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# Hidden puzzle of the correlation femtoscopy at the top RHIC and LHC energies and its possible solution

Yu. M. Sinyukov([1])([2]) and V. M. Shapoval([1])

([1]) *Department of High-Density Energy Physics, Bogolyubov Institute for Theoretical Physics 14b Metrolohichna Street, 03143, Kyiv, Ukraine*
([2]) *Faculty of Physics, Warsaw University of Technology - 75 Koszykowa Street, 00-662, Warsaw, Poland*

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**Summary.** — Two paradoxical results (puzzles) related to correlation femtoscopy of high-energy nucleus-nucleus collisions at the RHIC and the LHC accelerators are considered within the integrated hydrokinetic model (iHKM), describing all the stages of the produced system's evolution —from the initial non-equilibrium partonic state formation to the final expansion of interacting hadron-resonance gas. Possible solutions of the analyzed puzzles are proposed.

## 1. – Introduction

Analysis of relativistic heavy ion collision experimental data sometimes brings the results looking quite surprising in view of our initial theoretical considerations. The problem of interpretation of such results in particular complex cases is called a puzzle — a question that constitutes certain intellectual challenge for the researchers. One can mention, *e.g.* the well-known RHIC HBT puzzle [1] or the direct photon puzzle [2, 3]. Incidentally, both those puzzles were addressed in our previous studies within the integrated hydrokinetic model (iHKM) [4,5], see, *e.g.*, refs. [6-8], and potential solutions to the problems were proposed.

In the current work we report on the results of our recent study [9], dealing with the two "hidden" puzzles arising in the correlation femtoscopy studies of relativistic A+A collisions, when one reviews and generalizes the large set of results obtained for different experiments conducted at different collision energies. Within iHKM we successfully described the measured data on bulk observables, including meson and baryon production and femtoscopy scales, for a wide class of experiments, from the top RHIC energy Au+Au collisions to the LHC Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ GeV, see the review [10]. The model describes the full evolution process for the strongly interacting matter created in a high-energy collision, including the initial non-equilibrium state formation, its gradual thermalization, viscous hydrodynamics expansion of continuous medium, particlization, and, finally, the "afterburner" hadron cascade stage.

The first of the two mentioned puzzles is a nearly equal time of hydrodynamic evolution in all the considered collision experiments, despite the fact that the initial system's energy density is much higher in case of higher collision energy. The second puzzle is that when one tries to estimate the lifetime of the created system, defining the time of maximal emission for particles of different species, as we did in [11, 12] for pions and kaons, this time (at least for pions) appears to be close to the time of hydrodynamic expansion, despite the fact that the formation of various observables is clearly affected by the post-hydrodynamic evolution of hadronic matter, as our analysis shows [10].

## 2. – Results and discussion

In our articles [11-13] we proposed a method allowing to estimate the time of maximal emission for pions and kaons performing a simultaneous fitting of their $p_T$ spectra and longitudinal femtoscopy radii $R_{long}$ dependencies on $m_T$ with simple analytic formulas, containing only three free parameters — effective temperature $T$, the time of maximal emission $\tau$, and $\alpha$ characterizing the strength of transverse collective flow. The method was applied to the cases of $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC, as well as to the 2.76$A$ TeV and 5.02$A$ TeV Pb+Pb collisions at LHC, based on the iHKM simulation results for spectra and radii.

A puzzling observation in the obtained results was that the maximal emission times for pions in all the considered cases were close to the systems' particlization times and were close to each other (about $8 - 10$ fm/$c$). This looked surprising, since the maximal initial energy densities used in the model, *e.g.*, for the 5.02$A$ TeV and 200$A$ GeV collisions differed by the factor about 5, and particlization took place at the same energy density (*e.g.*, $\epsilon_p = 0.5$ GeV/fm$^3$ for the Laine-Schroeder equation of state in hydrodynamics regime). Another strange thing about these time values was that they did not reflect the presence of intensive post-hydrodynamic matter evolution, definitely affecting other observables, like particle number ratios or $K^*(892)$ production [10].

In figs. 1,2 we demonstrate the dependencies of the energy density in the center of

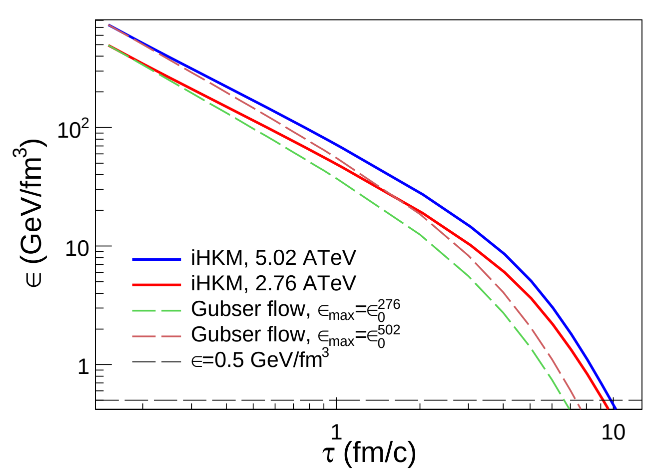


Fig. 1. – Energy density in the center of the system dependency on time. The iHKM curves for the LHC 2.76$A$ TeV and 5.02$A$ TeV Pb+Pb collisions are compared to the Gubser solutions with the same initial energy densities.

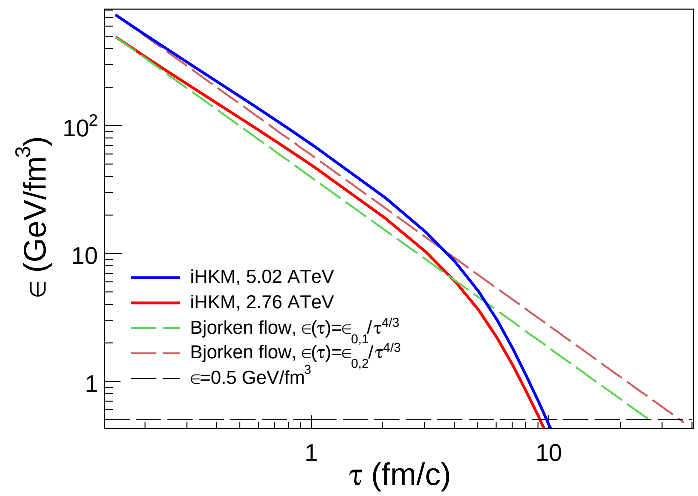


Fig. 2. – The same as in fig. 1, but iHKM results are compared to the Bjorken solutions.

the system for iHKM simulations of $2.76A$ TeV and $5.02A$ TeV LHC collisions together with the analytic solutions of relativistic hydrodynamics equations — one-dimensional Bjorken solution, $\epsilon(\tau) = \epsilon_0\tau^{-4/3}$, and three-dimensional Gubser solution [14]:

$$\epsilon(r_T, \tau) = \frac{\epsilon_0}{\tau^{4/3}} \frac{(2q)^{8/3}}{[1 + 2q^2(\tau^2 + r_T^2) + q^4(\tau^2 - r_T^2)^2]^{4/3}}. \tag{1}$$

The initial energy densities at $\tau = 0$ are taken the same as in iHKM and the parameter $q$ value in (1), $q = 0.15$ fm$^{-1}$, is defined from the Gubser fit to the iHKM distribution $\epsilon(r_T, 0)$.

As one can see from the plots, the fast system breakup and close particlization times for different initial energy density values do not take place in case of the 1D Bjorken expansion — in this case the two particlization times are quite large (26 fm/$c$ and 36 fm/$c$) and differ noticeably for the two collision energies. By contrast, the 3D Gubser solutions show a behavior rather similar to the iHKM curves, such that the energy density after $\tau = 3 - 4$ fm/$c$ drops very fast to the $\epsilon_p$ value for both collision energies. Thus, one can suppose that it is the intensive 3D expansion of the created fireball that leads to its fast decay at proper times about $8 - 10$ fm/$c$ in high-energy A+A collisions. This way one can presumably solve the first of the two mentioned femtoscopy puzzles.

Trying to unravel the second puzzle, *i.e.* the closeness of pion maximal emission times to particlization ones, one could recall that in heavy-ion collisions particles with different momenta $p$ are emitted from the different parts of the hadronization hypersurface — low-momentum particles come mainly from the parts near the center of the system, while those with higher momentum originate mainly from the periphery. And the particlization process begins from the periphery and gradually embraces the parts closer and closer to the system's center. That is why trying to estimate the particle emission duration based on the particle spectra and femtoscopy radii including high momenta region, one will obtain not the "upper-limit" value that could be associated with the overall system's lifetime (including the "afterburner" hadronic stage), but some mean, intermediate value, closer to the system's full hadronization time.

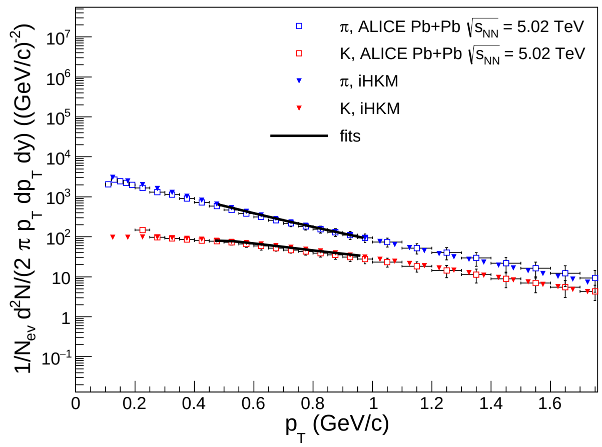


Fig. 3. – The iHKM pion and kaon combined $p_T$ spectra fitting for the most central LHC Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The ALICE Collaboration experimental results [15] are shown for comparison.

In fig. 3 we show the pion and kaon simultaneous $p_T$ spectra fitting performed in [12] for the intermediate $p_T$ range $0.45 < p_T < 1.0$ GeV/$c$. Correspondingly, that fit gave us the effective temperature $T = 138$ MeV, and the subsequent radii fitting in the full $k_T$ range (see fig. 4) gave the pion maximal emission time $\tau_\pi = 8.97$ fm/$c$. However, if one fits the same spectra in a low-momentum range $0.25 < p_T < 0.55$ GeV/$c$, much lower temperature value, $T = 106$ MeV, will be extracted, and the radii fit for $k_T < 0.6$ GeV/$c$ will give higher $\tau_\pi = 13.65$ fm/$c$, which is in accordance with the other our estimates for the duration of the intensive hadronic re-scatterings at the post-hydrodynamic stage of the collision, *e.g.*, those based on the $K^*(892)$ emission picture [16].

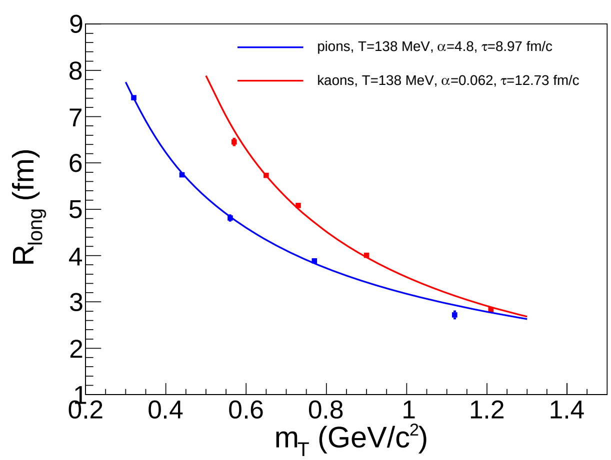


Fig. 4. – The iHKM pion and kaon radii $R_{long}(m_T)$ dependencies fitting for the most central LHC Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

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