STUDY OF THE ONSET OF DECONFINEMENT AND SEARCH FOR THE CRITICAL POINT OF STRONGLY INTERACTING MATTER AT THE CERN SPS*

Peter Seyboth

Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
and
Jan Kochanowski University, Żeromskiego 5, 25-369 Kielce, Poland

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Collisions of lead nuclei have been studied at the CERN SPS since 1994. A review is presented of the evidence for the production of deconfined matter, the location of the energy of the onset of deconfinement and the search for the critical point of strongly interacting matter.

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1. Introduction

The success of the quark model of hadrons and the discovery of point-like partons in nucleons and scaling of the cross sections in deep-inelastic scattering experiments led to the development of quantum chromodynamics QCD. Ordinary hadron matter is composed of hadrons in which the constituent quarks and gluons are confined. It was soon conjectured that at high temperature and/or pressure hadrons would dissolve into quasi-free quarks and gluons [1] the quark-gluon plasma (QGP). The development of QCD calculations on the lattice then allowed to explore the non-perturbative aspects of the theory, namely the phase diagram of strongly interacting matter. As schematically shown in Fig. 1 (left), the existence region of hadrons at low temperature T and baryochemical potential μ_B is thought to be separated from the QGP phase at high T by a first order phase boundary (shaded band), which ends in a critical point E and then turns into a crossover at low μ_B. The experimental investigation of the phase diagram and of the properties of the QGP is the main purpose of the study of heavy-ion collisions.

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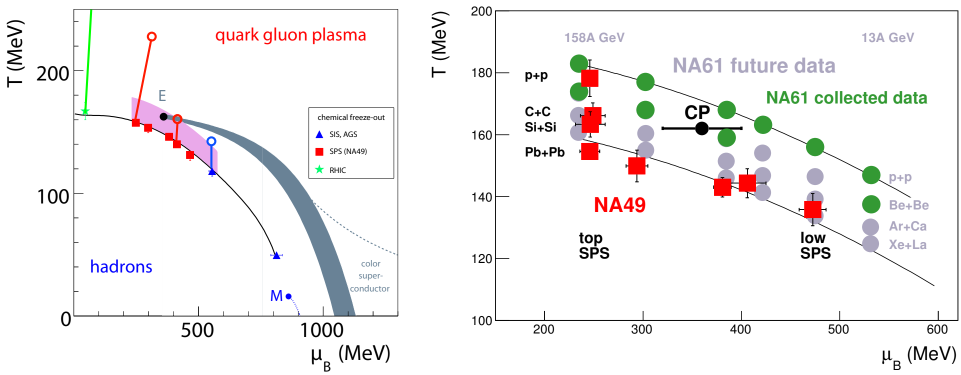

Fig. 1. Left: Phase diagram of strongly interacting matter. Locations of freezeout points of hadron composition were obtained from statistical model fits to particle yields. Right: Reactions studied by experiments NA49 (squares) and NA61 (dark grey/green dots — recorded, grey dots — planned).

Pb+Pb reactions have been investigated at the CERN SPS since 1994 by a variety of experiments in the available energy range from 158A down to 20A GeV ($\sqrt{s_{NN}}$ = 17.3–6.3 GeV). At top energy, an initial energy density of $\approx$ 3 GeV/fm^3 [2] was found, sufficient for deconfinement. Many of the predicted signatures for the QGP were observed [3], *e.g.* enhancement of strangeness production due to the smaller mass of strangeness carriers (s quark *versus* K meson), suppression of charmonium production in excess of cold nuclear matter effects due to screening of the color force, indication of photon emission from annihilation of the copious quarks and antiquarks in the QGP and strong modification of the ρ^0 meson line shape possibly connected to chiral restoration. However, none of these signatures turned out to be uniquely attributable to the QGP.

The NA49 Collaboration, therefore, proposed an energy scan (T and μ_B at freezeout increases respectively decreases with collisions energy) in order to look for a sharp change in hadron production properties which were predicted to signal the onset of deconfinement at the early stage of evolution of the collision fireball [4]. In fact, these signals were observed by NA49 [5] and their system size dependence is under study by the successor experiment NA61 [6]. The data from the energy scan also allowed to start the search for the predicted critical point CP. First tantalising hints obtained by NA49 are presently pursued by experiment NA61 [6] with a two dimensional scan of the phase diagram in nuclear size A and energy, by which the freezeout point is moved in T and μ_B (see Fig. 1 (right)). The expected signature of the CP is a maximum of fluctuations in the produced final state when freezeout occurs close to the CP location [7].

2. Onset of deconfinement

The results discussed in this section were mostly obtained by NA49 which was the only experiment to participate in the entire energy scan at the SPS (1999–2002). Measurements are thus restricted to charged hadrons detected in the large acceptance NA49 apparatus [8] consisting of time projection chambers (TPC) as the principal detectors. Results (see Ref. [5]) are compared to statistical model predictions and to interpretations of the data, in particular, to those of the SMES model [4] which motivated the SPS energy scan.

As seen in Fig. 2 (left), the pion yield per wounded nucleon starts to increase faster in central Pb+Pb and Au+Au collisions than in $p + p(\bar{p})$ reactions at the low end of the SPS energy range. Pion production is a measure of entropy production and the steepening of slope indicates a 3-fold increase of the initial degrees of freedom as expected for deconfinement. Figure 2 displays the energy dependence of the ratio of strangeness to pion yields which is given to good accuracy by $E_{\rm s} = (\langle K \rangle + \langle \Lambda \rangle)/\langle \pi \rangle$ at SPS energies. One observes a threshold rise to a sharp peak (the horn) and a decrease to a plateau value. In the SMES, these features were predicted as arising from the increase of temperature in the hadron phase, the onset of deconfinement at the peak and full initial transition of the fireball to the QGP phase (plateau with predicted height).

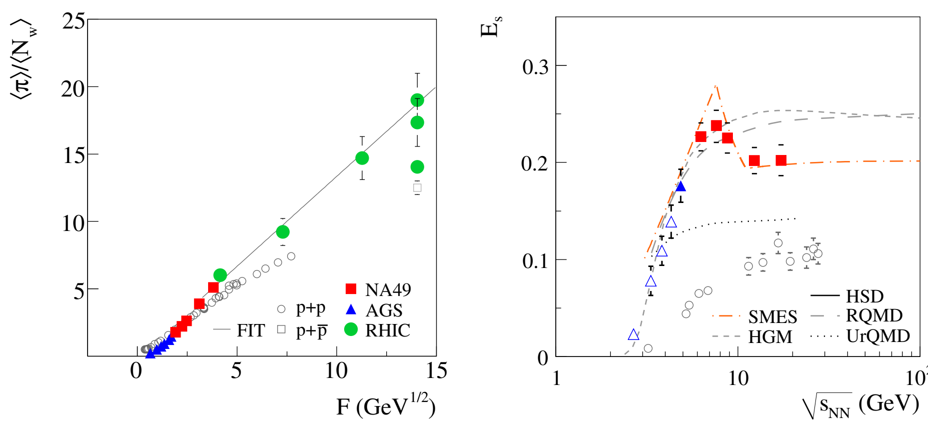

Fig. 2. Left: Mean pion multiplicity $\langle \pi \rangle$ per wounded nucleon $\langle N_W \rangle$ measured in central Pb+Pb and Au+Au collisions (full symbols) and $p(\bar{p}) + p$ collisions (open symbols) *versus* Fermi energy variable $F \approx s_{NN}^{0.25}$. Right: Ratio $E_{\rm s}$ (see the text) *versus* collision energy $\sqrt{s_{NN}}$ compared to model calculations.

Onset of deconfinement is expected to be accompanied by a soft region of the equation of state EoS [9] leading to observable structures in the energy dependence of transverse and longitudinal particle spectra. After a threshold rise, a stationary value (step) is found in the SPS region for the inverse slope parameter T for K^+ (see Fig. 3 (left)). T characterises the temperature and the pressure induced transverse flow in the produced fireball [10]. Similar behaviour is observed for K^- mesons, π mesons and protons. The sound velocity c_s in the fireball can be deduced from the width of the rapidity distribution of pions [11]. The results, plotted in Fig. 3 (right), show a minimum at SPS energies as expected for a soft mixed phase at the onset of deconfinement.

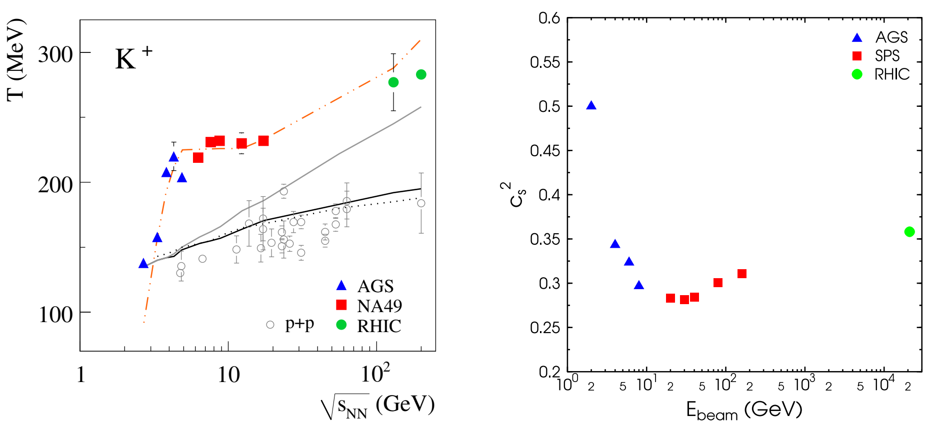

Fig. 3. Left: Inverse slope parameter T of K^+ transverse mass spectra compared to model calculations. Filled (open) symbols show results from central Pb+Pb and Au+Au ($p+p$) collisions. Right: Velocity of sound c_s derived from the width of pion rapidity spectra.

The discussed features, observed in central Pb+Pb and Au+Au collisions, are only explained by models which incorporate a phase transition for energies above about 30A GeV (see dash-dotted curves in Figs. 2, 3). Thus the most natural explanation of the hadron production measurements is the onset of deconfinement at low SPS energies [12]. Recent results of STAR from the RHIC low energy scan confirm the horn and step structures found by NA49 and measurements of ALICE at the LHC agree with the expected trends towards highest energy (see Fig. 4).

Crossing of a phase transition during the evolution of the produced particle system may lead to a modification of event-by-event fluctuations of various quantities. In particular, the different ratio of strange to non-strange degrees of freedom in hadron matter and QGP might give rise to fluctuations of the K/π ratio (Fig. 5 (left)) near the onset of deconfinement [13]. A rise towards lowest SPS energy is observed [14], but it is well described by generic multiplicity scaling [15] of the studied observable $\sigma_{\rm dyn}$ assuming constant intrinsic correlations. While the same conclusion holds for the p/π ratio, there is a sign change for the fluctuations of K/p. This indicates a

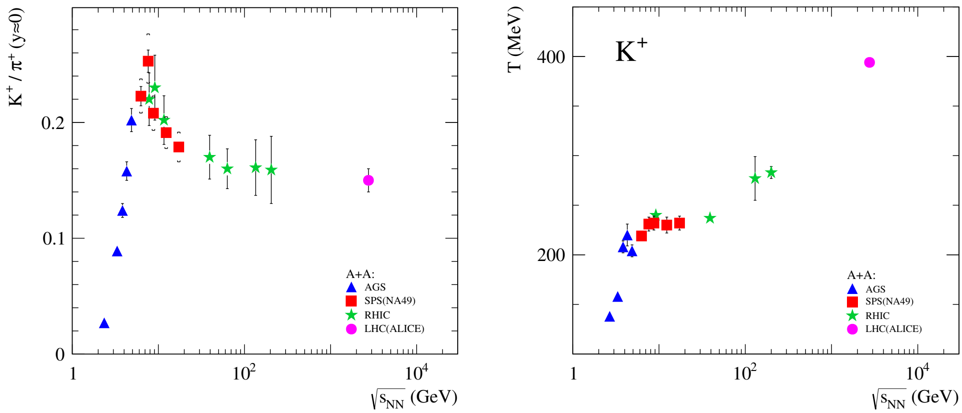

Fig. 4. Left: Yield ratio K^+/π^+ at midrapidity. Right: Inverse slope parameter T of K^+ transverse mass spectra. Plotted data on central Pb+Pb and Au+Au collisions are from E802 at AGS (triangles), NA49 at SPS (squares), STAR at RHIC (stars) and ALICE at LHC (dot).

qualitative change of correlations between baryons and strange particles [16]. Recent measurements of the related measure $\nu_{\rm dyn}$ by STAR [17] did not show any energy dependence. This difference has now been traced to the different phase space acceptance region covered by NA49 and STAR [18].

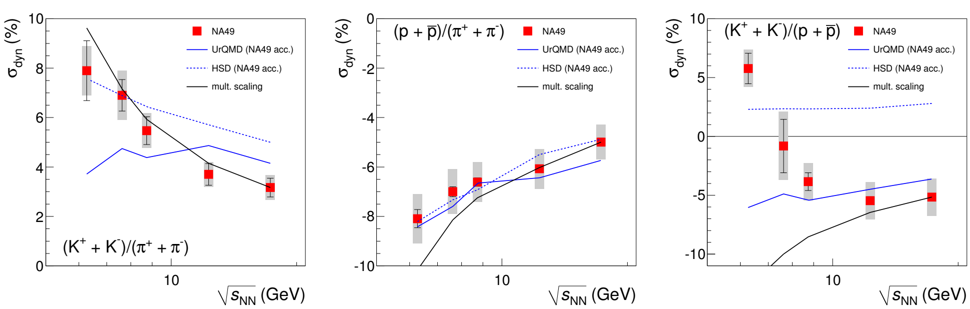

Fig. 5. Event-by-event fluctuations of particle ratios K/π (left), p/π (center) and K/p (right) *versus* collision energy in central Pb+Pb collisions [14] expressed in terms of the observable $\sigma_{\rm dyn}$. Curves show comparisons to a multiplicity scaling model [15], and microscopic models UrQMD and HSD.

The smaller charge of quarks in the QGP compared to hadrons was expected to reduce fluctuations of the net charge observed in not too large regions of phase space [19]. The effect has not been confirmed by measurements [20] and is believed to be erased by the hadronisation process. In the case of a phase transition, the evolution time of the fireball until freezeout is expected to increase and become manifest in a widening of the charge balance function [21]. Although such behaviour was found for Pb+Pb reactions at the highest SPS energy for increasingly central collisions [22], the effect may also be caused by increasing radial flow and local charge conservation.

3. Search for the critical point of strongly interacting matter

Lattice QCD calculations for finite μ_B are difficult and are still under development. Nevertheless, several groups obtained quantitative estimates [23] placing the CP in the region of the phase diagram which is accessible at SPS energies. If the evolution trajectory of the fireball passes close enough to the critical point enhanced fluctuations from event to event are predicted [7]. The size of such fluctuations is limited by the lifetime and the size of the fireball (correlation length less than 3–6 fm in central Pb+Pb collisions) and they may be erased by rescattering processes in the late hadron stage. In spite of such caveats, an intense search for the CP and its fluctuation signatures in *e.g.* average transverse momentum $\langle p_{\mathrm{T}} \rangle$, multiplicities and local density fluctuations is in progress.

Measurements were performed for the energy scan of central Pb+Pb collisions as well as for central C+C, Si+Si and inelastic $p + p$ reactions at highest SPS energy of $158A$ GeV. Results are plotted in Fig. 6 as a function of the phase diagram variables T and μ_B of the fireball freezeout as obtained from statistical model fits to the hadron type composition [25]. The fluctuation measures $\Phi_{p_{\mathrm{T}}}$, ω and Φ_ϕ vary smoothly with μ_B (top row in Fig. 6). However, there is an indication of a maximum in T for the lighter collision systems (see bottom row in Fig. 6). Curves show estimates of the possible effect of a CP [24, 26].

Another promising search strategy for the CP is the study of local density fluctuations of low-mass $\pi^+\pi^-$ pairs and protons produced near midrapidity. Theoretical investigations [27] expect power law fluctuations near the CP, which can be studied by the intermittency analysis method in transverse momentum space using scaled factorial moments $F_n(M)$, where M is the number of subdivisions in each p_{T} direction. The power law exponents from fits of the form $F_2(M) \propto M^{2\Phi_2}$ can be predicted and should be approached near the CP. In the experimental analysis, fits are applied to $\Delta F_2(M)$, the background corrected scaled factorial moment (an example with superimposed fit is shown in Fig. 7 (left)). Results for Φ_2 are plotted in Fig. 7 (center, left) for low-mass $\pi^+\pi^-$ pairs and protons, respectively. As found for the integrated fluctuation observables in the preceding paragraph, there is also an indication of a maximum and an approach to the CP prediction for the local density fluctuations in the Si+Si system. These tantalising hints need further confirmation and strongly motivate the more precise and systematic studies under way in NA61.

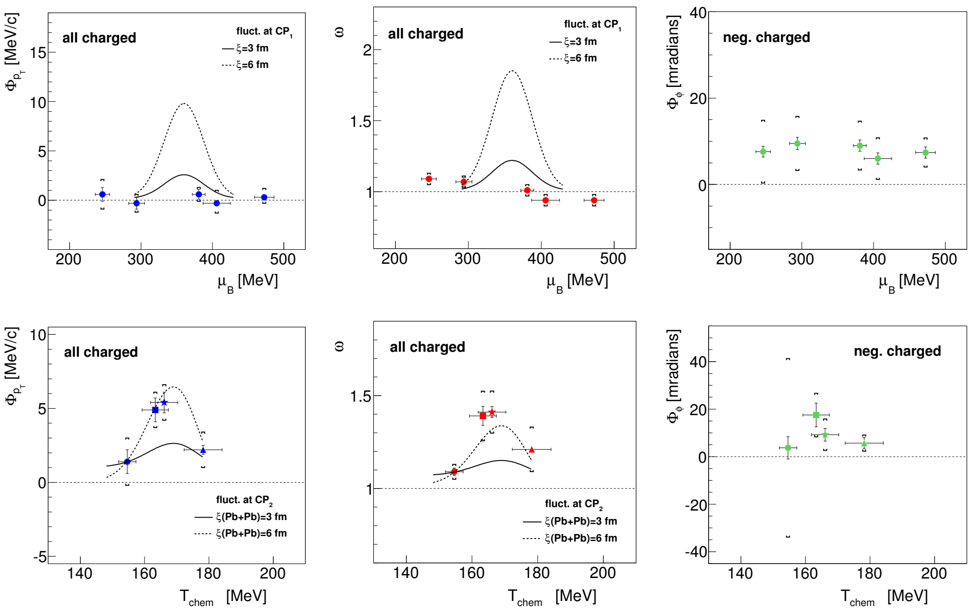

Fig. 6. Fluctuation measures $\Phi_{p_{\mathrm{T}}}$ for $\langle p_{\mathrm{T}} \rangle$ (left [24]), scaled variance ω of the charged particle multiplicity distribution (center [24]) and Φ_{ϕ} for the average azimuthal angle $\langle \phi \rangle$ (right (NA49 preliminary)) *versus* baryochemical potential μ_B (top row) and temperature T (bottom row) in c.m.s. rapidity $1.1 < y < 2.6$. Values of μ_B and T were estimated from statistical model fits [25] to particle yields.

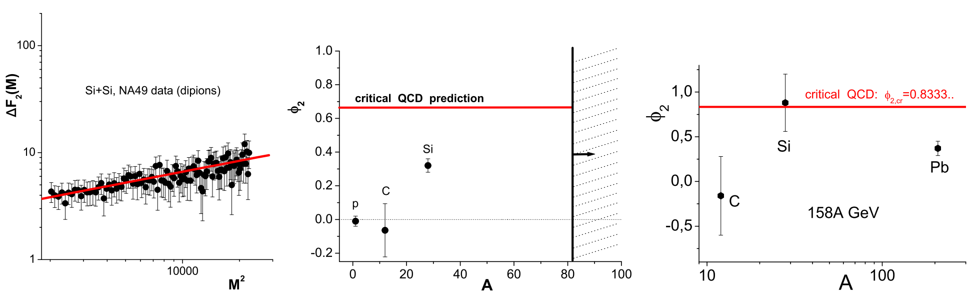

Fig. 7. Left: Background corrected scaled factorial moment ΔF_2 *versus* number of cells M^2 in transverse momentum space for central Si+Si collisions at 158A GeV [28]. Center and right: Fitted intermittency index Φ_2 for low-mass $\pi^+\pi^-$ pairs [28] and protons [29] in $p+p$ and central C+C, Si+Si and Pb+Pb collisions.

4. Conclusion

Evidence for the onset of deconfinement was found in central Pb+Pb collisions at the CERN SPS and confirmed by by the RHIC beam energy scan program. The critical point of strongly interacting matter has, so far, eluded convincing detection in collisions of heavy nuclei. The most suitable energy region for continued search is the range of the SPS energies which is being intensively studied by NA61, the beam energy scan BES at RHIC and in future also by NICA in Dubna. The ultra-high energies of the LHC, on the other hand, offer the best environment for measuring the properties of the QGP. The planned program at SIS-100 at FAIR in Darmstadt covers the lowest energy, high baryon density domain for which other exotic forms of matter are predicted.

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