Proton-proton interactions and onset of deconfinement

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Strongly interacting matter at very high densities is expected to be in a state of quasi-free quarks and gluons - the quark-gluon plasma. This hypothesis motivates studies of phases and transitions of strongly interacting matter by colliding atomic nuclei at high energies. Within a worldwide effort the NA61/SHINE experiment at the CERN SPS conducts unique measurements by varying collision energy and nuclear mass number of colliding nuclei. Here we show new results on proton-proton interactions which uncover similarities, and at the same time confirm with increased precision previously known qualitative differences, with results on lead-lead collisions - the latter showing evidence for the transition to the quark-gluon plasma at the low SPS energies. We found that the transition energy of selected hadron production properties between a fast rise at low energies and a slower increase at high energies in p+p interactions is close to the energy of the transition measured in Pb+Pb collisions.

One of the important issues of contemporary physics is the understanding of strong interactions and, in particular, the study of the properties of strongly interacting matter in equilibrium. What are the phases of this matter and what do the transitions between them look like? At sufficiently high energy densities one expects a transition from the state in which quarks and gluons are confined in hadrons to the quark-gluon plasma - a state of quasi-free quarks and gluons. These questions have motivated broad experimental and theoretical efforts since about 50 years. The study of high energy collisions between two atomic nuclei offers the unique possibility to address these issues in well controlled laboratory experiments. In such reactions the collision energy is deposited in a volume roughly the size of a nucleus. This fireball of extremely high energy-density matter rapidly expands and cools, finally decaying into numerous observable particles. A popular version of the phase
Fig. 1. Phase diagram of strongly interacting matter in the temperature $T$ and baryon chemical potential $\mu_B$ plane with regions covered by running and planned experiments.

The lower boundary of the grey and blue shaded area follows the chemical freeze-out line. The upper boundary indicates the conditions at the early stage of the collisions. The potential critical end point is labeled with CP, the onset of deconfinement with OD. The black line at small temperatures and high densities corresponds to the nuclear liquid-gas transition, also ending in a critical end point CP. The temperature-density regions covered by LHC, LHC-FT and SPS experiments are indicated with the shaded green, grey and blue areas, respectively. The density ranges of other present and future experiments (RHIC at BNL, NICA at JINR, SIS100 at FAIR, J-PARC-HI at J-PARC, the Nuclotron at JINR (NUCL), and HIAF at HIRFL) are indicated in the bar below the figure.
diagram of strongly interacting matter is presented in Fig. 1 showing regions covered by running and planned experiments. Rich experimental results on central Pb+Pb and Au+Au collisions from experiments at the Alternating Gradient Synchrotron (BNL), the Super Proton Synchrotron (CERN), the Relativistic Heavy Ion Collider (BNL) and the Large Hadron Collider (CERN) lead to two main observations:

(i) The data from the lowest to the highest collision energies indicate that a system of strongly interacting particles close to, at least local, equilibrium is created. At freeze-out, the system occupies a volume which is much larger than the volume of an individual hadron. These findings are based on the success of statistical and hydrodynamical models. Thus, one concludes that strongly interacting matter is created in heavy-ion collisions.

(ii) The ratio of strangeness production to entropy (experimentally determined from the ratio of $K^+$ to $\pi^+$ production rates) and the matter transverse flow (experimentally deduced from the inverse slope parameter $T$ of the spectra of the transverse mass $m_T$ at mid-rapidity) rapidly change their dependence on collision energy in a common, narrow energy interval, $\sqrt{s_{NN}} \approx 7-12$ GeV \(^4-6\) ($\sqrt{s_{NN}}$ is collision energy per nucleon pair in the centre of mass system). This behaviour indicates the beginning of the creation of a quark-gluon plasma with increasing collision energy. It is referred to as the onset of deconfinement. Models which do not assume the onset of deconfinement cannot reproduce the data, for a review see Ref. \(^6\).

Proton-proton interactions played a special role in these two discoveries. It was commonly assumed that neither of the two effects is present in these interactions and thus experimental results on
p+p interactions served as an important reference with respect to which new physics in heavy-ion collisions was searched for. Strong, qualitative deviations of data on heavy-ion collisions from the p+p reference as well as the agreement of measurements in heavy-ion collisions with predictions of models assuming the creation of strongly interacting matter and its transition to a quark-gluon plasma at intermediate SPS collision energies are convincing arguments for the two discoveries. The most popular models of p+p interactions are qualitatively different from the most popular models of heavy-ion collisions. The former are resonance-string models in which the hydrodynamic expansion of the strongly interacting matter created in 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 replaced 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 $p_T$. 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 follow a pattern predicted by statistical models and transverse mass spectra at low and intermediate $p_T$ are close to expectations from the statistical approach. Moreover, recent LHC data on the azimuthal angle distribution of charged particles in high multiplicity p+p interactions show anisotropies up to now observed only in heavy-ion collisions and attributed to the hydrodynamical expansion of matter. Also enhanced strange particle production in high-
multiplicity p+p events was observed and particle ratios are close to the predictions of statistical models. This suggests that the first discovery of heavy-ion physics - the creation of strongly interacting matter - may also extend to those p+p interactions at LHC energies which produce sufficiently high particle multiplicity.

This paper addresses the relation between the second discovery of heavy-ion physics - the discovery of the onset of deconfinement - and related features in p+p interactions. New experimental insight is possible thanks to recent results on p+p interactions from NA61/SHINE at the CERN SPS. The measurements cover the energy range in which experimental effects attributed to the onset of deconfinement in heavy-ion collisions are located. 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 new p+p data uncover qualitative similarities between the collision energy dependence measured for p+p interactions and for heavy-ion collisions. At the same time, qualitative differences between the p+p and heavy-ion results observed previously are confirmed with higher precision and significance by the NA61/SHINE p+p measurements.

The recent NA61/SHINE measurements of spectra of $\pi^\pm$, $K^\pm$, p and $\bar{p}$ produced in p+p interactions allow to significantly extend and improve the world data on the $K^+/\pi^+$ ratio and the inverse slope parameter $T$ of transverse mass spectra of kaons.

The energy dependence of the $K^+/\pi^+$ ratio at mid-rapidity and in the full phase-space for inelastic p+p interactions is shown in Fig. 2 top-left and top-right, respectively. The results for
heavy-ion collisions are plotted for comparison. The new NA61/SHINE measurements in p+p interactions at CERN SPS energies are shown together with the world data \cite{17,18,20–22}. 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 $K^+/\pi^+$ 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 $K^+/\pi^+$ ratio at SPS energies was shown to be a good measure of the strangeness to entropy ratio \cite{6} which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons). The collision energy dependence of the $K^+/\pi^+$ ratio in inelastic p+p interactions is different from the one in heavy-ion collisions. 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 suppression factor decreases with increasing energy, at LHC it is only about 0.9. 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.

The energy dependence of the inverse slope parameter of transverse mass spectra of $K^+$ and $K^-$ mesons produced at mid-rapidity in inelastic p+p interactions is presented in Fig. 2 bottom-left.
Fig. 2. Energy dependence of the $K^+ / \pi^+$ ratio in inelastic p+p interactions as well as central Pb+Pb and Au+Au collisions at mid-rapidity (top-left) and in the full phase-space (top-right). Energy dependence of 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 compared with the world data on p+p interactions as well as central Pb+Pb and Au+Au collisions$^{19, 21, 23, 24}$. Shaded bands show the systematic uncertainty.
and bottom-right, respectively. The NA61/SHINE results\textsuperscript{15} are compared to the world data for p+p and heavy-ion collisions\textsuperscript{19,20,22,23}. 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 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 collision energy dependence of the $T$ parameter in inelastic p+p interactions is surprisingly 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. It seems that the plateau region is broader in p+p interactions than in central heavy-ion collisions.

In Fig. 3 the results on p+p interactions presented in Fig. 2 are compared with predictions of a resonance-string model, UrQMD\textsuperscript{25}. This model includes a sharp transition between particle production by resonance formation at low energies and string formation at high energies\textsuperscript{26}. The model does not reproduce the collision energy dependence of the $K^+/$\pi$^+$ ratio. The threshold behaviour of the inverse slope parameter of transverse mass spectra of charged kaons is qualitatively described but the model fails to reproduce the increase of $T$ above the SPS energy region. To estimate the transition energy between a fast rise at low energies and a 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 transition energy is $8.3 \pm 0.6$ GeV, $7.70 \pm 0.14$ GeV, $6.5 \pm 0.5$ GeV and $7.9 \pm 0.2$ GeV, for the $K^+/$\pi$^+$, $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratios
Fig. 3. Energy dependence of the $K^+/\pi^+$ ratio in inelastic p+p interactions at mid-rapidity (top-left) and in the full phase-space (top-right). Energy dependence of the inverse slope parameter $T$ of transverse mass spectra at mid-rapidity for $K^-$ (bottom-left) and $K^+$ (bottom-right) mesons.

The experimental results are compared with predictions of the resonance-string model, UrQMD$^{25}$, and fitted by two straight lines. Only statistical uncertainties are shown.
and \( T(K^-), T(K^+) \), respectively. These values are close to each other and close to the energy of the onset of deconfinement, \( \approx 8 \text{ GeV} \), established by the results from central Pb+Pb collisions (see Fig. 2).

The similarity of the UrQMD model results and the measurements at low collision energies suggest that the step is likely due to a transition from a resonance dominated to a string dominated particle production mechanism. Thus the step may not be a unique feature of the onset of deconfinement although, of course, it is consistent with it.

The presented results from inelastic p+p interactions are puzzling. The unexpected qualitative similarity of the collision energy dependence of the \( T \) parameter in p+p interactions and heavy-ion collisions uncovered in this paper suggests that this feature may not be a unique signature of the onset of deconfinement, or alternatively, effects related to the onset of deconfinement are present in p+p interactions at the CERN SPS energies. This asks for a unified approach in which both reactions could be interpreted. Such an approach would make it possible to clarify whether the onset of deconfinement is, or is not, a universal feature of both small and large colliding systems. There are already attempts of common modelling of p+p interactions and heavy ion collisions. In particular, a unified description of the Regge limit (p+p) and Color Glass Condensate mechanism (A+A) is considered.

In summary, new results of NA61/SHINE on the collision energy dependence of the \( K^+/\pi^+ \) 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 similarities between the collision energy dependence in p+p interactions and central heavy ion collisions, namely a rapid change in the same energy range.

Clearly, understanding particle production in inelastic p+p interactions, and, in general in collisions of small atomic nuclei, is one of the key objectives of heavy-ion physics today.

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15. Aduszkiewicz, A. *et al.* Measurements of $\pi^\pm$, $K^\pm$, p and $\bar{p}$ spectra in proton-proton interactions at 20, 31, 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS. *European Physical Journal C* 77, 671 (2017). 1705.02467.


The NA61/SHINE coordinate system is shown on the bottom, left. The nominal beam direction is along the \( z \) axis. The magnetic field bends charged particle trajectories in the \( x-z \) plane. The electron drift direction in the TPCs is along the \( y \) (vertical) axis.

1 Methods

NA61/SHINE is a fixed target experiment employing a large acceptance hadron spectrometer situated in the North Area H2 beam-line of the CERN SPS. A schematic layout is shown in Fig. 4. A detailed description of the NA61/SHINE detector and of its performance can be found in Ref. 29. Here only the detector components necessary for this analysis are briefly presented. The main tracking detectors are four large volume Time Projection Chambers (TPC). Two of them, called Vertex TPCs (VTPC), are located downstream of the target inside superconducting magnets with maximum combined bending power of 9 Tm. The Main Time Projection Chambers (MTPCs) and
two walls of pixel Time-of-Flight (ToF-L/R) detectors are placed symmetrically to the beam line downstream of the magnets. A GAP-TPC (GTPC) between VTPC-1 and VTPC-2 improves the acceptance for high-momentum forward-going tracks. Individual beam particles are identified and precisely measured by a set of scintillation and Cherenkov counters, as well as three beam position detectors (BPDs) placed upstream of the target. Secondary beams of positively charged hadrons at momenta of 20, 31, 40, 80 and 158 GeV/c were used to collect the data for the analysis presented in this paper. Secondary protons are selected by Cherenkov counters with a purity of about 99%.

A Liquid Hydrogen Target (LHT) of 20.29 cm length (2.8% interaction length) and 3 cm diameter was placed 88.4 cm upstream of VTPC-1. Data were taken with full and empty LHT. Interactions in the target are selected with the trigger system by requiring an incoming beam proton and no signal from S4, a small 2 cm diameter scintillation counter placed on the beam trajectory between the two vertex magnets. The final results refer to identified hadrons produced in inelastic p+p interactions by strong interaction processes and in electromagnetic decays of produced hadrons. Such hadrons are referred to as primary hadrons. The analysis was performed independently in \((y, p_T)\) bins. The bin sizes were selected taking into account the statistical uncertainties and the resolution of the momentum reconstruction. Corrections as well as statistical and systematic uncertainties were calculated for each bin.

Charged particle statistical identification in the NA61/SHINE experiment is based on the measurement of the ionization energy loss \(dE/dx\) in the gas of the TPCs and of the time of flight \(t_{of}\) obtained from the ToF-L and ToF-R walls. In the region of the relativistic rise of the ionization at large momenta the measurement of \(dE/dx\) alone allows identification. At lower momenta the \(dE/dx\)
bands for different particle species overlap and additional measurement of $t_{of}$ is required. These two methods allow to cover most of the phase space in rapidity and transverse momentum which is of interest for the strong interaction program of NA61/SHINE. In order to determine the true number of each type of identified particle produced in inelastic $p+p$ interactions a set of corrections was applied to the extracted raw results. The main effects for which corrections were introduced are the following: contribution of interactions outside the liquid hydrogen of the target (off-target events), detector effects (acceptance, efficiency) and particles from weak decays (feed-down). Note that the manner of application and the number of used correction factors depend on the particle identification technique (i.e. $dE/dx$ or $t_{of}$-$dE/dx$)

Final results where presented as two dimensional distributions normalised per event ($y$ vs. $p_T$) produced in inelastic $p+p$ interactions at different SPS energies.

Transverse momentum spectra were parametrized by the exponential function $^{31,32}$:

$$\frac{d^2n}{dp_T dy} = \frac{S c^2 p_T}{T^2 + m T} \exp\left(-\frac{(m_T - m)}{T}\right),$$

(1)

where $m$ is the particle mass and $S$ and $T$ are the yield integral and the inverse slope parameter, respectively. The obtained values of the inverse slope parameter $T$ as well as the yield integral $S$ for $K^+$ and $\pi^+$ at mid-rapidity are used in Fig. 2 and Fig. 3.

Next, mean multiplicities produced in the forward region $y > 0$ were calculated by integrating the rapidity distributions. The distributions of $K^+$ and $\pi^+$ are seen to be nearly Gaussian. In order to obtain a more precise description of the data, the rapidity spectra were parametrised by the sum
of two Gaussian functions symmetrically displaced with respect to mid-rapidity. The total mean multiplicity was calculated as the sum of measured and a contribution from the unmeasured region obtained from the fit function ($<K^+>$ and $<\pi^+>$).

Details of the calculation of statistical and systematic uncertainties can be found in Ref. 15.