Probing Hydrodynamics at $\sqrt{s_{NN}}$ =7.7 GeV: Model Comparisons of the Bulk Properties of Au+Au Collisions

Исследование гидродинамически при $\sqrt{s_{NN}}$ =7,7 ГэВ: модельное сравнение свойсив среды в столкновениях Au+Au

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We study hydrodynamic effects of bulk properties of the matter produced in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV measuring production of the following particles $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ with AMPT, EPOS4, SMASH and PYTHIA8 Monte Carlo models. Mid-rapidity ($|y| < 0.1$) analysis of the transverse momentum spectra, antiparticle-to-particle and mixed-particles ratios, in dependence of various collision centralities are presented and compared with the 2010 data collected by STAR experiment in the Beam Energy Scan (BES) program at the Relativistic Heavy Ion Collider (RHIC).

Мы изучаем гидродинамические эффекты свойств вещества, образованного в столкновениях Au+Au при $\sqrt{s_{NN}}$ = 7,7 ГэВ, измеряя рождение таких частиц как $\pi^{\pm}$, $K^{\pm}$, p и $\bar{p}$ с помощью Монте-Карло моделей AMPT, EPOS4, SMASH и PYTHIA8. Представлен анализ в центральной области быстрот ($|y| < 0,1$) спектров по поперечному импульсу, отношений выходов античастиц/частиц и смешанными частицами в зависимости от различных центральностей столкновения и дано сравнение с данными, собранными в 2010 году, в эксперименте STAR в рамках программы энергетического сканирования (BES) на Релятивистском коллайдере тяжелых ионов (RHIC).

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Introduction

The primary goal of high energy heavy ion collision experiments, such as those conducted at Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), is to explore the phase diagram of Quantum Chromodynamics (QCD). It is usually plotted as a function of Temperature (T)

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and baryon chemical potential (μ_B). Assuming a thermalized system is created in heavy ion collisions, a proper scan through these quantities can be performed by changing the collision energy. By mapping the low net baryon density region (at $\mu_B < 10$ MeV and $T \sim 150$ MeV) of the QCD phase diagram, for $\sqrt{s_{NN}} > 2600$ GeV, the LHC experiment have observed that the created medium behaves like a nearly perfect fluid with very low shear viscosity to entropy density ratio η/s [1] which confirms previous observations from RHIC [2]. Strangeness enhancement, hadronization and freeze-out characteristics have been observed as well [3]. Studies conducted at RHIC, for a wide range of collision energies $\sqrt{s_{NN}} = 200$ to 7.7 GeV [4, 5], corresponding to higher μ_B, show a smooth crossover in the transition from hadronic matter to deconfined QGP. Future programs like the Nuclotron-based Ion Collider fAcility (NICA) will study the high baryon density region ($\mu_B \sim 800$ MeV), through $\sqrt{s_{NN}} = 4 - 11$ GeV heavy-ion collisions [6].

We present the study of the transverse momentum (p_T) spectra, antiparticle-to-particle and meson-to-baryon ratios, in dependence of collision centralities, for $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ hadrons in the mid-rapidity region ($|y| < 0.1$) in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV with different Monte Carlo (MC) models: AMPT String Melting (AMPT) [7], EPOS4 [8,9], PYTHIA8.315 [10] and SMASH [11]. AMPT begins by implementing HIJING model to generate partons via hard scattering and strings from soft processes, which then undergo a QGP phase via Zhang's Parton Cascade model, followed by hadronization with a quark coalescence model. Generated hadrons further interact with the Extended ART model. EPOS4 employs Parton-Based Gribov-Regge theory and core/corona procedure for the initial state, followed by a (3+1)D viscous hydrodynamical evolution of the QPG; hadronization occurs on the Cooper-Fry hypersurface, converting the fluid into final particles. These particles undergo final-state interactions within the UrQMD afterburner. PYTHIA8.3 uses the Angantyr model for the generation of heavy-ion collisions. It primarily models the initial parton showers through perturbative QCD matrix elements and hadronization via the Lund string fragmentation; it lacks a true QGP phase or collective hadronic freeze-out stage, making it a baseline for non-QGP heavy ion collisions. SMASH does no consider a deconfined QGP phase either, hadronization is handled within PYTHIA8 approach and, hadronic re-scattering phase is explicitly performed using a Boltzmann-type hadronic transport until interactions cease. The distributions predicted by the models were compared with the data collected in 2010 by STAR experiment as part of the BES program at RHIC [4]. The $\pi^{\pm}$, $K^{\pm}$ were selected in the pT range of $0.2 - 2.0$ GeV and p and $\bar{p}$ for $0.4 - 2.0$ GeV. In addition, a cut in the vertex radius ($\sqrt{V_x^2 + V_y^2} < 2$ cm) was considered for all analyzed particles.

Transverse Momentum Spectra

Figure 1 presents mid-rapidity ($|y| < 0.1$) transverse momentum spectra for $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV obtained with

AMPT, EPOS4, PYTHIA8 and SMASH models and STAR experimental data. The analysis is conducted in dependence of collision centrality classes for 0-5% and 5-10% (central), 30-40% (mid) and 70-80% (peripheral). The p_T distributions were normalized by the averaged number of participating nucleons ($\langle N_{part} \rangle$) in each centrality class. We observe that the distributions follow the expected mass ordering $\pi < K < p$. From mid to central collisions, PYTHIA8 fairly describes the $\pi^{\pm}$, $K^{\pm}$ and p distributions. However, it presents a higher contribution of $\bar{p}$ for $p_T < 1.2$ GeV. EPOS4 and SMASH show similar distributions for $\pi^{\pm}$ and p, with more discrepancies in the low transverse momentum $p_T < 0.6$ GeV range. Both predict the transverse momentum distribution of p for $0.6 < p_T < 1.4$. In our analysis, AMPT fails to predict the production of $K^{\pm}$ and $\bar{p}$, showing a suppression of the rest of particles. Further tuning it will be required.

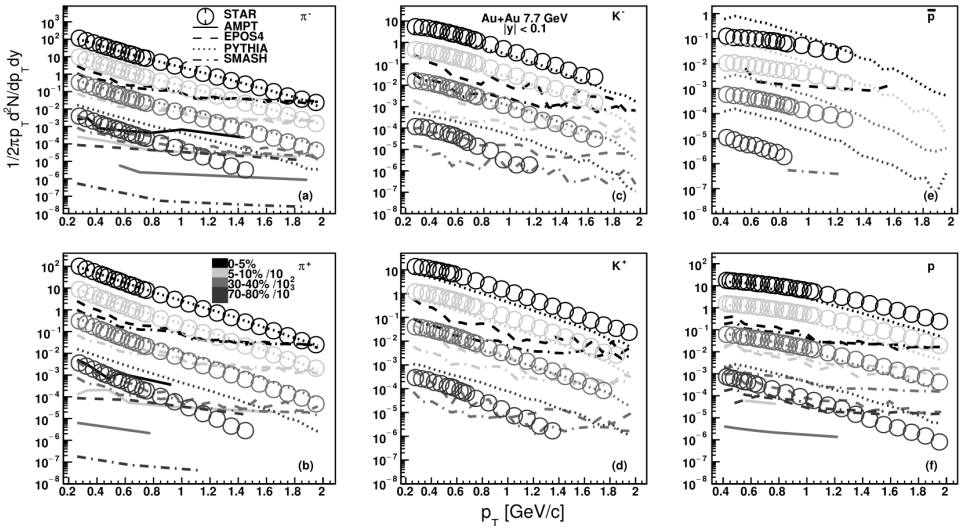


Fig. 1. Transverse momentum (p_T) spectra for (a) π^-, (b) π^+, (c) K^-, (d) K^+, (e) $\bar{p}$ and (f) p in the mid-rapidity range ($|y| < 0.1$) in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV for 0-5%, 5-10%, 30-40% and 70-80% centrality classes for AMPT, EPOS4, PYTHIA8 and SMASH models in comparison with STAR experimental data [4]. Excluding the 0-5% spectra, the rest were scaled by a factor of 10 for visual clarity.

Antiparticle-to-Particle Ratio

Particle ratios have been proven to be sensitive to hydrodynamic effects. Figure 2 presents the π^-/π^+, K^-/K^+ and $\bar{p}/p$ ratios as function of the number of participants in the collision $\langle N_{part} \rangle$. We observe that in the experiment $\pi^-/\pi^+ > 1$, indicating contributions from resonance decays. PYTHIA8 predicts its values within the uncertainty range reported by STAR experiment for all centrality classes. AMPT presents a π^-/π^+ with noticeable error bars. Ratios K^-/K^+ and $\bar{p}/p$, for mid-to-central collisions, were well described by the EPOS4 model. In the experimental data, both ratios are below 1, indicating large baryon stopping at 7.7 GeV, which is expected from theoretical

calculations as well. SMASH predicts for $\bar{p}/p$ ratio distribution an increase with collision centrality, which is not observed in the experimental data.

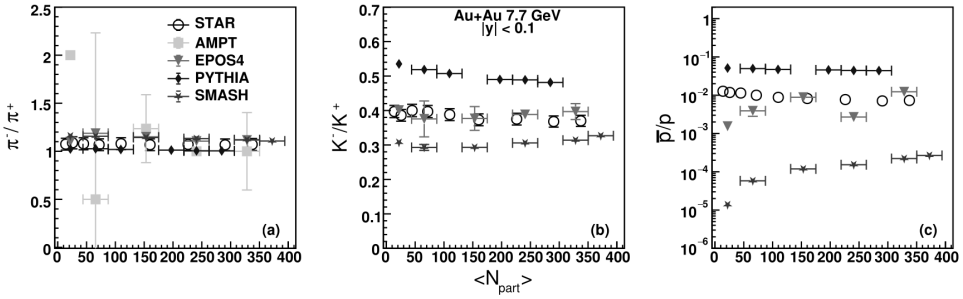


Fig. 2. (a) π^-/π^+, (b) K^-/K^+ and (c) $\bar{p}/p$ ratios as a function of $\langle N_{part}\rangle$ in Au-Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV for AMPT, EPOS4, PYTHIA8 and SMASH models in comparison with STAR experimental data. [4]

Mixed Ratio

Figure 3 presents the K^-/π^- , $\bar{p}/\pi^-$, K^+/π^+ and p/π^+ ratios as function of the number of participant nucleons in the collision $\langle N_{part}\rangle$. Ratios in dependence of π^- (π^+), predicted by the models, show a suppression (increase) in comparison with the experimental data. Experimental ratios shows smooth increases from peripheral to central collisions, which is only decribed by EPOS4 predictions for K^-/π^- ratio, deferring in central collisions. We need to notice that PYTHIA8 shows no dependence on centrality, which could be a consequence of the string fragmentation model. In the experimental data, $\bar{p}/\pi^- < 1$, which is only predicted by EPOS4 and PYTHIA8 models. The rest of the models in our analysis account for higher contributions.

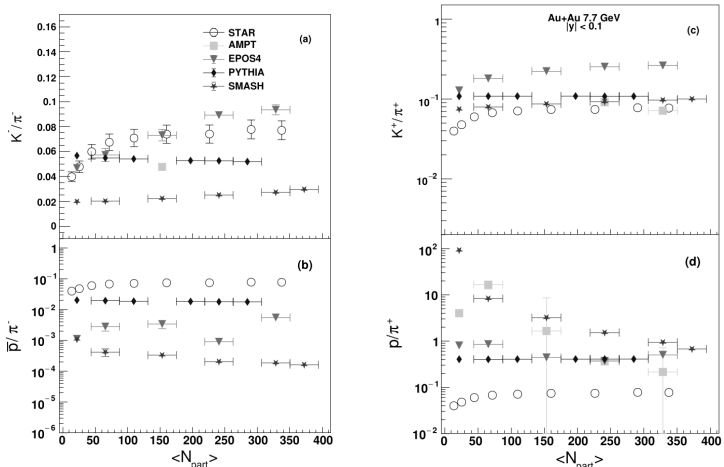


Fig. 3. (a) K^-/π^-, (b) $\bar{p}/\pi^-$, (c) K^+/π^+ and (d) p/π^+ ratios as a function of $\langle N_{part}\rangle$ in Au-Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV for AMPT, EPOS4, PYTHIA8 and SMASH models in comparison with STAR experimental data. [4]

Conclusions

We have presented the transverse momentum and particle ratios dependence of different collision centrality, for mid-rapidity ($|y| < 0.1$) particle production of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ with AMPT, EPOS4, PYTHIA8 and SMASH MC models. For the p_T spectra analysis, PYTHIA8 predicts well the distributions of $\pi^{\pm}$, $K^{\pm}$ particles from mid to central collisions. EPOS4 describes the K^-/K^+ and $\bar{p}/p$ ratios from mid-to-central collisions, indicating the hydrodynamical origin of this observable even at the low center-of-mass energy range. Other models demonstrated limited description of the experimental data, but can be improved by fine tuning of the MC model parameters.

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