed only due to resonance decays into expanding fluid. We include 359 hadron states made of u, d, s quarks with masses up to 2.6 GeV. The EoS in this non chemically equilibrated system depends on particle number densities  $n_i$  of all the 359 particle species  $i$ :  $p = p(\epsilon, \{n_i\})$ .

In the case of hHKM we provide a switch to UrQMD at the hypersurface  $\tau(r) = \tau_{sw} = const$  where  $\tau_{sw}$  is defined from the condition: temperature  $T(\tau = \tau_{sw}, r_T = 0) = 165$  MeV. Then the non-equilibrium distribution functions in hadron resonance gas calculated in HKM are the input distribution functions for UrQMD at  $\tau = \tau_{sw}$ .

### 3. Results and conclusions

In Fig. 1 we show the pion emission functions at mid-rapidity in hydrokinetic model, integrated over transverse momenta of particle. The emission functions are shown for for the top RHIC and LHC  $\sqrt{s} = 2.76$  TeV energies as a function of transverse radius  $r$  and proper time  $\tau$ . Particle emission is azimuthally symmetric in coordinate space, and the plot is integrated over the angle of particle momentum. As one can see the duration of particle emission in the central part of the fireball is half of its lifetime. At a periphery a surface emission is significant, it lasts a total lifetime of the fireballs. The hypersurface of the surface emission approaches the light cone when collision energy grows. The latter fact is correlated with a non trivial result on the energy behavior of the  $R_{out}/R_{side}$  ratio. It slowly drops when energy grows and apparently is saturated at fairly high energies at the value close to unity (Fig.1). In rough approximation  $R_{out}/R_{side} \approx 1 + const/\epsilon_0$  [9]. This effect is caused by a strengthening of positive correlations between space and time positions of pions emitted at the radial periphery of the system as one can see in Fig.1, top (see theoretical details in Ref. [9]). This central prediction of [9] as for the energy dependence of the femtoscopy scales with energy growth is completely conformed by the ALICE results, see Fig. 1.

The transverse femtoscopy scales, predicted for LHC are quite close (but slightly less) to the corresponding experimental data. As for the longitudinal HBT radius,  $R_{long}$ , it is underestimated in HKM by around 20%. As the result, HKM gives smaller interferometry volume than is observed at LHC, see Fig. 1, bottom. The reason could be that HKM describes a gradual decay of the system which evolves hydrodynamically until fairly large times. It is known [15] that at the isentropic and chemically frozen hydrodynamic evolution the interferometry volume increases quite moderate with initial energy density growth in collisions of the same/similar nucleus. The RHIC results support such a theoretical view (see experimental and HKM results for SPS and RHIC, Fig. 1, bottom), while the ALICE Collaboration observes a significant increase of the interferometry volume at LHC. An essential growth of the interferometry volume in Pb+Pb collisions at the LHC energy is conditioned by a dominance of very non-equilibrium and non-hydrodynamic stage of the matter evolution at LHC. We demonstrate it within the hHKM that contains such a stage, see Fig. 1. Then

the results obtained in [15] for isentropic and chemically frozen evolution are violated. Most significant effect is observed for the LHC energy. It is worthy noting that no one linear fit cannot be done to describe simultaneously  $V_{int}(dN/d\eta)$ -dependence for both heavy (Pb, Au) ion and proton collisions, see for the latter the data discovered by the ALICE Collaboration [23] (Fig. 1, bottom). This experimental observation supports the theoretical result that the interferometry volume depends not only on multiplicity but also on initial size of colliding systems [15]. So, qualitatively, we see no new “LHC HBT puzzle” in the newest HBT results obtained at LHC in Pb+Pb and p+p collisions.

We conclude that the behavior of femtoscopy scales at LHC energy can be understood with the same hydrokinetic basis as was used for RHIC [9, 7] supplemented by hadronic cascade model at the latest stage of the evolution: HKM  $\rightarrow$  hHKM. In this approach the following factors are important: a presence of prethermal transverse flow, a crossover transition between quark-gluon and hadron matters, non-hydrodynamic behavior of the hadron gas at the latest stage, and correct matching between hydrodynamic and non-hydrodynamic stages. Then the particle spectra together with the femtoscopy data at RHIC and LHC energies can be well described. The application of hHKM to the simultaneous description of the extended set of experimental data - particle spectra, elliptic flow coefficients and interferometry data, measured in central and non-central heavy ion collisions with unified model parameters is the subject of the next publication.

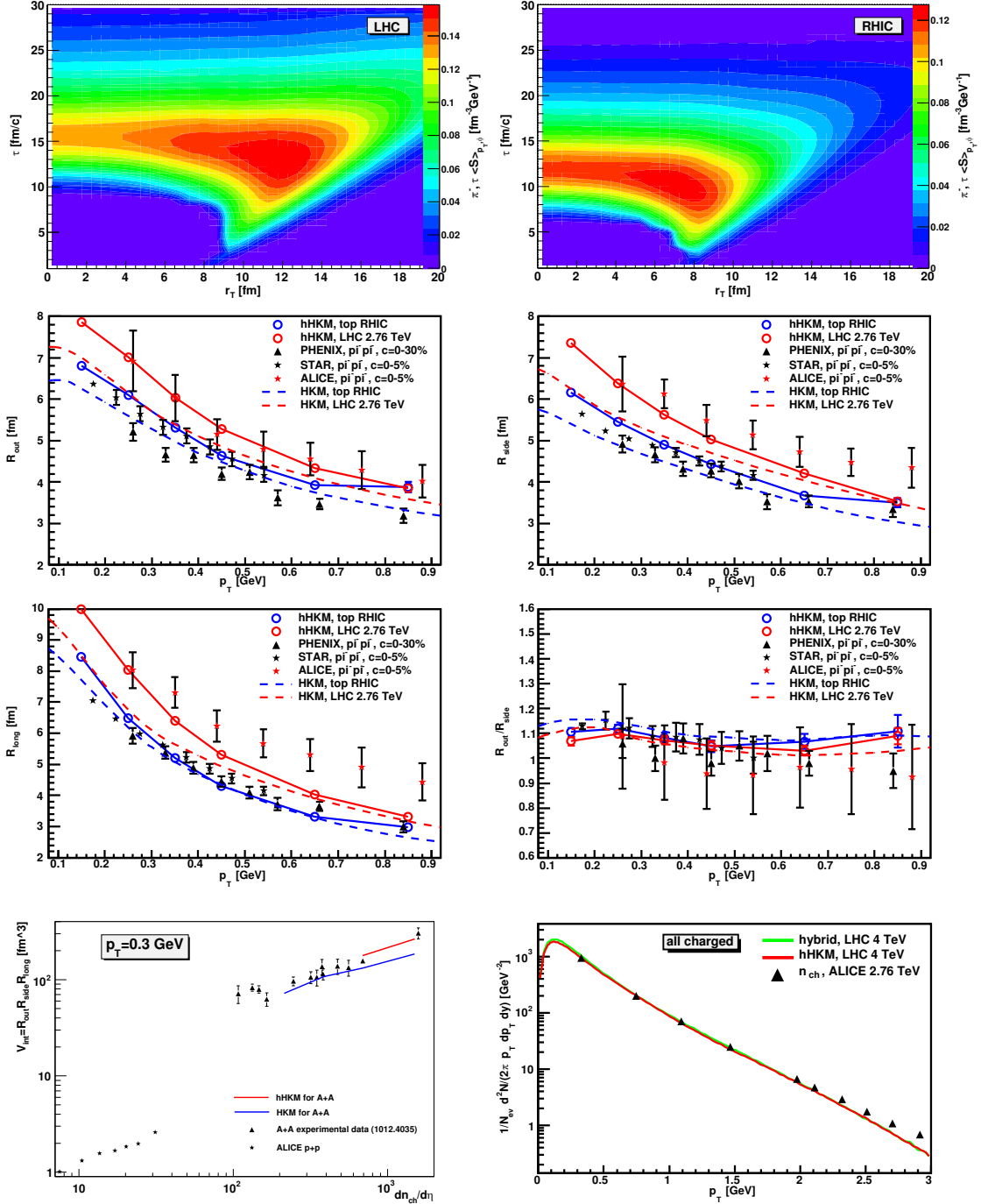
#### 4. Acknowledgments

The research was carried out within the scope of the EUREA: European Ultra Relativistic Energies Agreement (European Research Group: "Heavy ions at ultrarelativistic energies"), and is supported by the National Academy of Sciences of Ukraine (Agreement F3-2012) and by the State fund for fundamental researches of Ukraine (Agreement F33/42-2012).

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**Figure 1:** The  $p_T$ -integrated emission functions of negative pions for the top RHIC and LHC energies in hHKM(top); the interferometry radii and  $R_{out}/R_{side}$  ratio (middle); the transverse momentum spectra of all charged pions at the LHC energy 2.76 TeV in hHKM model, and multiplicity dependence of the pion interferometry volume for central heavy ion collisions at AGS, SPS, RHIC and LHC energies in comparison with the results in p+p collisions (bottom). The solid lines connect the points obtained within HKM and hHKM. The experimental data for A+A collisions are taken from [8, 16, 17, 18, 19, 20, 21, 22]. For p+p collisions at LHC the points for  $p_T = 0.3$  GeV are interpolated from the results of Ref. [23].