

Directed flow in relativistic heavy-ion collisions within the PHSD transport approach and 3FD hydrodynamical model

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Abstract. We analyze recent STAR data for the directed flow of protons, antiprotons and charged pions obtained within the beam energy scan program within the Parton-Hadron-String-Dynamics (PHSD) transport model and the 3-Fluid hydroDynamics (3FD) approach. We clarify the role of partonic degrees of freedom in the kinetic PHSD approach. The PHSD results, simulating a partonic phase and its coexistence with a hadronic one, are roughly consistent with data. The hydrodynamic results are obtained for two EoS, a pure hadronic EoS and an EoS with a crossover type transition. The latter case is favored by the STAR experimental data. Special attention is paid to the description of antiproton directed flow based on the balance of $p\bar{p}$ annihilation and the inverse processes for $N\bar{p}$ pair creation from multi-meson interactions. Generally, a semi-qualitative agreement between the measured data and model results supports the idea of a crossover type quark-hadron transition which softens the nuclear EoS.

1. Introduction

The study of the particle azimuthal angular distribution in momentum space is an important tool to probe the hot, dense matter created in heavy-ion collisions [1, 2]. The directed flow refers to a collective sideways deflection of particles and is characterized by the first-order harmonic v_1 of the Fourier expansion of the particle azimuthal angular distribution with respect to the reaction plane [3]. It is generally assumed that the directed flow is generated during the early nuclear passage time [4, 5]. The directed transverse flow therefore probes the onset of bulk collective dynamics during thermalization, thus providing valuable information on the pre-equilibrium stage [6, 7, 8, 9]. Apart from first measurements in the early nineties and till recent times, the directed flow was studied mainly theoretically [10, 11, 12] although some experimental information from the Schwerionen-Synchrotron (SIS), Alternating Gradient Synchrotron (AGS) and Super-Proton-Synchrotron (SPS) is available [13]. The interest in the directed flow $v_1(y)$ has recently been enhanced considerably due to new STAR data obtained in the framework of the beam energy scan (BES) program [14]. The directed flow of identified hadrons – protons, antiprotons, positive and negative pions – has been measured with high precision for semi-central Au+Au collisions in the energy range $\sqrt{s_{NN}} = (7.7-200)$ GeV. We analyse these data in the framework of the Parton-Hadron-String-Dynamics (PHSD) transport model and a 3-Fluid hydroDynamics (3FD) approach and refer the reader to Ref. [15] for the details.



2. Reminder of PHSD transport approach

The PHSD model is a covariant dynamical approach for strongly interacting systems formulated on the basis of Kadanoff-Baym equations [16, 17] or off-shell transport equations in phase-space representation, respectively. In the Kadanoff-Baym theory the field quanta are described in terms of dressed propagators with complex selfenergies. Whereas the real part of the selfenergies can be related to mean-field potentials of Lorentz scalar, vector or tensor type, the imaginary parts provide information about the lifetime and/or reaction rates of time-like particles [18]. Once the proper complex selfenergies of the degrees of freedom are known, the time evolution of the system is fully governed by off-shell transport equations for quarks and hadrons (as described in Refs. [16, 18]). The PHSD model includes the creation of massive quarks via hadronic string decay - above the critical energy density $\sim 0.5 \text{ GeV/fm}^3$ - and quark fusion forming a hadron in the hadronization process. With some caution, the latter process can be considered as a simulation of a crossover transition since the underlying EoS in PHSD is a crossover [18]. At energy densities close to the critical energy density the PHSD describes a coexistence of the quark-hadron mixture. This approach allows for a simple and transparent interpretation of lattice QCD results for thermodynamic quantities as well as correlators and leads to effective strongly interacting partonic quasiparticles with broad spectral functions. For a review on off-shell transport theory we refer the reader to Ref. [18]; PHSD model results and their comparison with experimental observables for heavy-ion collisions from the lower SPS to RHIC energies can be found in Refs. [18, 19, 20, 21]. In the hadronic phase, i.e. for energies densities below the critical energy density, the PHSD approach is identical to the Hadron-String-Dynamics (HSD) model [22, 23, 24].

3. Reminder of 3FD hydrodynamic approach

The 3FD model [25] is a straightforward extension of the two-fluid model with a radiation of direct pions [26, 27, 28] and the (2+1)-fluid model [29, 30]. These models have been extended to treat the baryon-free fluid on an equal footing with the baryon-rich ones. A certain formation time, τ , is allowed for the fireball fluid, during which the matter of the fluid propagates without interactions. The formation time τ is associated with the finite time of string formation and decay and is incorporated also in the kinetic transport models such as PHSD and HSD. The 3FD model [25] treats a nuclear collision from the very beginning, i.e., from the stage of the incident cold nuclei to the final freeze-out stage. Contrary to the conventional hydrodynamics, where a local instantaneous stopping of projectile and target matter is assumed, the specific feature of the 3FD is a finite stopping power resulting in a counter streaming regime of leading baryon-rich matter. The basic idea of a 3FD approximation to heavy-ion collisions [31, 32] is that at each space-time point a generally nonequilibrium distribution of baryon-rich matter can be represented as a sum of two distinct contributions initially associated with constituent nucleons of the projectile and target nuclei. In addition, newly produced particles, populating predominantly the midrapidity region, are associated with a fireball fluid. Therefore, the 3FD approximation is a minimal way to simulate the finite stopping power at high incident energies.

4. Directed flow results

The characteristic slope of the $v_1(y)$ distributions at midrapidity, $\frac{dv_1}{dy}|_{y=0} = F$, is presented in Fig. 1 for protons, antiprotons and pions. We compare (as in Ref. [15]) the results of transport approaches (l.h.s) and hydrodynamical models (r.h.s) with the experimental data from the STAR collaboration [14] as well as the results of prior experiments [34, 35].

For protons in Fig.1 (l.h.s) there is a qualitative agreement of the HSD/PHSD results with the experimental measurements. The standard UrQMD model results, as cited in the experimental paper [14] and in the more recent theoretical work [33], are displayed in Fig. 1 (l.h.s.) by the wide and narrow shaded areas, respectively. These results for protons are close to those from the HSD

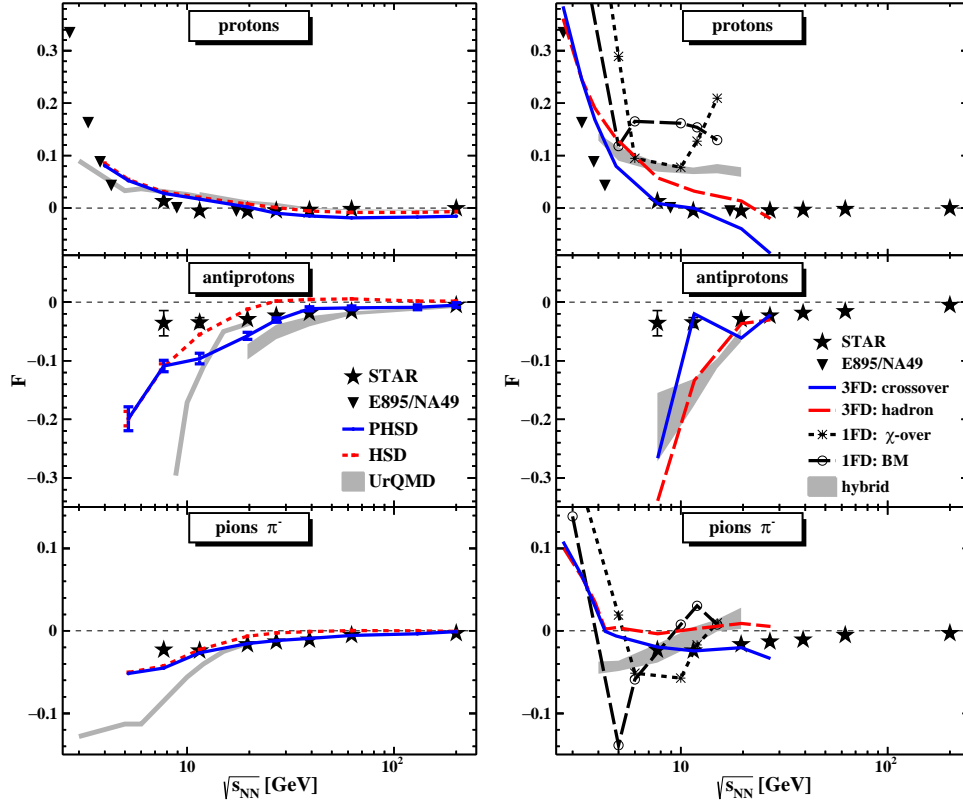


Figure 1. The beam energy dependence of the directed flow slope F at midrapidity for protons, antiproton and charged pions from semicentral Au+Au collisions for transport approaches (l.h.s.: PHSD/HSD, UrQMD [33, 14]) and hydrodynamical models (r.h.s.: 3FD, 1FD, hybrid [33]) in comparison to STAR experimental data [14] and results of prior experiments [34, 35].

and essentially overestimate the slope for energies below ~ 30 GeV. The predictions for the pure hadronic version of the transport model HSD (dotted lines in Fig. 1 (l.h.s.)) slightly differ from the PHSD results. For the antiproton slopes we again observe an almost quantitative agreement with the BES experiment [14]. The differences between the calculations and experimental data become apparent for the charged pion slopes at $\sqrt{s_{NN}} \leq 11$ GeV: the negative minimum of the charged pion slope is deeper than the measured one. The HSD and PHSD results practically coincide at low energy (due to a minor impact of partonic degrees of freedom) but dramatically differ from those of the UrQMD model for $\sqrt{s_{NN}} \leq 20$ GeV. This difference might be attributed to a neglect of the inverse processes for antiproton annihilation in UrQMD since in PHSD/HSD the antiprotons pick up some flow from the fusing mesons that is lower in magnitude than the direct flow for primary \bar{p} .

The excitation functions for the slopes of the v_1 distributions at midrapidity for 3FD model with different EoS are presented in Fig. 1 (r.h.s.). The discrepancies between experiment and the 3FD model predictions are larger for the purely hadronic EoS (dashed line) than for the crossover EoS (solid line) though it is far from being perfect. In Ref. [33] an essential part of the STAR data (for $\sqrt{s_{NN}} \leq 20$ GeV) is analyzed within collective approaches: the one-fluid (1F) hydrodynamical model with a first-order phase transition simulated by the bag model (BM) and a crossover chiral transition (χ -over), as well as within a modern hybrid model combining hydrodynamics with a kinetic model. The results of this work are also displayed in the Fig. 1 (r.h.s.) for comparison (open circles and stars).

5. Conclusions

The microscopic PHSD transport approach reproduces the general trend in the differential $v_1(y)$ excitation function and leads to an almost quantitative agreement for protons, antiprotons, and pions especially at higher energies. It is noteworthy that 3FD demonstrates high sensitivity to the nuclear EoS and provides the best results with a crossover for the quark-hadron phase transition being in a reasonable agreement with the STAR results in the considered energy range $\sqrt{s_{NN}} < 30$ GeV. Note also that a crossover transition is implemented by default in PHSD. Our flow analysis shows no indication of a first-order transition.

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