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ONSET OF DECONFINEMENT AND THE CRITICAL POINT AT SPS ENERGIES*

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The NA61/SHINE experiment at the CERN SPS pursues a rich program on strong interactions, which covers the study of the onset of deconfinement and the search for the critical point. A broad region of the phase diagram of strongly interacting matter is scanned by varying the beam momentum ($13\,A$–$158\,A$ GeV/c) and the size of the colliding system (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, and Pb+Pb reactions). This paper presents a selection of NA61/SHINE results on particle production and intermittent behavior, discussed together with existing data from the NA49 Collaboration. The evolution of non-monotonic structures in pion and strangeness production as a function of system size and energy is addressed in detail. The change of hadron production properties from p+p up to Pb+Pb collisions can be interpreted as the beginning of the formation of large clusters of strongly interacting matter (the onset of fireball). The intermittency signal gives an indication for a possible critical behavior in the Si+Si system at top SPS energy but none in Be+Be reactions. Additionally, the potential of large acceptance NA61/SHINE measurements for investigating the longitudinal evolution of the system is discussed.

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1. Introduction

The non-perturbative nature of the strong interaction makes the exploration of the QCD phase diagram one of the most challenging tasks in theoretical physics. In this context, the NA61/SHINE experiment at the CERN SPS pursues a versatile research program, scanning the phase diagram by varying the beam momentum and the colliding system size. NA61/SHINE

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is a fixed target, large acceptance spectrometer with good particle identification and coverage in the projectile hemisphere in the collision c.m.s., with centrality of the collision selected by the energy of the projectile spectators measured in a forward calorimeter.

2. Tentative conclusions from the NA61/SHINE scan

Following the hypothesis formulated, *e.g.*, in Ref. [1], the two-dimensional scan conducted by NA61/SHINE may reveal four domains of hadron production, separated by two thresholds: the onset of deconfinement and the onset of fireball. The situation is illustrated in Fig. 1. The onset of deconfinement is well-established in central Pb+Pb reactions but questionable in p+p collisions. The onset of fireball would mark the transition from small, "non-statistical" systems into the regime of large clusters of strongly interacting matter which can be described by statistical models. Some of the experimental results which inspired these conclusions will be discussed below.

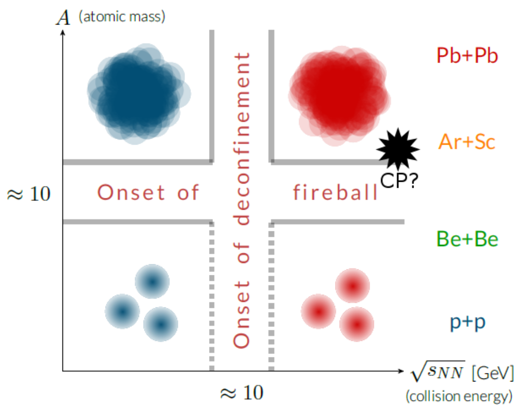

Fig. 1. Onset of deconfinement and onset of fireball as a function of collision energy and system size [1]. The position of the critical point which could be implied by NA49 and NA61/SHINE intermittency studies (see the text) is also indicated in the plot.

Figure 2 shows the energy dependence of the mid-rapidity positive kaon over pion ratio and the inverse slope T, obtained from a fit to the negative kaon $m_{\rm T}$ distribution for central heavy-ion (Pb+Pb, Au+Au) and p+p collisions. The well-known non-monotonic structure in the left panel was predicted, within the Statistical Model of the Early Stage [2], as a signature of the onset of deconfinement. Since the original publication by the NA49 Collaboration [3], the energy dependence of p+p collisions was assumed to be very different: a smooth, monotonic increase of the K^+/π^+ ratio with increasing collision energy. The new experimental data by NA61/SHINE [4] do not exclude such a trend within error bars but can, in fact, indicate a step-like behaviour reminiscent of the "horn" seen in $A+A$ reactions. On the other hand, the step-like energy dependence of the "apparent temperature" T seen for K^- marking, in analogy to melting of ice into water, the transition from confined matter to quark–gluon plasma seems to be qualitatively reproduced in $p+p$ collisions. Interestingly, it is known that high multiplicity $p+p$ events at the LHC energies exhibit properties similar to those attributed to deconfined matter in $A+A$ collisions [5]. If the latter exists also in high-energy $p+p$ reactions, then it is tempting to conclude that the structures apparent for these reactions in Fig. 2 mark their transition from a confined system, as this was the case for $A+A$ data. Notwithstanding, such a conclusion remains for now questionable due to the lack of a precise theoretical description of the notion of deconfinement for $p+p$ collisions. In addition, the present uncertainties in the experimental $p+p$ data constitute a limitation for any claims involving structures in their energy dependence.

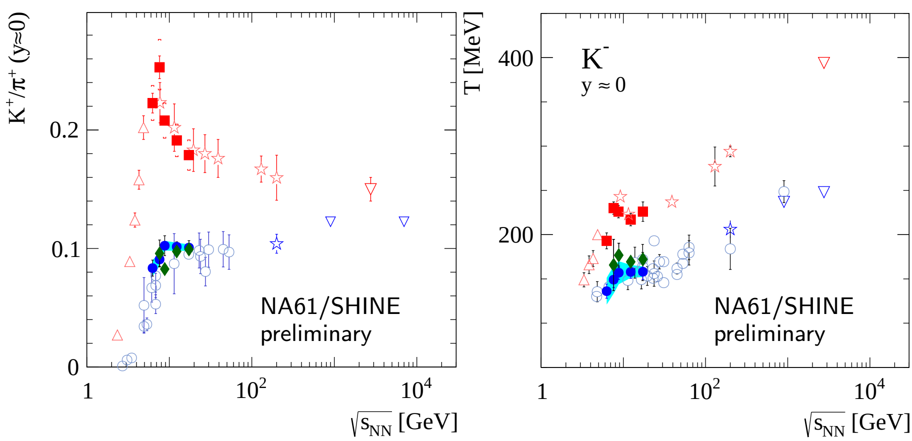

Fig. 2. (Colour on-line) Compilation of experimental data on the K^+/π^+ ratio (left) and inverse slope parameter T for K^- (right) in Pb+Pb and Au+Au (red, top data points), Be+Be (green diamonds) and $p+p$ (blue, bottom data points) reactions. The closed symbols mark NA49 and NA61/SHINE data, while the open symbols indicate all other "world" data (see Ref. [4] for a detailed reference list).

The vertical direction of Fig. 1 is illustrated by Fig. 3 (a), which shows the system size dependence of the K^+/π^+ ratio as a function of system size at top SPS energy. Although the error bars are large, the data clearly show an increase from $p+p$ up to Pb+Pb collisions. This is qualitatively reminiscent of the weakening of canonical suppression of strangeness with increasing cluster size predicted in the framework of statistical SM(IB-CE) and SM(IB-GCE) models (see Fig. 3 (b)), with two important provisos:

(1) the preliminary Be+Be point in Fig. 3 (a) remains close to $p+p$ data, which seems consistent with the Wounded Nucleon Model [6] rather than with statistical model predictions shown in Fig. 3 (b);

(2) while the preliminary results on multiplicity fluctuations in central Pb+Pb collisions at this collision energy indicate a scaled variance below unity, this is not the case for $p+p$ reactions where the latter remains in the range 1.1–1.2 [4]. The latter is in qualitative disagreement with what is expected from small statistical clusters (Fig. 3 (c)) and, in fact, places $p+p$ collisions beyond the regime described by statistical models.

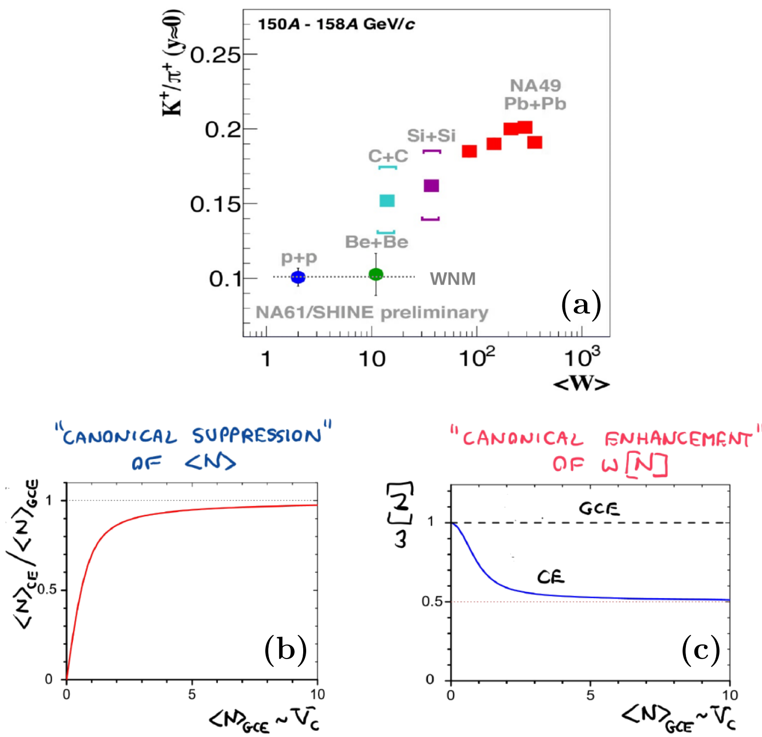

Fig. 3. (a) Dependence of the mid-rapidity K^+/π^+ ratio on the mean number $\langle W \rangle$ of nucleons participating in the collisions. Dependence on the cluster volume $V_{\rm C}$ of (b) the number of particles produced within the Canonical Ensemble CE over those produced within the Grand Canonical Ensemble GCE, and (c) of the scaled variance $\omega = {\rm var}(N)/\langle N \rangle$ [1].

Taking into account the above observations, the present conclusion from the system size dependence of hadron production measured by the NA61/SHINE 2-d scan is that indeed a transition occurs from non-statistical, small systems in $p+p$ collisions, into a statistical regime of large clusters of strongly interacting matter in heavy-ion reactions. This transition is known as the onset of fireball [7].

3. Intermittency

Several studies of fluctuations, in particular made by means of intensive and strongly intensive quantities in charged particle multiplicity and transverse momentum, brought no evidence for the presence of the critical point of strongly interacting matter at SPS energies [4]. A potentially important exception is the analysis of proton intermittency, aimed at detecting local fluctuations of baryon density as a function of cell size in (p_x, p_y) space [10–12]. Two results are presented in Fig. 4. Following Ref. [13], for a collision system in the vicinity of the critical point, the critical component of second order factorial moments $F_2(M)$ of proton multiplicity in the cell (n_m) should scale like a power law with the number of cells M^2.

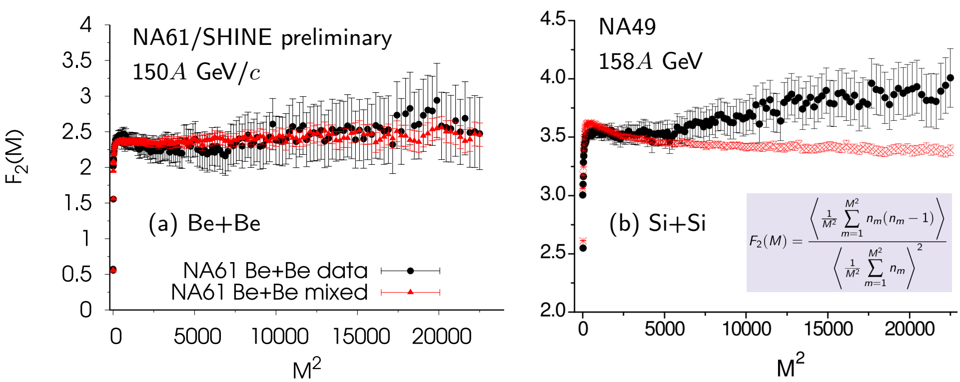

Fig. 4. (Colour on-line) Factorial moments $F_2(M)$ for identified protons emitted close to mid-rapidity in Be+Be (a) and Si+Si (b) collisions, drawn as a function of the number M^2 of (p_x, p_y) cells, for physics data (black) and mixed events (grey/red). From [8, 9].

For central Be+Be reactions at top SPS energy, the obtained values of $F_2(M)$ appear to be fully reproduced by mixed events, indicating no signal of an intermittent component. For central Si+Si collisions, on the other hand, a deviation from the event-mixed, non-critical background is evident from the data. The interpretation of this apparent intermittent signal as a signature of the critical point is at present still to be met with caution. However, it should be underlined that very recent, preliminary results on

Ar+Sc collisions from NA61/SHINE support the Si+Si result [8]. Thus, new experimental data from the NA61/SHINE 2-d scan, in particular also on the energy dependence of the intermittent signal (see Fig. 1 for comparison), can soon unravel the question of the presence of the critical point in the SPS energy regime.

4. The longitudinal evolution of the system

A recent addition to the NA61/SHINE program is the study of spectator-induced electromagnetic (EM) effects, aimed at obtaining new information on the longitudinal evolution of the system [14–16]. New preliminary data on these effects in Ar+Sc collisions at 150 A GeV/c [17], put together with other existing data, indicate that the distance d_{E} between the pion at freeze-out and the spectator decreases with increasing pion rapidity. An attempt to explain this behaviour in the framework of a simple model based on local energy-momentum conservation in the initial stage is presented in Fig. 5 (a), where the excited initial matter forms longitudinal "streams" which are assumed to fragment quasi-independently into pions following a uniform emission function which (statistically) obeys energy-momentum conservation [18] (see Refs. [19, 20] for comparison). As it is apparent in Fig. 5 (b), this simple model provides a good description of the absolute dn/dy distributions of negative pions and their shape evolution as a function of centrality. This suggests that the longitudinal evolution of the system at the considered top SPS energy is largely governed by initial, local energy-momentum conservation and collision geometry. This surprisingly simple phenomenological picture is to be verified by measurements at different collision energies, also available from NA61/SHINE.

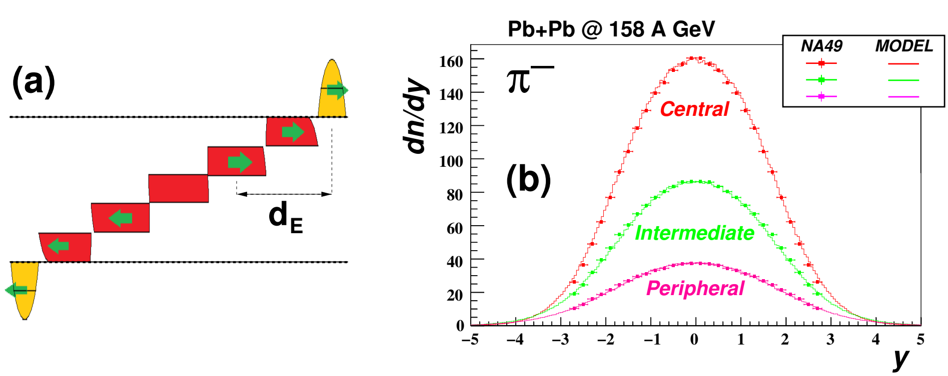

Fig. 5. (a) Simple model of A+A reaction, (b) description of π^- rapidity distributions in Pb+Pb collisions by the model. The experimental data were taken from Ref. [21] and the plots are redrawn from Ref. [18].

5. Summary and outlook

NA61/SHINE is at present the only CERN experiment providing hadron production data as a function of energy, reaction type and centrality in the SPS regime of the phase diagram of strongly interacting matter. The present picture of onset of deconfinement crossed with the onset of fireball apparent from these data points at the need for new dedicated measurements from CERN and other facilities. In particular, a high statistics $p+p$ data taking in the range of $\sqrt{s}$ from 3 to 100 GeV would be highly indicated to pinpoint the possible similarities between the onset of deconfinement in Pb+Pb reactions and the energy dependence of $p+p$ data. The continuation of the analysis of fluctuations and particle yields is necessary to further clarify the issue of the onset of fireball and its precise dependence on system size. The extension of intermittency studies, most of all to different energies, gives a hope to localize and investigate the critical point of strongly interacting matter. Finally, further new data on spectator-induced EM effects and on the centrality dependence of particle spectra will allow for a scan of the longitudinal evolution of the system as a function of system size and energy, complementary to the study of its evolution into deconfined matter and of the formation of large statistical clusters.

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