The SPS ion program and the first LHC data

Marek Gazdzicki

Goethe University Frankfurt, Germany and Jan Kochanowski University, Kielce, Poland

Abstract. For the first time in the CERN history two experimental programs devoted to study nucleus-nucleus collisions at high energies are performed in parallel. In the SPS ion program, carried out by NA61/SHINE, interactions of light and medium size ions in the energy range \( \sqrt{s_{NN}} = 5-20 \) GeV are investigated. The program aims to discover the critical point of strongly interacting matter as well as establish properties of the onset of deconfinement. In 2010 ALICE, ATLAS and CMS at LHC recorded first data on Pb+Pb collisions at the highest energy reached up to now, \( \sqrt{s_{NN}} = 2760 \) GeV. This opens a new exciting area in the field of heavy ion collisions. The relation between the two programs is discussed in this presentation. Surprisingly, the first LHC results strongly support the NA49 discovery of the onset of deconfinement and thus further experimental study of nucleus-nucleus collisions at the CERN SPS.

Keywords: heavy ion collisions, onset of deconfinement, critical point

PACS: 25.75.-q, 25.75.Ag, 25.75.Nq

INTRODUCTION

Experimental studies of nucleus-nucleus (A+A) collisions started at the Super Proton Synchrotron (SPS) of the European Organization for Nuclear Research (CERN) in the mid 1980s. They were motivated by the possibility to discover a new state of matter, the quark-gluon plasma (QGP). Firstly, beams of oxygen and sulfur at 60A and 200A GeV/c were available. Then, starting from the mid 1990s the lead beam at 158A GeV/c was used. These pioneering studies suggested that matter of unusual properties is created at the early stage of A+A collisions at the top SPS energy [1]. Unambiguous evidence of the QGP was, however, missing. This should be attributed to the difficulty of obtaining unique predictions of the QGP signals from the theory of strong interactions, the QCD.

For this reason, at the end of 1990, the NA49 Collaboration at the CERN SPS started systematic search for the signals of the onset of QGP creation. This search was motivated by a statistical model of the early stage of A+A collisions [2] predicting that the onset of deconfinement should lead to rapid changes of the collision energy dependence of bulk properties of produced hadrons, all appearing in a common energy domain. Data on central Pb+Pb collisions at 20A, 30A, 40A, 80A and 158A were recorded and the predicted features were observed at low SPS energies [3, 4].

The NA49 evidence for the onset of deconfinement motivates the ion program of NA61/SHINE [5] at the CERN SPS, as well as the beam energy scan at BNL RHIC and the construction of the NICA ion collider at JINR, Dubna. The basic goals of this experimental effort are the study of the properties of the onset of deconfinement and the search for the critical point of strongly interacting matter [5]. Both relay on the correctness of the NA49 results and their interpretation.

Up to recently, the evidence for the onset of deconfinement was based on data of a
single experiment, NA49 at the CERN SPS. Thus, an independent verification of the relevant NA49 measurements is important. Furthermore, it is very crucial to confirm the interpretation of the NA49 results in terms of the onset of deconfinement, firstly, for confirming the discovery of the onset of deconfinement and, secondly, to strengthen arguments for the NA61/SHINE and other experimental programs with high energy ion beams.

This year rich data from the RHIC beam energy scan program were released [6]. They agree with the NA49 measurements relevant for the onset of deconfinement. Furthermore, the first results on Pb+Pb collisions at the CERN LHC were presented [7]. The latter strongly confirm the interpretation of the NA49 results as an observation of the onset of deconfinement. This contribution summarizes the status of the evidence for the onset of deconfinement including the new LHC and RHIC results.

**STATUS OF THE EVIDENCE FOR THE ONSET OF DECONFINEMENT**

The NA49 evidence for the onset of deconfinement [3, 4] is based on the observation that numerous hadron production properties measured in central Pb+Pb collisions change their energy dependence in a common energy domain (starting from $\sqrt{s_{NN}} \approx 7.6$ GeV ($\approx 30A$ GeV/c beam momentum)) and that these changes are consistent with the predictions for the onset of deconfinement [2]. The four representative plots with the structures referred to as horn, kink, step and dale [4] are shown in Fig. 1. They present the experimental results available in the mid of 2010.

The relation between the horn, kink, step and dale structures and the onset of deconfinement is briefly discussed below. More detailed explanation is given in Ref. [4], where a comparison with quantitative models is also presented.

*The horn.* The most dramatic change of the energy dependence is seen for the ratio of particle yields of kaons and pions, Fig. 1 (top-left). The steep threshold rise of the ratio characteristic for confined matter changes at high energy into a constant value at the level expected for deconfined matter. In the transition region (at low SPS energies) a sharp maximum is observed caused by the higher strangeness to entropy production ratio in confined matter than in deconfined matter. This feature is not observed for proton–proton reactions as shown by the open dots in Fig. 1 (top-left).

*The kink.* The majority of all particles produced in high energy interactions are pions. Thus, pions carry basic information on the entropy created in the collisions. On the other hand, entropy production should depend on the form of matter present at the early stage of collisions. Deconfined matter is expected to lead to a final state with higher entropy than that created by confined matter. Consequently, the entropy increase at the onset of deconfinement is expected to lead to a steeper increase of the collision energy dependence of the pion yield per participating nucleon. This effect is observed for central Pb+Pb collisions as shown in Fig. 1 (top-right). When passing the low SPS energies the slope of the $\langle \pi \rangle / \langle N_p \rangle$ vs $F \approx \sqrt{s_{NN}}$ dependence increases by a factor of about 1.3. Within the statistical model of the early stage [2] this corresponds to an increase of the effective number of degrees of freedom by a factor of about 3.
FIGURE 1. Heating curves of strongly interacting matter, status at the mid of 2010. Hadron production properties (see Ref. [4] for details) are plotted as a function of collision energy ($\sqrt{s_{NN}}$ and $F \approx \sqrt{s_{NN}}$) for central Pb+Pb (Au+Au) collisions and p+p interactions (open circles): top-left – the $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratio, top-right – the mean pion multiplicity per participant nucleon, bottom-left – the inverse slope parameter of the transverse mass spectra of $K^+$ mesons, bottom-right: the width of the $\pi^-$ rapidity spectra relative to predictions of the Landau ideal hydrodynamics. The observed changes of the energy dependence for central Pb+Pb (Au+Au) collisions are related to: decrease of the mass of strangeness carriers and the ratio of strange to non-strange degrees of freedom (horn: top-left plot), increase of entropy production (kink: top-right plot), weakening of transverse (step: bottom-left plot) and longitudinal (dale: bottom-right plot) expansion at the onset of deconfinement.

The step. The experimental results on the energy dependence of the inverse slope parameter, $T$, of $K^+$ and $K^-$ transverse mass spectra for central Pb+Pb (Au+Au) collisions are shown in Fig. 1 (bottom-left). The striking features of the data can be summarized and interpreted [8] as follows. The $T$ parameter increases strongly with collision energy up to the low SPS energies, where the creation of confined matter at the early stage of the collisions takes place. In a pure phase increasing collision energy leads to an increase of the early stage temperature and pressure. Consequently the transverse momenta of pro-
duced hadrons, measured by the inverse slope parameter, increase with collision energy. This rise is followed by a region of approximately constant value of the $T$ parameter in the SPS energy range, where the transition between confined and deconfined matter with the creation of mixed phases is located. The resulting softening of the equation of state, EoS, ‘suppresses’ the hydrodynamical transverse expansion and leads to the observed plateau structure in the energy dependence of the $T$ parameter [8]. At higher energies (RHIC data), $T$ again increases with the collision energy. The EoS at the early stage becomes again stiff and the early stage pressure increases with collision energy, resulting in a resumed increase of $T$.

**The dale.** As discussed above, the weakening of the transverse expansion is expected due to the onset of deconfinement because of the softening of the EoS at the early stage. Clearly the latter should also weaken the longitudinal expansion. This expectation is checked in Fig. 1 (bottom-right), where the width of the $\pi^-$ rapidity spectra in central Pb+Pb collisions relative to predictions of the Landau ideal hydrodynamics is plotted as a function of the collision energy. In fact, the ratio has a clear minimum at low SPS energies.

In 2011 new results on central Pb+Pb collisions at the LHC and data on central Au+Au collisions from the RHIC beam energy scan program were released. The updated plots [9] are shown in Fig. 2. The RHIC results [6] agree with the NA49 measurements at the onset energies.

The LHC data [7] demonstrate that the energy dependence of hadron production properties shows rapid changes only at low SPS energies. A smooth evolution is observed between the top SPS (17.2 GeV) and the current LHC (2.76 TeV) energies. This strongly supports the interpretation of the NA49 structures as due to the onset of deconfinement. Above the onset energy only a smooth change of the quark-gluon plasma properties with increasing collision energy is expected. Consequently, in agreement with the first LHC data, one expects:

- an approximate independence of the $K^+/\pi^+$ ratio of energy above the the top SPS energy, Fig. 2 (top-left),
- a linear increase of the pion yield per participant with $F$ with the slope defined by the top SPS data, Fig. 2 (top-right),
- a monotonic increase of the kaon inverse slope parameter with energy above the top SPS energy, Fig. 2 (bottom).

The width of the $\pi^-$ rapidity spectra in central Pb+Pb collisions relative to predictions of the Landau ideal hydrodynamics should continuously increase from the top SPS to LHC energies. The LHC data on rapidity spectra are needed to verify this expectation.

The confirmation of the relevant NA49 measurements and their interpretation in terms of the onset of deconfinement by the new LHC and RHIC data strengthen the arguments for the planned [5] NA61/SHINE measurements with secondary Be and primary Ar as well as Xe beams in the SPS beam momentum range (13A-158A GeV/c).
FIGURE 2. Heating curves of strongly interacting matter: status at the mid of 2011. For more details see Ref. [4] and the caption of Fig. 1. The new LHC and RHIC data are included in the horn (top-left), kink (top-right) and step (bottom) plots. The $K^+/\pi^+$ ratio is measured by ALICE [7] and STAR [6] at mid-rapidity only and thus the horn plot is shown here for the mid-rapidity data. There are no new results for the dale plot.

ACKNOWLEDGMENTS

I would like to thank the organizers of the workshop on Early Physics with heavy–Ions at LHC in Bari for their kind invitation to this stimulating and pleasant event. This work was supported by the German Research Foundation under grant GA 1480/2-1.

REFERENCES

1. U. W. Heinz, M. Jacob, [nucl-th/0002042].
2. M. Gazdzicki, M. I. Gorenstein, Acta Phys. Polon. B30, 2705 (1999), [hep-ph/9803462].
3. C. Alt et al. [NA49 Collaboration], Phys. Rev. C 77, 024903 (2008) [arXiv:0710.0118 [nucl-ex]].
4. M. Gazdzicki, M. Gorenstein, P. Seyboth, Acta Phys. Polon. B42, 307 (2011) [arXiv:1006.1765 [hep-ph]].
5. N. Antoniou et al. [NA61/SHINE Collaboration], CERN-SPSC-2006-034.
6. L. Kumar [for the STAR Collaboration], arXiv:1106.6071 [nucl-ex].
   B. Mohanty [STAR Collaboration], arXiv:1106.5902 [nucl-ex].
7. J. Schukraft et al. [for the ALICE Collaboration], arXiv:1106.5620 [hep-ex],
   A. Toia et al. [for the ALICE Collaboration], arXiv:1107.1973 [nucl-ex].
8. M. I. Gorenstein, M. Gazdzicki and K. A. Bugaev, Phys. Lett. B 567, 175 (2003) [arXiv:hep-ph/0303041].
9. A. Rustamov, https://indico.cern.ch/conferenceDisplay.py?confId=144745