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Can Baryon Stopping Be Understood within a Hadronic Transport Approach †

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Abstract: The changing shape of the rapidity spectrum of net protons over the SPS energy range is still lacking theoretical understanding. In this work, a model for string excitation and string fragmentation is implemented for the description of high energy collisions within a hadronic transport approach. The free parameters of the string model are tuned to reproduce the experimentally measured particle production in proton-proton collisions. With the fixed parameters we advance to calculations for heavy ion collisions, where the shape of the proton rapidity spectrum changes from a single peak to a double peak structure with increasing beam energy in the experiment. We present calculations of proton rapidity spectra at different SPS energies in heavy ion collisions. Qualitatively, a good agreement with the experimental findings is obtained. In a future work, the formation process of string fragments will be studied in detail aiming to quantitatively reproduce the measurement.

Keywords: baryon stopping; string fragmentation; hadron transport

1. Introduction

Heavy ion collisions provide the opportunity of probing strongly interacting matter under hot and dense conditions. Within this work we focus on the energy range between $\sqrt{s_{NN}} \approx 6\,\text{GeV}$ and $\sqrt{s_{NN}} \approx 17\,\text{GeV}$. In lead-lead collisions in this energy range, a region in the phase diagram of strongly interacting matter with large baryon chemical potential can be studied. Going to larger energies, the shape of the rapidity spectrum of net baryons changes from a single peak at mid-rapidity to a double peak structure with a dip in the mid-rapidity region [1]. The stopping of baryons is of major interest, since the net-baryon density determines the baryon chemical potential within heavy ion collisions. A theoretical understanding of the stopping has not been achieved yet. However, there are many ongoing efforts for describing this effect in hybrid approaches [2,3].

Within a transport model SMASH [4], binary collisions between hadrons at low energies are modeled via resonance formation. For the description of interactions at large $\sqrt{s}$ we implement a string model. While Pythia [5] is employed directly for treating hadronic interactions at high energies, another calculation is necessary in the lower energy region, where perturbative methods are not applicable. The additional string mechanism is split into the string excitation, which is inspired by the implementation in UrQMD [6,7], and the string fragmentation, which is performed using Pythia.

Comparing to experimental results for heavy ion collisions is only meaningful, if the interactions between nucleons are understood. Comparisons to experimental data for proton-proton collisions are therefore shown in Section 2. Finally we conclude with results for heavy ion collisions in Section 3.

2. Proton-Proton Collisions

Comparing to proton-proton collisions provides the opportunity to test the string model and fix free parameters in order to obtain the best possible agreement with the experimental measurement in elementary collisions. The most abundantly produced particles are pions. Therefore, it is important to obtain a good understanding of their dynamics, since the pion momenta will propagate to other particle species in secondary interactions when investigating heavy ion collisions.

The rapidity spectrum and the mean transverse momentum of negatively charged pions in each bin of $x_F = p_z / p_{z,\mathrm{beam}}$ is shown in comparison to experimental data in Figure 1.

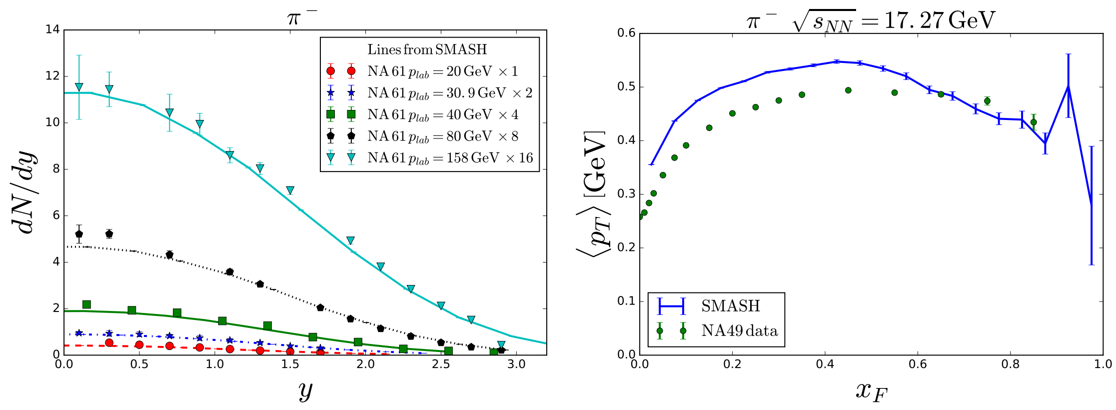

Figure 1. Rapidity spectra of negatively charged pions in proton-proton collisions at different energies compared to experimental data [8] on the left hand side and the mean transverse momentum of negatively charged pions in proton-proton collisions at $\sqrt{s} = 17.27\,\mathrm{GeV}$ compared to experimental data [9] on the right hand side.

The multiplicity and longitudinal momentum of the produced pions matches the experimental data very well over the entire SPS energy range. The agreement with the experiment is achieved by tuning the parameters of the symmetric Lund fragmentation function [10] used in PYTHIA. The mean transverse momentum is slightly overestimated within the SMASH calculation. The transverse momentum can be tuned by reducing either the transverse momentum, that is exchanged between colliding hadrons before a string is produced, or the transverse momentum sampled for each string fragment within PYTHIA. The transverse momentum for different particle species can not be modified independently. Tuning to all hadron species simultaneously leads to a slight overshoot of $\langle p_T \rangle$ in the case of pions.

The protons are of major interest for this study, because they contribute a lot to the net-baryon number in heavy ion collisions. Understanding the dynamics of protons in proton-proton collisions proves to be very challenging. Since protons are baryons, they are mainly produced at the ends of a string, because the probability of producing a diquark during the string fragmentation is small. Using the symmetric Lund fragmentation function, the protons are observed to carry too little longitudinal momentum. An additional fragmentation function, which is used only for leading baryons, is implemented in order to enhance the light cone momentum fraction of leading baryons. The rapidity spectrum and the mean transverse momentum as a function of x_F of protons is shown in Figure 2.

The rapidity spectrum of protons is not quite matching the data but over a large range of rapidity the shape of the spectrum follows the measurement qualitatively. The transverse momentum of protons is underestimated in the region at low x_F. A better agreement is observed at large x_F. With all free parameters tuned to proton-proton collisions, it is possible to advance to heavy ion collisions in order to investigate the interaction of string fragments.

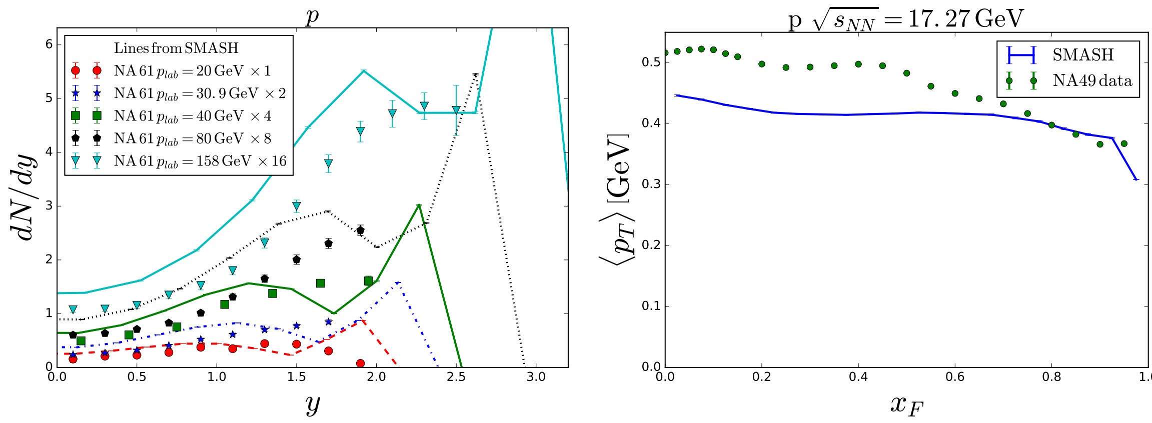

Figure 2. Rapidity spectrum of protons in proton-proton collisions at different energies compared to experimental data [8].

3. Heavy Ion Collisions

Heavy ion collisions provide an opportunity to study the formation process of string fragments. Since the system of a heavy ion collision is very dense, the string fragments interact immediately once they are formed. Hence, the time, the string fragments take to form, influences the rapidity spectra in the final state.

The formation times are calculated using the yoyo-formalism as described in [6]. Within this work all cross sections of a particle are reduced by a constant factor f_σ until the formation time of that particle has passed. For the most string fragments this factor is $f_\sigma = 0$. Only leading string fragments who carry a valence quark of the initially colliding hadrons have a non-zero cross section scaling factor.

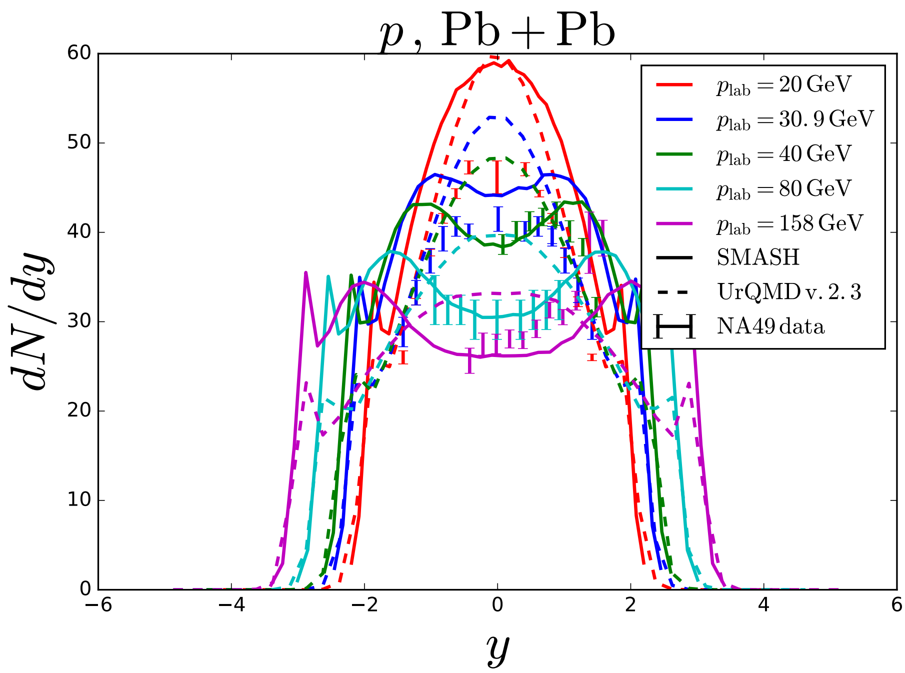

Figure 3. Rapidity spectrum of protons in central lead-lead collisions over the entire SPS energy range compared to experimental data [11] and UrQMD calculations [12].

Figure 3 shows the rapidity spectra of protons in lead-lead collisions at different SPS energies compared to UrQMD results and experimental data. For the lowest two energies, the proton production is overestimated in both transport calculations. Going to larger energies, the agreement between the experimental data and the SMASH calculation is improved. The UrQMD results do not reproduce the double-peak structure, which is observed in the experimental data. The main ingredient, besides the applied string model, that is necessary for correctly describing this structure, is the angular distribution of elastic collisions, which is more forward-backward peaked at larger energies.

Even though the general shape of the rapidity spectrum follows the experimental data, there are still differences visible. As a future work, the influence of changing the formation time and cross section scaling factors on the stopping of baryons can be studied in order to obtain insights on the fragmentation process.

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