

## (Anti-)strangeness production in heavy-ion collisions

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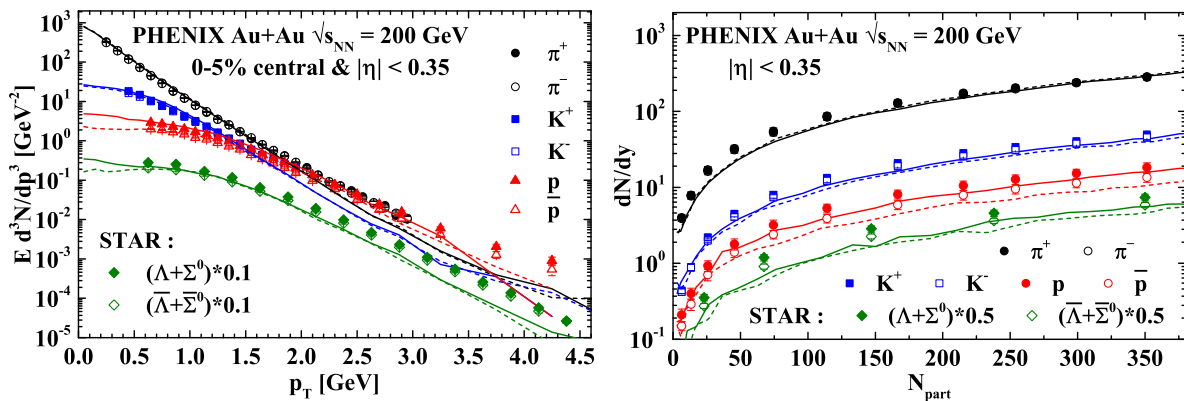
**Abstract.** The production and dynamics of strange and antistrange hadrons in heavy-ion reactions from  $\sqrt{s_{NN}} \approx 3$  GeV to 200 GeV is analyzed within the Parton-Hadron-String-Dynamics (PHSD) transport model. The PHSD results for strange baryon and antibaryon production are roughly consistent with the experimental data starting from upper SPS energies. Nevertheless, hadronic final state flavor-exchange reactions are important for the actual abundances, in particular at large rapidities where hadronic dynamics, parton fragmentation and string decay dominate. A striking disagreement between the PHSD results and the available data persists, however, for bombarding energies below  $\sqrt{s_{NN}} \approx 8$  GeV where the strangeness production is significantly underestimated as in earlier HSD studies. This finding implies that the strangeness enhancement seen experimentally at FAIR/NICA energies cannot be attributed to a deconfinement phase transition or crossover but probably involves the approximate restoration of chiral symmetry in the hadronic phase.

The production of strange hadrons in heavy-ion collisions has long been suggested to provide a sensible probe for the heavy-ion dynamics and its degrees-of-freedom at relativistic energies [1, 2]. However, while the production of kaons and antikaons in Pb+Pb collisions (158 A GeV or  $\sqrt{s_{NN}} = 17.3$  GeV) at top SPS energies turned out to be well described by hadron/string models such as the Hadron-String-Dynamics (HSD) or URQMD [3], the abundances of antistrange baryons were clearly underestimated. Furthermore, the kaon and hyperon abundances have been underestimated by up to a factor of two at the lower bombarding energies of 4 to 40 A GeV [3]. This surprising result has led to the suggestion that a quark-gluon plasma (QGP) might have already been produced at lower energies [4]. But this raises the question why we did not see a similar strangeness enhancement at the top super-proton-synchrotron (SPS) or even the Relativistic Heavy Ion Collider (RHIC) energies where a QGP is more likely produced. The answer to this problem is not straightforward since to differentiate between the hadronic and partonic degrees-of-freedom and their impacts on the various hadronic final-state interactions requires a fully microscopic description of these reactions. To this aim, an off-shell covariant transport approach – denoted as the Parton-Hadron-String Dynamics (PHSD) – has been developed to incorporate all necessary ingredients. This model has proven in the past to provide a good description of light hadron abundances, collective flow and electromagnetic radiation from nucleus-nucleus collisions [5, 6, 7, 8, 9, 10] up to the Large-Hadron-Collider (LHC) energies.



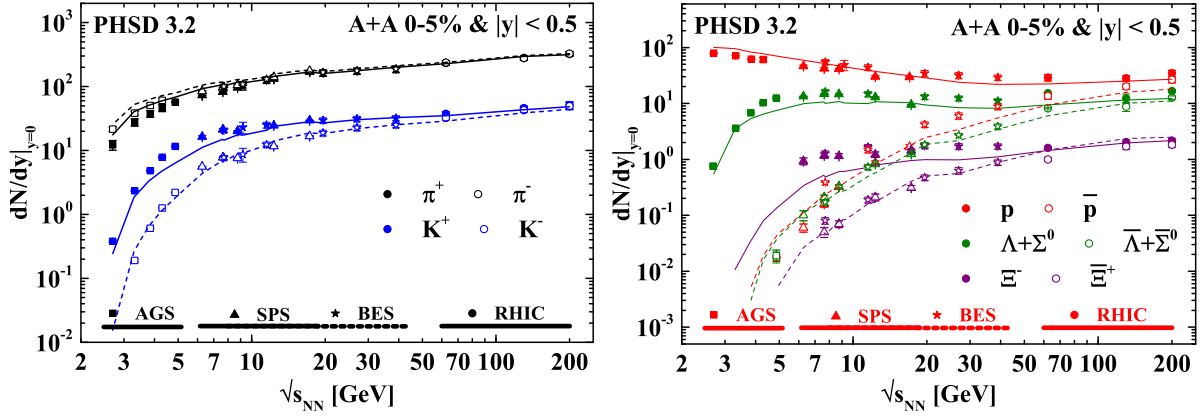
We recall that the PHSD model is a covariant dynamical approach for strongly interacting systems formulated on the basis of Kadanoff-Baym equations [11, 12] or off-shell transport equations in the phase-space representation. In the Kadanoff-Baym theory, the field quanta are described in terms of dressed propagators with complex selfenergies. Whereas the real part of the selfenergies can be related to mean-field potentials of Lorentz scalar or vector type, the imaginary parts provide information about the lifetime and/or reaction rates of time-like particles [12]. 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. [11, 12]). The PHSD model includes the creation of massive quarks via hadronic string decay to partons 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 [12]. 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. [12]. Results from the PHSD model and their comparison with experimental observables for heavy-ion collisions from the lower SPS to RHIC energies can be found in Refs. [5, 8, 9, 10]. In the hadronic phase, i.e. for energies densities below the critical energy density, the PHSD approach is identical to the HSD model [13, 14], which has been successfully employed for p-p, p-A and A-A reactions up to top SPS energies.

We here present an overview of (anti-) strangeness production in central Au+Au (Pb+Pb) collisions from  $\sqrt{s_{NN}} \approx 3 \text{ GeV}$  to 200 GeV within the PHSD with a particular focus on the multi-antistrange baryon production. Compared to the HSD study in Ref. [14], we now have incorporated in the hadronic sector all strangeness exchange reactions  $\pi + N \leftrightarrow K + Y$ ,  $N + N \leftrightarrow N + K + Y$ ,  $\bar{K} + N \leftrightarrow \pi + Y$ ,  $\pi + \Xi \leftrightarrow \bar{K} + Y$ ,  $Y + Y \leftrightarrow N + \Xi$ , and  $\bar{K} + \Xi \leftrightarrow \Omega + \pi$ ,  $\Xi + \Xi \leftrightarrow \Omega + Y$  in meson-baryon and baryon-baryon collisions following Refs. [15, 16, 17]. It is essential to recall that in PHSD (as in HSD) the dominant three-body channels  $B + \bar{B} \leftrightarrow 3 \text{ mesons}$  are included on the basis of 'detailed-balance' [18], where the dominant mesons involve the  $\pi, \rho, \omega, K, K^*$  degrees-of-freedom.



**Figure 1.** The invariant yield  $E d^3N/dp^3$  as a function of the transverse momentum  $p_T$  (left window) and the yield  $dN/dy$  as a function of the number of participating nucleons  $N_{part}$  (right window) at midrapidity for pions, kaons, protons, antiprotons,  $\Lambda$  and  $\bar{\Lambda}$  for Au+Au collisions at  $\sqrt{s_{NN}} = 200 \text{ GeV}$  in comparison to the experimental data from the PHENIX [19] and STAR collaboration [20].

We start with PHSD results for the transverse momentum distributions of particles (solid lines) and antiparticles (dashed lines), shown in the left window of Fig. 1 for 5% central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV in comparison to the data from PHENIX and STAR [19, 20]. Apart from a reasonable description of the data, we find baryons and antibaryons to differ only at low  $p_T < 0.5$  GeV/c where some net absorptions of antibaryons becomes visible. The centrality dependence of the particle yield (at midrapidity) is displayed in the right window of Fig. 1 as a function of the number of participants  $N_{part}$  in comparison to the PHENIX and STAR data [19, 20]. Here we find only a small difference between protons and antiprotons, whereas hyperons and antihyperons are about the same roughly in line with the data. We mention that the differences between baryons and antibaryons increase drastically when going down in bombarding energy, where nucleons from the target and projectile are shifted to the midrapidity region and dominate over antibaryons, which are preferentially produced in the hadronization process from the QGP at midrapidity.



**Figure 2.** (Left window) The yield at midrapidity for pions and kaons as a function of  $\sqrt{s_{NN}}$  for central Au+Au and Pb+Pb collisions in comparison to the experimental data from [21] for AGS energies, from [22] for SPS energies, from [23] for the preliminary results from the BES program at RHIC, and from [24] for RHIC energies. (Right window) The yield at midrapidity for protons, antiprotons,  $\Lambda$ ,  $\bar{\Lambda}$ ,  $\Xi^-$  and  $\bar{\Xi}^+$  as a function of  $\sqrt{s_{NN}}$  for central Au+Au and Pb+Pb collisions in comparison to the experimental data from [25] for AGS energies, from [26] for SPS energies, from [23] for the preliminary results from the BES program at RHIC, and from [24, 27] for RHIC energies.

We further display in the left window of Fig. 2 the excitation function for  $\pi^\pm$  and  $K^\pm$  mesons from 5% central Au+Au collisions (at midrapidity) as a function of  $\sqrt{s_{NN}}$  in comparison to the available data. We observe an overestimation of pion production by PHSD at low invariant energy and an underestimation of  $K^+$  mesons as in the HSD model [3]. An underestimation of strangeness at low invariant energy is also seen in the baryon-antibaryon sector (cf. Fig. 2 (right window)) where the hyperons ( $\Lambda + \Sigma^0$ ) and cascade baryons ( $\Xi^-$ ) are missed substantially. On the other hand, the antihyperons ( $\bar{\Lambda} + \bar{\Sigma}^0$ ) and  $\bar{\Xi}^+$  are reasonably described, and this can be traced back to the dominant production in the hadronization process from the QGP.

A closer analysis of the explicit rapidity distribution of baryons and antibaryons shows that antibaryon production close to midrapidity can essentially be attributed to hadronization from the QGP, whereas at forward or backward rapidities (closer to the target and projectile rapidities) hadrons are mainly produced from fragmentation or hadronic string decay in the PHSD. This allows for a scan in the partonic fraction of the dynamics when analyzing separately baryons and antibaryons as a function of rapidity.

In summary: we have extended the PHSD transport approach to include all strangeness exchange reactions  $\pi + N \leftrightarrow K + Y$ ,  $N + N \leftrightarrow N + K + Y$ ,  $\bar{K} + N \leftrightarrow \pi + Y$ ,  $\pi + \Xi \leftrightarrow \bar{K} + Y$ ,  $Y + Y \leftrightarrow N + \Xi$ , and  $\bar{K} + \Xi \leftrightarrow \Omega + \pi$ ,  $\Xi + \Xi \leftrightarrow \Omega + Y$  in meson-baryon and baryon-baryon collisions, thus allowing for a detailed study of multistrange baryon production in the hadronic phase and to compare their production in the hadronization process from the QGP. We find that an underestimation of strangeness production at low invariant energy is seen in the meson as well as baryon sector (cf. Fig. 2), whereas the multistrange baryon/antibaryon dynamics at the top SPS and RHIC energy are rather well described by hadronization from the QGP at midrapidity. This finding implies that the strangeness enhancement seen experimentally at FAIR/NICA (AGS and lower SPS) energies cannot be attributed to a deconfinement phase transition (or crossover) but probably involves the approximate restoration of chiral symmetry in the hadronic phase, which would lead to a change of hadron properties and thus an enhanced production of multistrange baryons.

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