Proton-proton interactions and onset of deconfinement

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The NA61/SHINE experiment at the CERN SPS is performing a uniqe study of the phase diagram of strongly interacting matter by varying collision energy and nuclear mass number of colliding nuclei. In central Pb+Pb collisions the NA49 experiment found structures in the energy dependence of several observables in the CERN SPS energy range that had been predicted for the transition to a deconfined phase. New measurements of NA61/SHINE find intriguing similarities in p+p interactions for which no deconfinement transition is expected at SPS energies. Possible implications will be discussed.

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The standard approach to heavy-ion collisions [1] assumes creation of strongly interacting matter in local equilibrium at

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the early stage of a collision. The matter properties depend on energy and baryon densities via an equation-of-state. The matter expansion is modelled by hydrodynamics and its conversion to final state hadrons by statistical hadronization models [2–4]. The early stage energy density monotonically increases with collision energy and at sufficiently high energies the state of matter is expected to change from the confined phase to the quark-gluon plasma (QGP).

In an energy scan of central Pb+Pb collisions at the CERN SPS the NA49 experiment found structures in a common narrow energy interval $\sqrt{s_{NN}} \approx$ 7-12 GeV [5–7] ($\sqrt{s_{NN}}$ is the collision energy per nucleon pair in the centre of mass system) for several observables that had been predicted [8] for the transition to the QGP phase. The most conclusive are:

(i) a fast rise and and sharp peak in the ratio of strangeness to entropy production

(ii) a fast rise and following plateau of the temperature as measured by the inverse slope parameter of the kaon transverse mass distributions

Experimental results on p+p interactions served as an important reference with respect to which new physics in heavy-ion collisions was searched for. The most popular models of p+p interactions are qualitatively different from the standard approach to heavy-ion collisions. They are resonance-string models [9] in which the hydrodynamic expansion of the strongly interacting matter created in nucleus-nucleus (A+A) collisions is replaced in p+p collisions by excitation of resonances or strong fields between colour charges of quarks and di-quarks (strings). The assumption of statistical hadronization of matter is substituted by dynamical modelling of resonance and/or string decays as well as quark/gluon fragmentation into hadrons. Since the early days, the different modelling of p+p interactions and heavy-ion collisions was supported by qualitative disagreement of the p+p data with predictions of statistical and hydrodynamical models - large particle multiplicity fluctuations and a power-law shape of transverse momentum spectra at high p_{T} [10]. On the other hand, the different modelling has been questioned by striking agreement of the p+p data with other predictions of statistical and hydrodynamical models - mean multiplicities of hadrons and transverse mass spectra at low and intermediate p_{T} follow a similar pattern. Moreover, recent LHC data on the azimuthal angle distribution of charged particles in high multiplicity p+p interactions [11–13] show anisotropies up to now observed only in heavy-ion collisions and attributed to the hydrodynamical expansion of matter [14]. Also it was reported that relative strange particle yields in p+p interactions at LHC smoothly increase with increasing charged particle multiplicity and for high multiplicity collisions are close to those in Pb+Pb collisions [15].

These results suggests that the observation of strongly interacting matter in nucleus-nucleus collisions may also extend to those p+p interactions at LHC energies which produce sufficiently high particle multiplicity.

This paper addresses the relation between the observation of effects possibly indicating the onset of deconfinement in Pb+Pb collisions and recently uncovered, still unexplained features in p+p interactions.

New experimental insight is possible thanks to recent results on p+p interactions at the CERN SPS from the NA61/SHINE [16] fixed target large acceptance hadron detector. The measurements [17, 18] cover the energy range in which experimental effects attributed to the onset of deconfinement in heavy-ion collisions are located. They allow to significantly extend and improve the world data on the K^+/π^+ ratio [19, 20] and the inverse slope parameter T of transverse mass spectra of kaons [21]. Furthermore, recent data on p+p interactions at LHC energies allow to establish the collision energy dependence of bulk hadron production properties in the energy range in which the quark-gluon plasma is likely to be created in heavy-ion collisions.

The energy dependence of the K^+/π^+ ratio at mid-rapidity and in the full phase-space for inelastic p+p interactions is shown in Fig. 1 *top-left* and *top-right*, respectively. The results for heavy-ion (Pb+Pb and Au+Au) collisions are plotted for comparison. The NA61/SHINE results on p+p interactions at CERN SPS energies are shown together with the world data [19, 20, 22–38]. Results on the mid-rapidity ratio (the top-left plot) cover the range from low SPS energy to LHC energies. For comparison the mid-rapidity plot includes also p+p data of other experiments on the full phase-space ratio. The p+p data on the full phase-space ratio (the top-right plot) extends only to $\sqrt{s_{NN}} \approx 50$ GeV, whereas the heavy-ion data reach 200 GeV. The energy dependence of the mid-rapidity and full phase-space ratio in inelastic p+p interactions is similar. This seems to be also true for heavy-ion collisions.

The collision energy dependence of the K^+/π^+ ratio in heavy-ion collisions shows the so-called *horn* structure. Following a fast rise the ratio passes through a maximum in the SPS range and then settles to a plateau value at higher energies.

The K^+/π^+ ratio at SPS energies was shown to be a good measure of the strangeness to entropy ratio [7] which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons). This is because at high baryon to meson ratio (SPS energies and below) the anti-hyperon yield is small and the main carriers of anti-strange quarks are K^+ and K^0 with $\langle \mathrm{K}^+ \rangle \approx \langle \mathrm{K}^0 \rangle$ due to approximate isospin symmetry in heavy ion collisions. Thus the K^+ yield counts about half of the strange quark - anti-quark pairs ($\langle s\bar{s} \rangle$) produced in the collisions and contained in the reaction products [7]. In contrast, fractions of strange quarks carried by K^-, $\bar{\mathrm{K}}^0$ and hyperons are comparable and change significantly with the baryon to meson ratio. At lower collision energies relatively more strange quarks are carried by hyperons and less by anti-kaons. Thus the energy dependence of the K^- yield does not follow the energy dependence of $\langle s\bar{s} \rangle$. This is illustrated in Fig. 2 where the energy dependence of the K^-/π^- ratio at mid-rapidity (the left plot) and in the full phase-space (the right plot) for inelastic p+p interactions and heavy-ion collisions is shown. In conclusion, the K^+ yield is preferred over K^- and Λ yields when the total number of $s\bar{s}$ pairs is of interest as in the search for the QGP [39] and the onset of deconfinement [8].

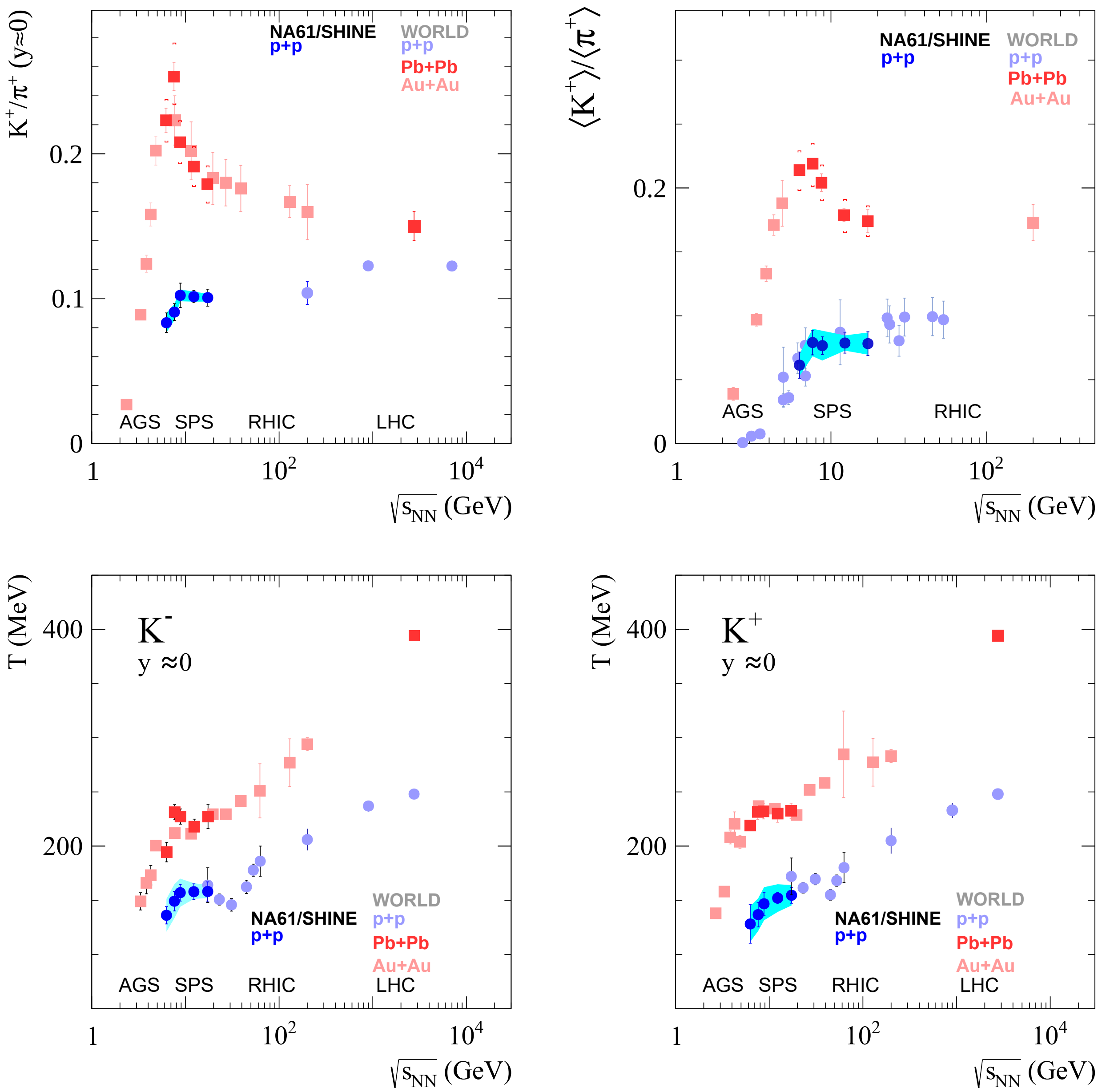

FIG. 1: Energy dependence of the K$^+$/π^+ ratio at mid-rapidity (*top-left*) and in the full phase-space (*top-right*) as well as the inverse slope parameter T of transverse mass spectra at mid-rapidity for K$^-$ (*bottom-left*) and K$^+$ (*bottom-right*) mesons. The NA61/SHINE results for inelastic p+p interactions are shown together with the world data on p+p interactions as well as central Pb+Pb and Au+Au collisions [21, 23, 25–38]. Shaded bands show the systematic uncertainty.

Further comment is in order here. Since many years it has been popular to fit mean hadron multiplicities, which include multiplicities of kaons and pions, assuming that a hadron gas in equilibrium is created when strongly interacting matter hadronizes. The temperature, the baryon chemical potential, and the hadronization volume are free parameters of the model and are fitted to the data at each energy. In this formulation, the hadron gas model cannot make any prediction about the energy dependence of hadron production so that an extension of the model was proposed, in which the values of the temperature and baryon chemical potential evolve smoothly with collision energy (see Ref. [4] for a recent review). By construction (fits to the energy dependence of data on mean hadron multiplicities), the prevailing trend in the data is reproduced by the models. This parametrization of the measured energy dependence of hadron yields is often confused with predicting the energy dependence without invoking the phase transition.

The collision energy dependence of the K^+/π^+ ratio in inelastic p+p interactions is different from the one in heavy-ion collisions, see Fig. 1. First of all, the ratio is smaller in p+p interactions than in Pb+Pb and Au+Au collisions and does not show the horn structure.

The p+p ratio approaches that in heavy-ion reactions with increasing energy, at LHC it is only about 10% smaller than the corresponding ratio for central Pb+Pb collisions. Starting from the threshold energy the ratio in p+p interactions steeply increases to reach a plateau at CERN SPS energies. The plateau is followed by a weak increase towards LHC energies. Notably, the beginning of the plateau in p+p interactions coincides with the horn maximum in heavy-ion collisions.

According to the standard model of heavy ion collisions the inverse slope parameter T obtained from exponential fits of transverse mass spectra is sensitive to both the temperature and the radial flow in the final state. The energy dependence of T of transverse mass spectra of K^+ and K^- mesons produced at mid-rapidity in inelastic p+p interactions is presented in Fig. 1 *bottom-left* and *bottom-right*, respectively. The NA61/SHINE results [17] are compared to the world data for p+p and heavy-ion collisions [21, 23, 25–38]. Unless the T parameter was given directly by the experiment, it was taken from Ref. [21] or determined from transverse mass/momentum spectra according to the procedure of Ref. [21]. The collision energy dependence of the T parameter in heavy-ion collisions shows the so-called *step* structure. Following a fast rise the T parameter passes through a stationary region (or even a weak minimum for K^-), which starts at the low SPS energies, and then (above the top SPS energy) enters a domain of a steady increase. The increase continues up to the top LHC energy. The step was predicted as a signal of the onset of deconfinement [8, 40] resulting from the softening of the equation of state in the transition region. The collision energy dependence of the T parameter in inelastic p+p interactions is similar to the one for central Pb+Pb and Au+Au collisions. The main difference is that the T parameter in p+p interactions is significantly smaller than for heavy-ion collisions which is usually attributed to smaller radial flow.

To estimate the break energy between a fast rise at low energies and a plateau or slower increase at high energies two straight lines were fitted to the p+p data (see Fig. 3). The low energy line was constrained by the threshold energy for kaon production. The fitted break energy is 8.3 ± 0.6 GeV, 7.70 ± 0.14 GeV, 6.5 ± 0.5 GeV and 7.9 ± 0.2 GeV, for the K^+/π^+, $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratios and $T(K^-)$, $T(K^+)$, respectively. These values are close to each other and surprisingly close to the energy of the beginning of the horn and step structures in central Pb+Pb collisions - the transition energy being approximately 8 GeV (see Fig. 1).

Figure 3 presents also predictions of a resonance-string model, UrQMD [41]. This model assumes the transition between particle production by resonance formation at low energies and string formation at high energies [42] - *the resonance-string transition*. The postulate allows to approximately fit the fast low-energy increase of the K^+/π^+ ratio and the inverse slope parameter of transverse mass spectra of charged kaons and its slowing down at high energies. The sharpness of the break is not reproduced by the model.

The unexpected similarity of the transition energy in central Pb+Pb collisions and the break energy in p+p interactions provokes the question whether there is a common physics origin of the two effects. Is this coincidence accidental? If not, do we see effects included in standard modelling of heavy-ion collisions in p+p interactions, or reversely non-equilibrium processes in p+p interactions lead to the horn and step in heavy-ion collisions? The recent LHC results on hydrodynamical properties of p+p interactions suggest the former interpretation. However, the discussed experimental results are brand new and the community is far from reaching a consensus. An obstacle is that the validity of quantitative models is usually restricted to a limited range in collision energy, size of colliding nuclei and concerns only selected observables. Examples of recent developments are given in Refs. [43–46].

In summary, new results of NA61/SHINE on the collision energy dependence of the K^+/π^+ ratio and the inverse slope parameter of kaon m_T spectra in inelastic p+p interactions are presented together with a compilation of the world data. The p+p results are compared with the corresponding measurements in central Pb+Pb and Au+Au collisions. The comparison uncovers a similarity between the collision energy dependence in p+p interactions and central heavy ion collisions - a rapid change of collision energy dependence of basic hadron production properties in the same energy range. Possible interpretations are briefly discussed. Clearly, understanding of the origin for the similarity between results on heavy ion collisions and p+p interactions is one of the key objectives of heavy ion physics today. Emerging results from the NA61/SHINE (nuclear mass number) - (collision energy) scan as well as results from LHC and RHIC on collisions of small and medium size systems qualitatively change the experimental landscape. In parallel, significant progress is needed in the modelling of collision energy and system size dependence which would extend the validity of models to the full range covered by the data.

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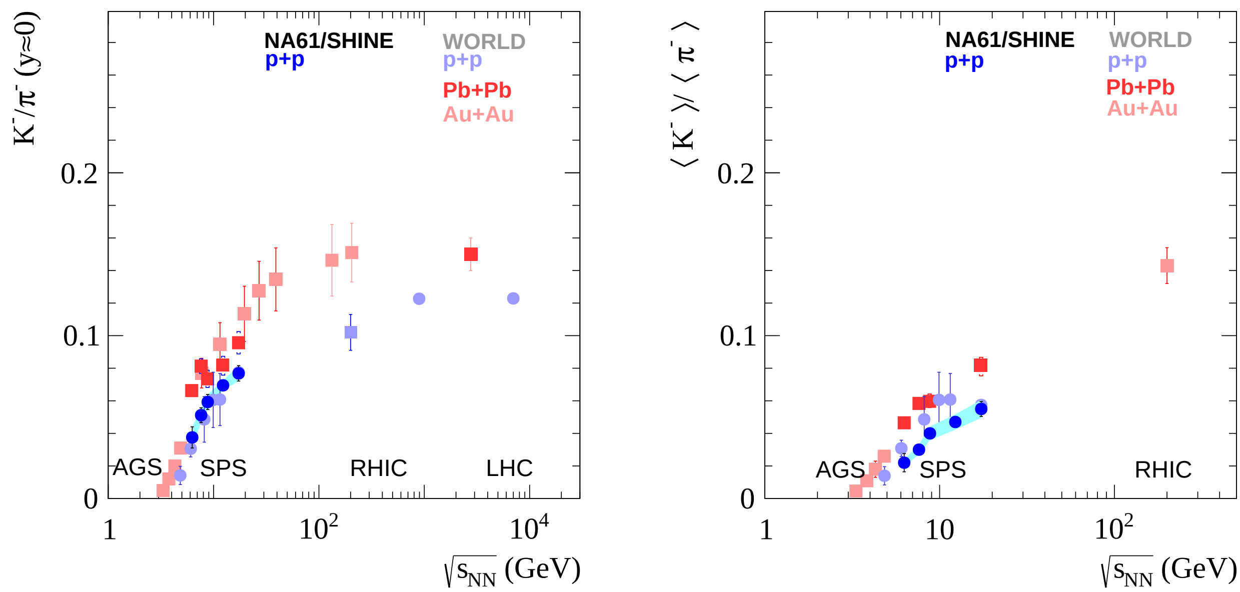

FIG. 2: Energy dependence of the K^-/π^- ratio at mid-rapidity (*left*) and in the full phase-space (*right*). The NA61/SHINE results for inelastic p+p interactions are shown together with the world data on p+p interactions as well as central Pb+Pb and Au+Au collisions [21, 23, 25–38]. Shaded bands show the systematic uncertainty.

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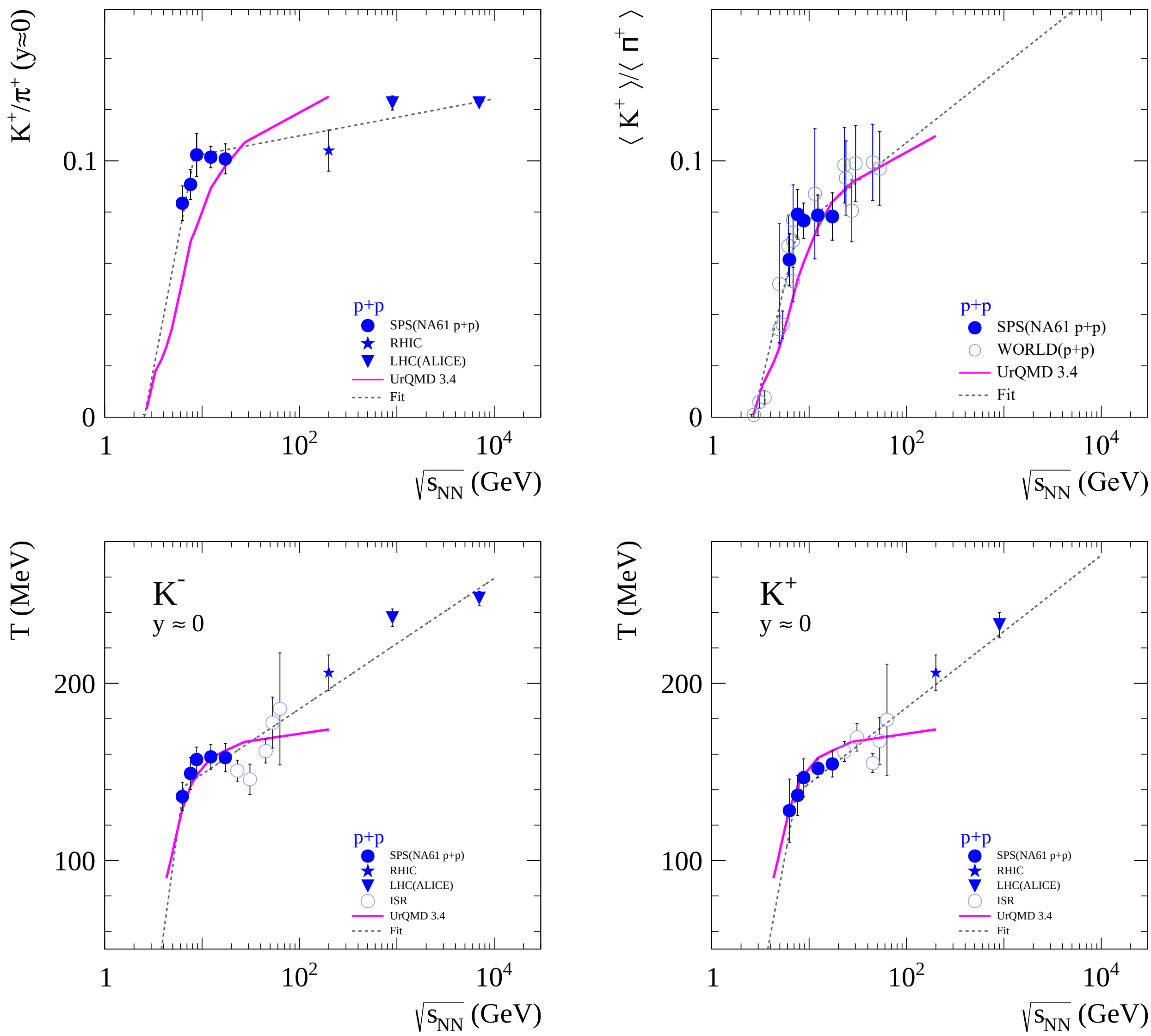

FIG. 3: Energy dependence of the K^+/π^+ ratio in inelastic p+p interactions at mid-rapidity (*top-left*) and in the full phase-space (*top-right*) as well the inverse slope parameter T of transverse mass spectra at mid-rapidity for K^- (*bottom-left*) and K^+ (*bottom-right*) mesons. The data are fitted by two straight lines in order to locate a position of the break in the energy dependence. The experimental results are compared with predictions of the resonance-string model, UrQMD [41].

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