

# Transverse momentum spectra of mesons in $p+p$ collisions at CERN SPS energies from the UrQMD transport model

Vitalii Ozvenchuk<sup>1,\*</sup> and Andrzej Rybicki<sup>1</sup>

<sup>1</sup>H. Niewodniczański Institute of Nuclear Physics, PAS, Radzikowskiego 152, 31-342 Kraków, Poland

**Abstract.** The UrQMD transport model, version 3.4, is used to study the new experimental data on total yields, rapidity distributions and transverse momentum spectra of  $\pi^\pm$ ,  $K^\pm$ ,  $p$  and  $\bar{p}$  produced in inelastic  $p+p$  interactions at SPS energies, recently published by the NA61/SHINE Collaboration. The comparison of model predictions to these new measurements is presented as a function of collision energy. In addition, we compare with the experimental data the results on kaon-over-pion multiplicity ratio and the inverse slope parameter of negative kaons produced at midrapidity. A complicated pattern of discrepancies between the experimental data and the UrQMD transport model is apparent. We conclude that new experimental data analyzed in this contribution still constitute a challenge for the present version of the model.

## 1 Introduction

The NA61/SHINE Collaboration published new, detailed experimental results [1] on inclusive spectra and mean multiplicities of  $\pi^\pm$ ,  $K^\pm$ ,  $p$  and  $\bar{p}$  produced in inelastic  $p+p$  interactions at 20, 31, 40, 80 and 158 GeV/c at the CERN Super Proton Synchrotron (SPS). These measurements were meant as a baseline in the study of the properties of the onset of deconfinement and the possibility to observe the critical point of strongly-interacting matter in nucleus-nucleus collisions. In particular, these experimental results suggest a plateau-like structure in the energy dependence of positive kaons over positive pions ratio [2]. The position of the plateau (in collision energy) agrees with that of the "horn" which was observed previously [3, 4] in central  $Pb+Pb$  reactions by the NA49 Collaboration at the CERN SPS and was predicted, within the statistical model of the early stage [5], as a signature of the onset of deconfinement.

Another important observable is the inverse slope parameter of the  $p_T$ -distributions of negative kaons. Recent NA61/SHINE data on particle production in inelastic  $p+p$  collisions at CERN SPS energies suggests a step-like structure in the inverse slope parameter of  $K^-$  at midrapidity, qualitatively similar to that observed in  $Pb+Pb$  collisions [4]. In the analogy to the boiling of water such a step-like structure in  $Pb+Pb$  reactions was meant to indicate a phase transition to the deconfined matter [5]. In this situation, the application of theoretical models in order to study the new  $p+p$  experimental data is particularly valuable as it gives a chance to follow in detail whether these similarities between  $p+p$  and heavy-ion collisions have a decisive or only a casual importance for our knowledge of deconfined matter.

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\*e-mail: Vitalii.Ozvenchuk@ifj.edu.pl

## 2 The UrQMD transport model

The UrQMD (Ultra-relativistic Quantum Molecular Dynamics) transport model [6, 7] is the non-equilibrium approach based on an effective solution of the relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i(x^\nu, p^\nu) = C_i, \quad (1)$$

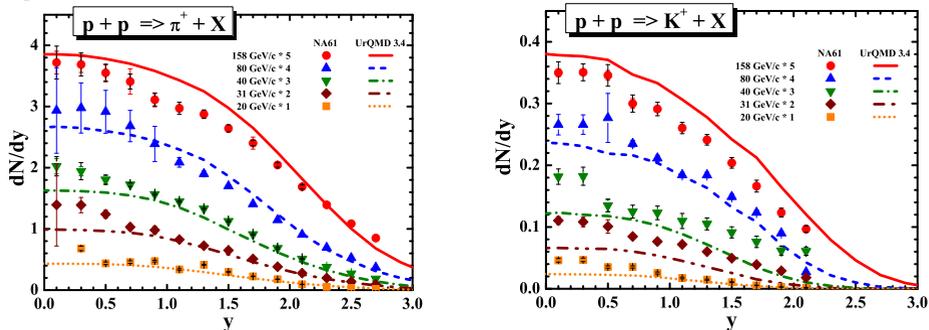
which is used to describe the time evolution of the distribution functions for particle species  $i$  and includes the full collision term on the right hand side. The underlying degrees of freedom are hadrons and strings. UrQMD includes 55 baryon and 32 meson species, ground state particles, and all resonance with masses up to  $2.25 \text{ GeV}/c^2$ . Full particle-antiparticle, isospin and flavor  $SU(3)$  symmetries are applied.

The hadrons propagate on straight lines until the covariant relative distance between two particles gets smaller than a critical distance given by the corresponding total cross section. The elementary cross sections are calculated by the detailed balance or the additive quark model or fitted and parametrized according to the available experimental data. For resonance excitations and decays the Breit-Wigner formalism is used.

In the present study, we use the most recent version of UrQMD transport model, UrQMD v3.4 [8], which has been successfully applied to describe particle yields and transverse dynamics in the energy range from  $E_{lab} = 2$  to  $160 \text{ AGeV}$  [9].

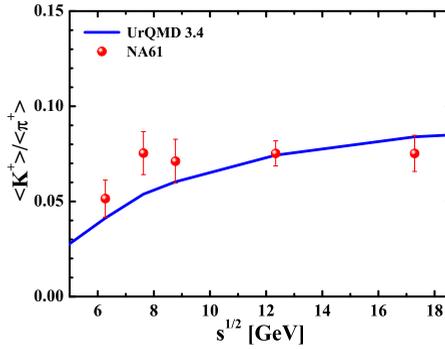
## 3 Results

In this Section we present the results for the rapidity distributions of  $\pi^+$  and  $K^+$  as well as for the transverse momentum spectra of  $K^-$  produced in inelastic  $p + p$  interactions at different collision energies obtained from the UrQMD calculations. We also show the results extracted from the UrQMD simulations for the positive kaons over positive pions ratio and for the inverse slope parameter of negative kaons at midrapidity in comparison to the experimental data from the NA61/SHINE Collaboration. Prior to this we note that the UrQMD results for the rapidity distributions, mean multiplicities, transverse momentum spectra and inverse slope parameters of all identified particles for all energies were shown and analyzed in Ref. [1, 10].



**Figure 1.** The UrQMD v3.4 predictions (lines) for the rapidity distributions of  $\pi^+$  (left) and  $K^+$  (right) mesons produced in inelastic  $p + p$  interactions at beam momenta of 20, 31, 40, 80 and  $158 \text{ GeV}/c$  in comparison to experimental data from the NA61/SHINE Collaboration (symbols) [1].

One can see from Fig. 1 that for positive pions, the model reasonably well describes the  $dN/dy$  spectra at high SPS energies, but it gradually underestimates the yields at lower energies. In the 20-31  $\text{GeV}/c$  beam momentum regime, the discrepancies may reach up to 30%

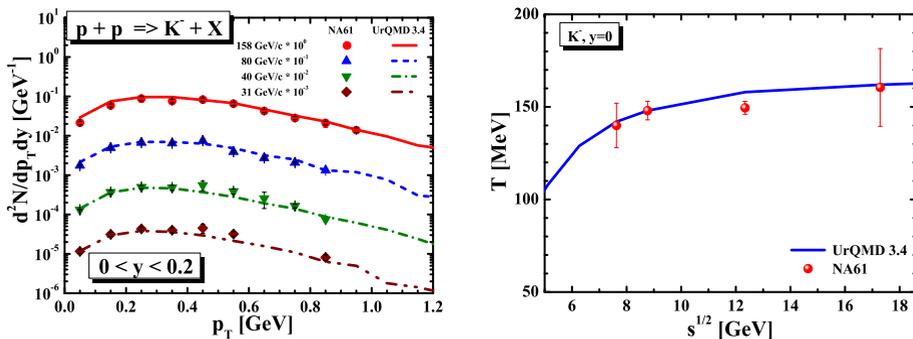


**Figure 2.** The UrQMD v3.4 predictions (line) for positive kaons over positive pions ratio in inelastic  $p + p$  interactions at CERN SPS energies in comparison to experimental data from the NA61/SHINE Collaboration (symbols). The NA61 data points have been obtained from total positive kaon and pion yields published in Ref. [1], and their error bars have been taken as the corresponding statistical and systematic errors added in quadrature.

for positive pion  $dN/dy$  values at  $y \approx 0$ . For positive kaons, the model gives a rough description of  $dN/dy$  spectra for the two top beam momenta, but systematically underestimates the yields at lower energies, with discrepancies reaching a factor of two for  $dN/dy(y \approx 0)$ .

We integrate the rapidity spectra of  $\pi^+$  and  $K^+$  over the whole rapidity range and obtain the results for the mean multiplicities (see Ref. [10]). Having the values for the mean multiplicities of  $\pi^+$  and  $K^+$  we construct the positive kaons over positive pions ratio, which is shown in Fig. 2. One observes that the UrQMD model does not describe the plateau-like structure in the energy dependence of  $K^+$  over  $\pi^+$  ratio suggested by the data from the NA61/SHINE experiment.

In Fig. 3 (left plot) we present the UrQMD results for the transverse momentum spectra of  $K^-$  produced at  $0 < y < 0.2$  in inelastic  $p + p$  interactions at 31, 40, 80 and 158 GeV/c. Our model predictions are compared to the experimental data from the NA61/SHINE Collaboration [1] obtained at the same rapidity. For better visibility, the experimental and model spectra are scaled by common factors at the different beam momenta. The model well describes the transverse momentum distributions of negative kaons for the two top beam momenta, but it systematically predicts smaller yields than visible in the experimental data at lower energies.



**Figure 3.** (Left:) the UrQMD v3.4 results (lines) for the transverse momentum spectra of  $K^-$  produced at  $0 < y < 0.2$  in inelastic  $p + p$  interactions at 31, 40, 80 and 158 GeV/c in comparison to experimental data from the NA61/SHINE Collaboration (symbols) [1]. (Right:) the UrQMD v3.4 simulations for the inverse slope parameter of  $K^-$  at  $y \approx 0$ , in comparison to experimental data from the NA61/SHINE Collaboration (symbols). The NA61 data points have been read off from Fig. 33 in Ref. [1].

In order to keep the consistency with the NA61/SHINE Collaboration, we attempt to parametrize the results presented in Fig. 3 (left plot) using the same exponential function [11]:

$$\frac{d^2N}{dp_T dy} = \frac{S p_T}{T^2 + mT} \exp[-(m_T - m)/T], \quad (2)$$

where  $m$  is the mass of the particle,  $m_T = \sqrt{m^2 + p_T^2}$  is its transverse mass,  $S$  and  $T$  are the yield integral and the inverse slope parameter, respectively. In Fig. 3 (right plot) we show the UrQMD results for the inverse slope parameter of  $K^-$  produced at midrapidity in comparison to the experimental data extracted by the NA61/SHINE experiment. The UrQMD model shows a slow increase of the inverse slope parameter with the increasing of energy. The overall agreement between the presented NA61/SHINE data points and the model is satisfactory.

## 4 Summary

In the present contribution we analyzed the new data on particle production in inelastic  $p + p$  collisions in the laboratory momentum range of 20 to 158 GeV/c published by the NA61/SHINE Collaboration [1]. These new experimental results were compared to simulations performed using the recent version 3.4 of the UrQMD transport model.

In view of the importance of the SPS energy regime which is claimed to host the onset of deconfinement from hadronic matter to quark-gluon plasma in heavy ion collisions [3, 4], the significance of reference  $p + p$  collisions cannot be stressed enough. This is even more evident in view of the apparent similarities in the energy dependence of kaon inverse slopes in  $p + p$  and heavy-ion collisions, and of the plateau structure suggested by the kaon-over-pion ratio measured by the NA61/SHINE Collaboration [2]. Altogether, the recent version of the UrQMD model cannot describe the energy dependence of the kaon-over-pion ratio in inelastic  $p + p$  collisions at CERN SPS energies observed by the NA61/SHINE experiment, but provides a fair overall description of the inverse slope parameter of negative kaons.

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