TRANSVERSE-MOMENTUM SPECTRA OF HADRONS IN $p+p$ COLLISIONS AT CERN SPS ENERGIES FROM THE UrQMD TRANSPORT MODEL*

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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 $\pi^{\pm}$ and $K^{\pm}$ 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 for central and forward particle rapidity intervals. In addition, the inverse slope parameters characterising the transverse-momentum distributions are extracted from the predicted spectra and compared to corresponding values obtained from experimental distributions, as a function of particle rapidity and collision energy. A complex pattern of deviations between the experimental data and the UrQMD model emerges. We conclude that new experimental data at SPS energies still constitute a challenge for specific transport models, at least as far as the present version of the UrQMD code is concerned.

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1. Introduction

New NA61/SHINE data [1] on particle production in inelastic $p+p$ collisions at the CERN Super Proton Synchrotron (SPS) energies show a rapid changes in the energy dependence of positive kaons over positive pions ratio (similarly to Pb+Pb collisions, known as K/π "horn"). Such a behavior was predicted by the authors in [2] within the statistical model of the early stage as a signature of the onset of deconfinement. In addition, the recent NA61/SHINE data [1] show a step-like structure in the inverse slope of negative kaons at midrapidity (as was previously observed in Pb+Pb collisions as well), which can indicate a phase transition to the deconfined matter.

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In the present contribution, we perform the comparison of the NA61/SHINE data to the UrQMD transport model. We analyze the transverse-momentum spectra of $\pi^\pm$ and $K^\pm$ produced in inelastic $p+p$ interactions at the SPS energies and extract the inverse slope parameters as a function of the particle rapidity and collision energy.

2. The UrQMD transport model

The UrQMD (Ultra-relativistic Quantum Molecular Dynamics) transport model [3, 4] is the non-equilibrium approach based on an effective solution of the relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i \left(x^\nu, p^\nu\right) = C_i \,, \tag{1}$$

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 particle, and all resonance with masses up to 2.25 GeV. 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.

We use the most recent version of UrQMD transport model, UrQMD version 3.4 [5], which has been successfully applied to describe particle yields and transverse dynamics in the energy range from $E_{\mathrm{lab}} = 2$ to $160A$ GeV [6].

3. Results

In this section, we present the results for the rapidity distributions, total yields (K^+/π^+ ratio), the transverse-momentum spectra and the inverse slope parameters of $\pi^\pm$ and $K^\pm$ produced in inelastic $p+p$ interactions at different collision energies, obtained from the UrQMD calculations.

3.1. Rapidity distributions of charged pions and kaons

We start with the results for the rapidity distributions of charged pions and kaons. In Fig. 1 and Fig. 2, we present the results obtained from the UrQMD simulations for the rapidity spectra of charged pions and kaons, respectively, produced in inelastic $p+p$ interactions at SPS energies, in comparison to experimental data from the NA61/SHINE Collaboration. The conclusions from this comparison to the experimental data can be summarized as follows.

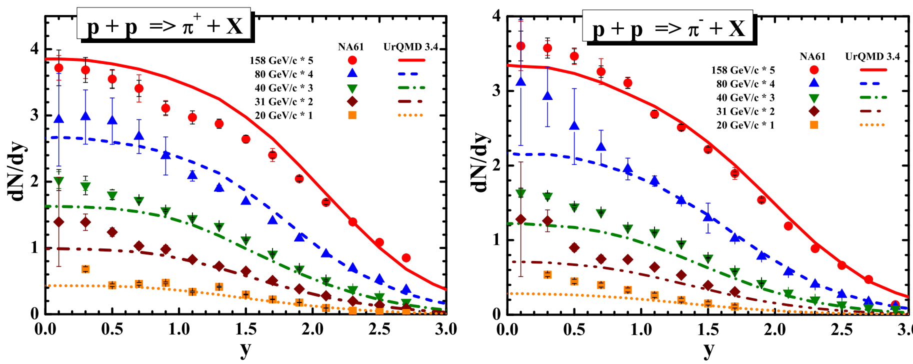

Fig. 1. The UrQMD predictions (lines) for the rapidity distributions of π^+ (left) and π^- (right) mesons produced in inelastic $p+p$ interactions at beam momenta of 20, 31, 40, 80 and 158 GeV/c in comparison to the NA61/SHINE data (symbols).

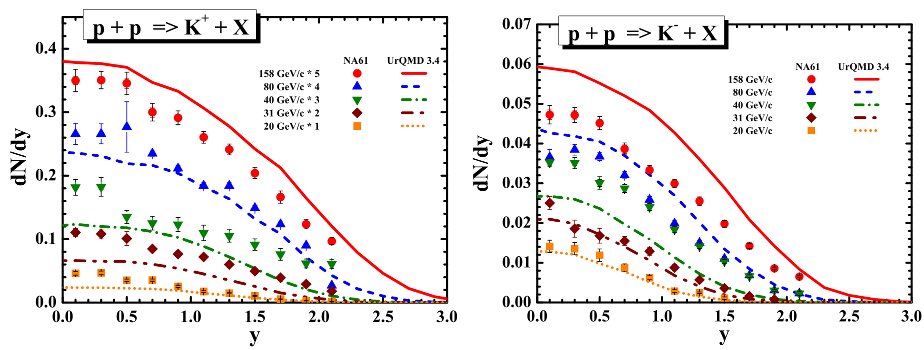

Fig. 2. The UrQMD predictions (lines) for the rapidity distributions of K^+ (left) and K^- (right) mesons produced in inelastic $p+p$ interactions at beam momenta of 20, 31, 40, 80 and 158 GeV/c in comparison to the NA61/SHINE data (symbols).

The UrQMD model describes reasonably well the rapidity spectra of both pions at high SPS energies, but it underestimates the pion yields at lower energies. For K^+, the model provides a rough description of rapidity spectra for the two top beam momenta, but systematically underestimates at lower energies with the discrepancy reaching a factor of two for the midrapidity values. For K^-, UrQMD slightly underestimates the data at beam momenta of 20 and 31 GeV/c, underestimates it by about 30% at 40 GeV/c, and overestimates it by up to 30% at higher beam momenta.

3.2. K^+/π^+ ratio

Having the rapidity spectra, we can extract the mean multiplicities of K^+ and π^+ and construct their ratio. In Fig. 3, we show the UrQMD results for the K^+/π^+ ratio in comparison to experimental data. One can see that the UrQMD model does not describe any rapid changes in the energy dependence of the K^+/π^+ ratio observed by the NA61/SHINE experiment.

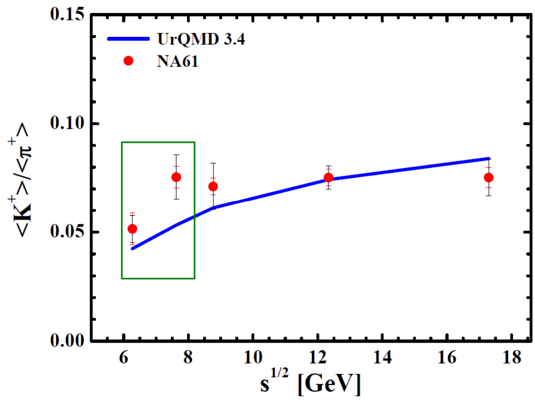

Fig. 3. The UrQMD predictions (line) for the K^+/π^+ ratio as a function of colliding energy, in comparison to the NA61/SHINE data (symbols).

3.3. Transverse-momentum spectra of charged pions and kaons

In Fig. 4 and Fig. 5, we present the transverse-momentum distributions of pions produced at forward rapidity ($1.4 < y < 1.6$) and kaons produced at central rapidity ($0 < y < 0.2$) in inelastic $p+p$ collisions at the SPS energies, respectively. Our model predictions are compared to the experimental data from the NA61/SHINE Collaboration [1] obtained at the same pion rapidity.

One observes that UrQMD gives a good description of the transverse-momentum spectra of pions for $p_{\mathrm{T}} > 0.8$ GeV/c, but overestimates the pion yield for $p_{\mathrm{T}} > 0.8$ GeV/c at all considered beam energies. For both kaons, the model describes well the p_{T}-distributions for the two top beam momenta, but it systematically predicts smaller yield at lower energies.

3.4. Inverse slope parameter

We attempt to parametrize the transverse-momentum spectrum of charged pions and kaons by the exponential function

$$\frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y} = \frac{S p_{\mathrm{T}}}{T^2 + mT} \exp\left[\frac{-(m_{\mathrm{T}} - m)}{T}\right], \tag{2}$$

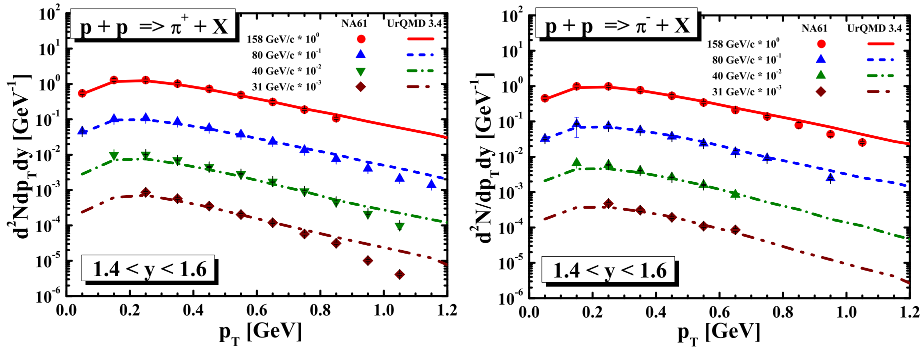

Fig. 4. The UrQMD predictions (lines) for p_{T}-spectra of π^+ (left) and π^- (right) mesons produced at $1.4 < y < 1.6$ in inelastic $p+p$ interactions at beam momenta of 31, 40, 80 and 158 GeV/c, in comparison to the NA61/SHINE data (symbols).

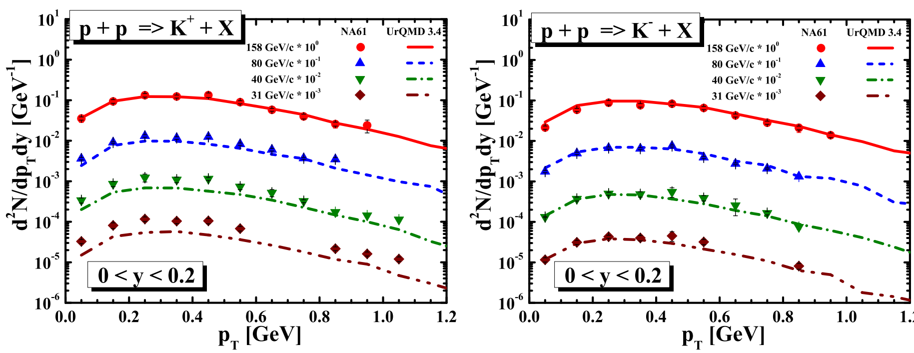

Fig. 5. The UrQMD predictions (lines) for p_{T}-spectra of K^+ (left) and K^- (right) mesons produced at $0 < y < 0.2$ in inelastic $p+p$ interactions at beam momenta of 31, 40, 80 and 158 GeV/c, in comparison to the NA61/SHINE data (symbols).

where m is the mass of the particle, $m_{\mathrm{T}} = \sqrt{m^2 + p_{\mathrm{T}}^2}$ is its transverse mass, S and T are the yield integral and the inverse slope parameter, respectively. We apply the fit to all particles studied at all considered values of rapidity and at all colliding energies. The extracted values of the inverse slope parameter T are shown in Fig. 6.

We take the values of the inverse slope parameter of K^- at midrapidity and compare them to the NA61/SHINE data (see Fig. 7). One sees that the UrQMD shows the similarities in a step-like structure of the inverse slope parameter of K^- at midrapidity shown by the NA61/SHINE Collaboration.

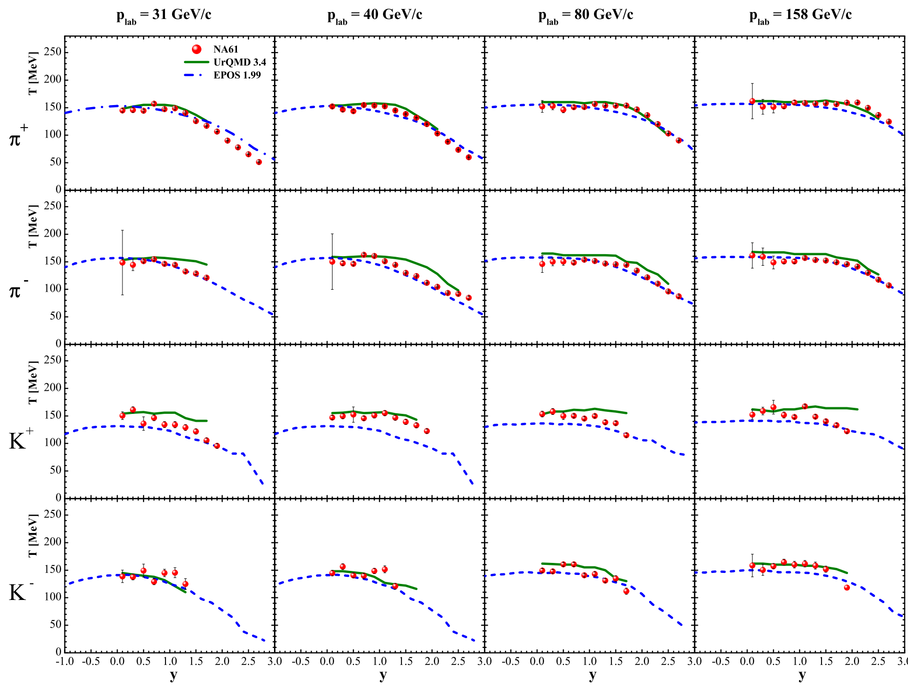

Fig. 6. Solid lines: the inverse slope parameter T extracted from fits with the parametrization (2) to the $p_{\rm T}$-distributions of $\pi^{\pm}$ and $K^{\pm}$ mesons produced in inelastic $p+p$ interactions at 31, 40, 80 and 158 GeV/c, obtained from UrQMD calculations as a function of pion and kaon rapidity. These results are compared to the values of T obtained from fits to the NA61/SHINE data (symbols) and to the EPOS model [7] predictions (dashed lines).

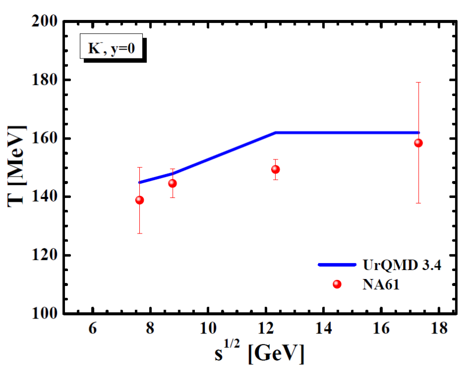

Fig. 7. The UrQMD predictions (lines) for the rapidity distributions of π^+ (left) and π^- (right) mesons produced in inelastic $p+p$ interactions at beam momenta of 20, 31, 40, 80 and 158 GeV/c in comparison to the NA61/SHINE data (symbols).

4. Summary

We analyzed new NA61/SHINE data on particle production in inelastic $p+p$ collisions at SPS energies using the UrQMD model. The rapidity distributions, K^+/π^+ ratio, p_{T}-spectra at central and forward rapidity, and the extracted inverse slope parameters of $\pi^{\pm}$ and $K^{\pm}$ were shown.

The UrQMD model does not describe any rapid changes in K^+/π^+ ratio, however, it shows the similarities in a step-like structure of the inverse slope parameter of K^- at midrapidity.

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