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SPACE-TIME PICTURE AND OBSERVABLES IN HEAVY ION COLLISIONS AT THE LARGE HADRON COLLIDER ENERGIES[1]

In the present work, we combine and systemize the results of our recent research activity aiming to reveal the spatiotemporal structure of those extremely hot, dense, and rapidly expanding systems, which form in ultrarelativistic heavy ion collisions, as well as to reproduce in computer simulations the experimentally measured bulk observables. The latter include hadronic yields, particle number ratios, transverse momentum spectra, v_n coefficients, and the femtoscopy scales, calculated for different collision energies within the integrated hydrokinetic model. We investigate how our simulation results depend on the model tuning, in particular, the utilized equation of state for quark-gluon matter and discuss the effect of the post-hydrodynamic stage of the system's evolution on the observables formation.

Keywords: ultrarelativistic heavy ion collisions, particle yields, transverse momentum spectra, femtoscopy scales.

1. Introduction

The studies of relativistic heavy ion collisions, particularly, the analysis of the behavior of the soft physics observables in the corresponding experiments (e.g., the ALICE Collaboration activity at the Large Hadron Collider (LHC) in Geneva or the STAR and the PHENIX Collaboration research at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven), combined with a comparison of the measured data to the theoretical description obtained within elaborate realistic models, simulating the complicated collision processes, open the way to revealing the properties of new exotic forms of strongly interacting matter (such as quark-gluon plasma), created in course of high-energy A + A collisions. For instance, the powerful correlation femtoscopy method provides a unique possibility to restore the intricate space-time structure of the created systems, and the final state interaction technique helps to investigate the details of fundamental interactions between produced hadrons, including strange and charmed ones [1, 2]. The analysis of bulk observables, such as particle yields and their ratios, or particle momentum spectra, allows making certain conclusions about the dynamics of the system's evolution at its different stages.

The integrated hydrokinetic model (iHKM) [3, 4] simulates the full process of evolution of strongly interacting matter, created in a high-energy nuclear collision, describing each stage of this process within a suitable approach. A Monte Carlo Glauber GLISSANDO model [5] is utilized to construct the initial transverse energy density profile – together with a Color-Glass-Condensate-like anisotropic momentum distribution, it forms the initial conditions (IC) for the subsequent simulation. The IC correspond to the initial proper time, which in iHKM is assumed to be about 0.1 fm/*c* (see [3, 4] for details). The initial energy density profile can be scaled by changing the model parameter ε_0, which defines the maximal initial energy density in the center of the system, thus allowing one to adjust the model to different collision energies.

Starting from the defined IC, the model simulates the prethermal equilibration dynamics of the system using an energy-momentum transport approach in a relaxation time approximation. As a result of prethermal dynamics, at the time about 1 fm/*c* one obtains a nearly thermalized (close to local equilibrium) system, whose expansion is described in the relativistic viscous hydrodynamics approximation within the Israel - Stewart formalism. Such a collective movement of liquid-like quark-gluon matter continues until the system finally loses equilibrium and breaks up into particles (in iHKM it is supposed to happen at some particlization temperature T_p, depending on the equation of state utilized at the hydrodynamics stage). The final stage of matter evolution is described in our model with the help of the UrQMD hadron cascade [6]. During this stage, hadrons forming our system intensively collide with each other and the resonance decays take place.

In the present work, we consider the results obtained in iHKM for a set of experiments with varying collision energy and type of colliding nuclei

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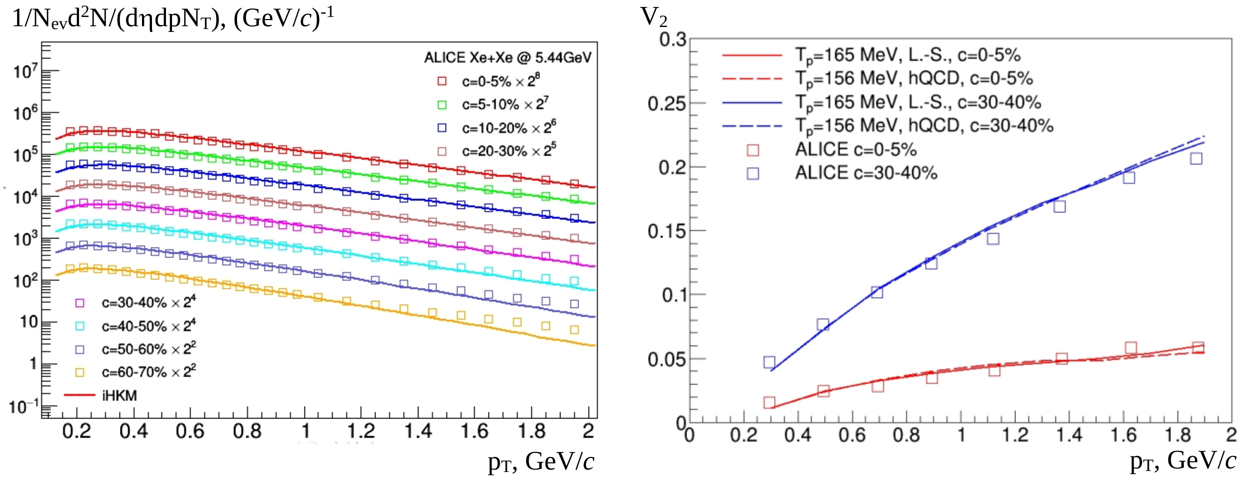
[4, 7 - 9], which give (as one can see below) a quite successful data description for different particle spectra and correlations and in such a way form a reliable basis for understanding the peculiarities of particle emission from the systems formed in these collisions, as well as the character of their expansion. Our consideration covers a wide class of the relativistic nucleus-nucleus collision experiments at the LHC, namely, Pb + Pb collisions at the energies 2.76 and 5.02 ATeV, as well as the Xe + Xe collisions at 5.44 ATeV. The case of the top RHIC energy Au + Au collisions (at 200 AGeV) is also addressed.

2. Results and discussion

Proper model calibration for each collision type can be achieved, in fact, by adjusting only two parameters – the initial energy density in the center of the system and the weight of the binary collision model contribution to the energy density profile in GLISSANDO. These parameters are defined from the best fit of the model charged particle multiplicity dependency on collision centrality and pion $p_{\rm T}$ spectrum slope for the most central events to the experimental data.

Reviewing the obtained results, one can conclude that the iHKM successfully describes the experimental data on all the soft-physics observables, typically addressed in the experimental analysis, including the femtoscopy radii for all the considered collision energies (Figs. 1 - 5).

The iHKM is able to describe transverse momentum spectra for different centrality classes not only for the case of mixing all charged particle data, as it is shown in Fig. 1, but for individual hadron species as well (see papers [4, 7 - 9] for details). The calculated pion, kaon, proton, antiproton spectra are in agreement with the measured data with good accuracy in $p_{\rm T}$ region, corresponding to the soft physics regime, from the lowest measurable values to about 2 GeV/*c*. Thus, in iHKM one does not need to include additional mechanisms for soft pion radiation, such as the Bose - Einstein condensation to reproduce the soft part of the pion spectrum.



a *b*

Fig. 1. *a* – All charged particles transverse momentum spectra for 5.44 ATeV Xe + Xe collisions at the LHC calculated in iHKM (lines) compared to the corresponding experimental data from the ALICE Collaboration [10] (squares). Different colors correspond to different collision centralities. *b* – Elliptic flow for all charged particles dependency on the transverse momentum in iHKM (at the two different equations of state for quark-gluon matter and corresponding particlization temperatures) compared to the ALICE Collaboration experimental data [11] for the LHC Pb + Pb collisions at 5.02 ATeV. The results for the two centrality classes are shown. (See color Figure on the journal website.)

From Fig. 2 one can see that apart from the commonly presented results on the mostly produced pions, kaons, and protons, the iHKM can also describe the hyperon momentum spectra (here we show Lambda and Xi spectra, but data on Omega production can be reproduced as well [8]).

In Figs. 1 and 3 we demonstrate the iHKM results on flow harmonics v_2, v_3 and v_4 for all charged particles dependencies on transverse momentum, calculated using the standard event plane method.

The model reproduces well the experimental data on elliptic flow for both central and semi-central events. As for the higher flow harmonics, the agreement between the model and the experiment is better for low $p_{\rm T}$ and central events.

It is worth noting, that v_n coefficients and the other bulk observables can be described in the model with practically equivalent accuracy at the two different equations of state for quark-gluon matter associated with the corresponding particlization temperatures – the Laine - Schroeder EoS (with T_p = 165 MeV) [13] and the HotQCD Collaboration EoS (with T_p = 156 MeV) [14]. The particlization temperature value for each utilized EoS is defined independently, typically based on the results for particle number ratios within thermal models featuring the corresponding EoS (see, e.g. [15, 16]).

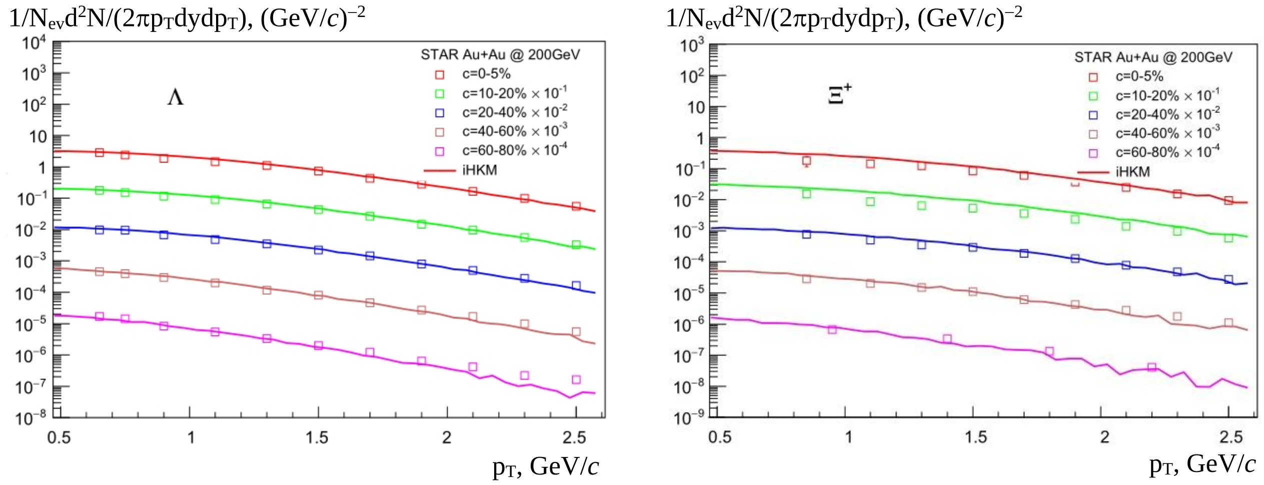


Fig. 2. The iHKM results on Lambda and Xi^+ transverse momentum spectra for the top RHIC energy Au + Au collisions of different centrality compared to the experimental results from the STAR Collaboration [12]. (See color Figure on the journal website.)

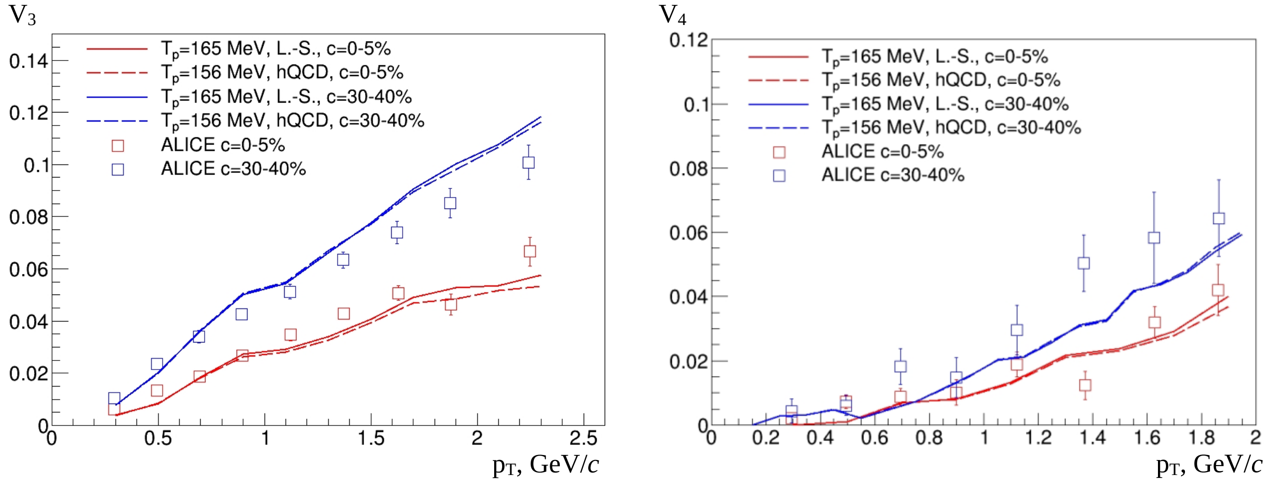


Fig. 3. The v_3 and v_4 flow harmonics for all charged particles dependency on the transverse momentum in iHKM (at the two different equations of state for quark-gluon matter and corresponding particlization temperatures) compared to the ALICE Collaboration experimental data [11] for the LHC Pb + Pb collisions at 5.02 ATeV. The results for the two centrality classes are shown. (See color Figure on the journal website.)

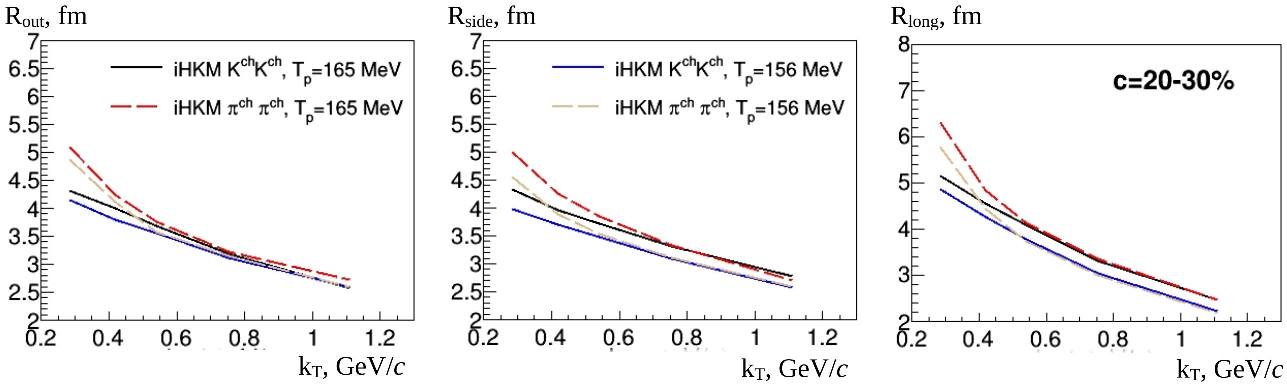
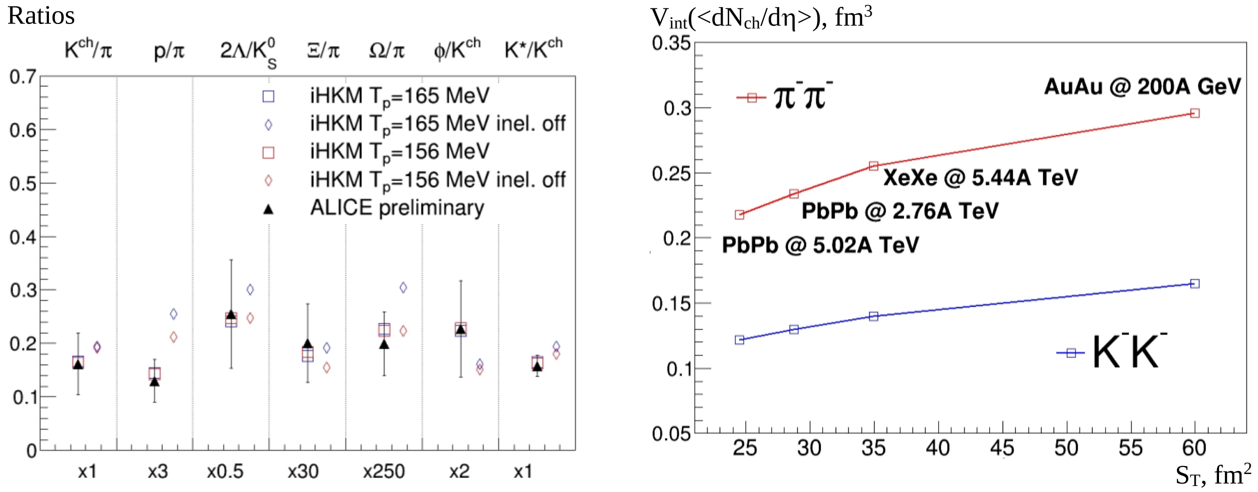


Fig. 4. The predictions for pion and kaon femtoscopy radii calculated for the LHC Pb + Pb collisions at 5.02 ATeV in iHKM at the two particlization temperatures and respective equations of state for the quark-gluon matter. (See color Figure on the journal website.)

The same applies to the model predictions, such as those presented in Fig. 4 for the pion and kaon femtoscopy radii dependencies on the pair mean transverse momentum – the curves corresponding to the two utilized equations of state practically coincide. From the plot, one can also see that iHKM predicts k_T scaling for pion and kaon radii at relatively high momenta.

The iHKM results on various particle number ratios, shown in Fig. 5, also appear to be similar for the Laine - Schroeder and the HotQCD Collaboration equations of state. Here, along with the points corresponding to full model calculation, which are again quite close to the experimental ones, one can find the ratios calculated in iHKM with inelastic processes switched off. These “reduced” ratios differ from the “full” ones and do not always coincide for the two different equations of state. Such a result likely implies that the particle spectra freeze-out, taking place in the course of the system’s expansion, is rather continuous (lasting different times for different particle species and including the afterburner stage of the collision), than sharp (happening suddenly for all particle species at the single particlization hypersurface).



a *b*

Fig. 5. *a* – Different particle number ratios calculated in iHKM at the two particlization temperatures and the corresponding equations of state for quark-gluon phase compared to the ALICE Collaboration experimental data [17, 18]. The results for the two simulation regimes are presented: the full model and the mode with inelastic processes switched off at the afterburner stage. *b* – The pion and kaon interferometry volume dependency in iHKM on the area of the initial transverse overlapping region between the colliding nuclei for different collision types at nearly the same particle multiplicity. (See color Figure on the journal website.)

The “multiplicity scaling issue” is also addressed in our research. We carried out some investigation in order to check if the scaling hypothesis, supposing that the femtoscopy radii should depend only on the mean charged particle multiplicity so that this dependency should be universal for different experimental setups. In our analysis, we selected events with a similar multiplicity of produced particles for each considered collision experiment and compared respective pion and kaon interferometry radii and volume. We also associated each collision type with the corresponding transverse area of the initial energy density profile in iHKM, which should reflect the initial transverse size of the overlapping nuclei. As one can see from Fig. 5, *a*, the dependency of the interferometry volume on the particle multiplicity is not uniform for different systems and varies with the geometrical scales of the colliding nuclei (the femtoscopy scales are larger for the systems with the larger initial transverse area). The same applies to the individual interferometry radii (especially to the *out* radius).

3. Conclusions

The iHKM is applied to the theoretical description of the most commonly analyzed soft-physics observables in four modern ultrarelativistic heavy-ion collision experiments at LHC and RHIC. The model provides a simultaneous successful description of particle yields and their ratios, transverse momentum spectra, flow harmonics, and femtoscopy scales with a single tuning of the model parameters for each collision type.

The results of simulations for the two different equations of state for the hydrodynamics regime can be obtained very close to each other, provided that the initial maximal energy density parameter is correspondingly returned when one switches to another equation of state. The comparison of particle number ratios and other observables at the two utilized equations of state suggests that the particle spectra formation has a continuous character, in contrast with the commonly accepted hypothesis of sudden freeze-out taking place at a single hypersurface.

The multiplicity scaling hypothesis seems to need revision and clarification, since the interferometry scales clearly depend not only on multiplicity but also on the geometrical sizes of the colliding nuclei, as it follows from our study.

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REFERENCES

1. S.V. Akkelin, Yu.M. Sinyukov. The HBT-interferometry of expanding sources. Phys. Lett. B 356 (1995) 525.
2. R. Lednicky, V.L. Lyuboshitz. Final State Interaction Effect on Pairing Correlations Between Particles with Small Relative Momenta. Sov. J. Nucl. Phys. 35 (1982) 770.
3. V.Yu. Naboka et al. Initialization of hydrodynamics in relativistic heavy ion collisions with an energy-momentum transport model. Phys. Rev. C 91 (2015) 014906.
4. V.Yu. Naboka, Iu.A. Karpenko, Yu.M. Sinyukov. Thermalization, evolution, and observables at energies available at the CERN Large Hadron Collider in an integrated hydrokinetic model of A + A collisions. Phys. Rev. C 93 (2016) 024902.
5. W. Broniowski, M. Rybczyński, P. Bożek. GLISSANDO: GLauber Initial-State Simulation and mOre… Comput. Phys. Commun. 180 (2009) 69.
6. S.A. Bass et al. Microscopic models for ultrarelativistic heavy ion collisions. Prog. Part. Nucl. Phys. 41 (1998) 255.
7. V.M. Shapoval, Yu.M. Sinyukov. Bulk observables in Pb + Pb collisions at $\sqrt{S_{NN}}$ = 5.02 TeV at the CERN Large Hadron Collider within the integrated hydrokinetic model. Phys. Rev. C 100 (2019) 044905.
8. M.D. Adzhymambetov, V.M. Shapoval, Yu.M. Sinyukov. Description of bulk observables in Au + Au collisions at top RHIC energy in the integrated hydrokinetic model. Nucl. Phys. A 987 (2019) 321.
9. Yu. Sinyukov, M. Adzhymambetov, V. Shapoval. Particle Production in XeXe Collisions at the LHC within the Integrated Hydrokinetic Model. Particles 3 (2020) 114.
10. ALICE Collaboration. Transverse momentum spectra and nuclear modification factors of charged particles in Xe-Xe collisions at $\sqrt{S_{NN}}$ = 5.44 TeV. Phys. Lett. B 788 (2019) 166.
11. J. Adam et al. (The ALICE Collaboration). Anisotropic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{S_{NN}}$ = 5.02 TeV. Phys. Rev. Lett. 116 (2016) 132302.
12. J. Adams et al. (STAR Collaboration). Scaling Properties of Hyperon Production in Au + Au Collisions at $\sqrt{S_{NN}}$ = 200 GeV. Phys. Rev. Lett. 98 (2007) 062301.
13. M. Laine, Y. Schröder. Quark mass thresholds in QCD thermodynamics. Phys. Rev. D 73 (2006) 085009.
14. A. Bazavov et al. (HotQCD Collaboration). The equation of state in (2+1)-flavor QCD. Phys. Rev. D 90 (2014) 094503.
15. A. Andronic, P. Braun-Munzinger, J. Stachel. Thermal hadron production in relativistic nuclear collisions. Acta Phys. Polon. B 40 (2009) 1005.
16. J. Stachel et al. Confronting LHC data with the statistical hadronization model. J. Phys.: Conf. Ser. 509 (2014) 012019.
17. F. Bellini (for the ALICE Collaboration). Testing the system size dependence of hydrodynamical expansion and thermal particle production with π, K, p, and ϕ in Xe-Xe and Pb-Pb collisions with ALICE. Nucl. Phys. A 982 (2019) 427.
18. D.S.D. Albuquerque (for the ALICE Collaboration). Hadronic resonances, strange and multi-strange particle production in Xe-Xe and Pb-Pb collisions with ALICE at the LHC. Nucl. Phys. A 982 (2019) 823.

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ПРОСТОРОВО-ЧАСОВА КАРТИНА ТА СПОСТЕРЕЖУВАНІ У ЗІТКНЕННЯХ ВАЖКИХ ІОНІВ НА ВЕЛИКОМУ АДРОННОМУ КОЛАЙДЕРІ

У цій роботі об’єднано і систематизовано результати наших недавніх досліджень, направлених на з’ясування особливостей просторово-часової структури тих надзвичайно гарячих, густих і швидко розширювальних систем, що утворюються в ульрарелятивістських зіткненнях важких іонів, а також на теоретичне відтворення комп’ютерними симуляціями відповідних вимірюваних в експерименті спостережуваних з області м’якої фізики. Ці спостережувані включають виходи адронів, відношення чисел частинок, поперечно-імпульсні спектри, v_n коефіцієнти та фемтоскопічні масштаби, обчислені для різних енергій зіткнення в рамках інтегрованої гідрокінетичної моделі. Досліджено залежність результатів моделювання від налаштувань моделі, зокрема, від застосованого рівняння стану для кварк-глюонної матерії, та обговорюється вплив постгідродинамічної стадії еволюції системи на формування спостережуваних.

Ключові слова: ультрарелятивістські зіткнення важких іонів, виходи частинок, спектри поперечного імпульсу, фемтоскопічні масштаби.

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