Onset of deconfinement and search for the critical point of strongly interacting matter at CERN SPS energies

Grzegorz Stefanek for the NA49 Collaboration

Jan Kochanowski University, Kielce, Poland

The study of central collisions of heavy nuclei at CERN SPS energies revealed rapid changes in the energy dependence of hadron production properties in a narrow range around 30A GeV. The results indicate the onset of deconfinement in the early stage of the produced system and motivates the ongoing search for the predicted critical point. NA49 data on event-by-event fluctuations of transverse momentum, multiplicity, particle ratios as well as low mass pion pairs number fluctuations are shown as a function of beam energy and system size.

§1. Introduction

Theoretical investigations found that the phase transition between QGP and hadron gas is of first order for finite quark masses and large non-zero baryon density. The phase boundary is predicted to end in a critical point and turn into a rapid crossover as the net baryon density decreases. The SPS covers one of the most intersting regions of the QCD phase diagram. On the one hand it is expected that the energy threshold for deconfinement is reached already at low SPS energy. On the other hand QCD calculations locate the critical point in the SPS energy range.

§2. Onset of deconfinement in the SPS energy range

NA49 results [1)] on the energy dependence of hadron production in central Pb+Pb collisions at $20A$, $30A$, $40A$, $80A$, $158A$ GeV from the energy scan program at the CERN SPS allow to deduce when strongly interacting matter reaches deconfinement. The most dramatic effect can be seen in the energy dependence of the ratio $\langle \mathrm{K}^+\rangle/\langle\pi^+\rangle$ of the mean multiplicities of K^+ and π^+ plotted in Fig. 1(left). The horn structure shows that the relative strangeness content of produced matter passes through a sharp maximum at the SPS in nucleus-nucleus collisions. A phase transition is expected to also manifest itself in the momentum distributions and correlations of produced particles. A plot of the inverse slope parameter T of the invariant mass distribution of K^+ mesons at midrapidity is shown in Fig. 1 (center). One observes a steep rise at low energies turning into a plateau at SPS energies and a further increase at RHIC and LHC energies. The structure is interpreted as an effect of the softening Equation of State (EOS) due to a mixed phase which weakens transverse expansion. The softness of the EOS is also seen as a minimum in the ratio of widths of the rapidity distributions for negative pions and a massless gas, Fig. 1 (right). These features are neither seen in p+p collisions nor in purely hadronic model calculations using microscopic transport models. RHIC and ALICE points shown in Fig. 1 seem to confirm the general trend in hadron production properties at SPS energies. The rapid changes are most naturally explained by the onset of deconfinement in the early stage of the produced fireball for beam energies of about $30A$ GeV.

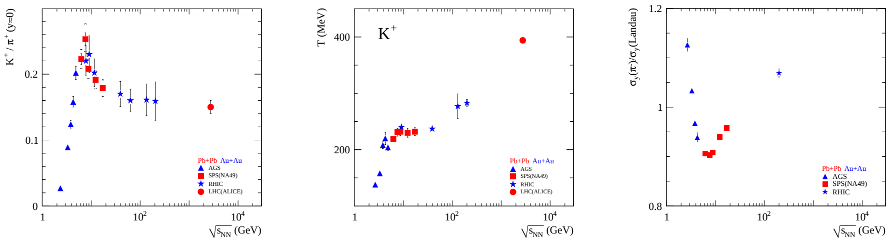

Fig. 1. Left: energy dependence of the K^+/π^+ ratio at mid-rapidity - horn; Center: the inverse slope parameter of the transverse mass distribution for K^+ (center) - step; Right: the ratio of widths of rapidity distributions for negative pions and a massless gas - dale. NA49 and LHC data from central Pb+Pb and RHIC results from central Au+Au collisions

§3. Search for the critical point

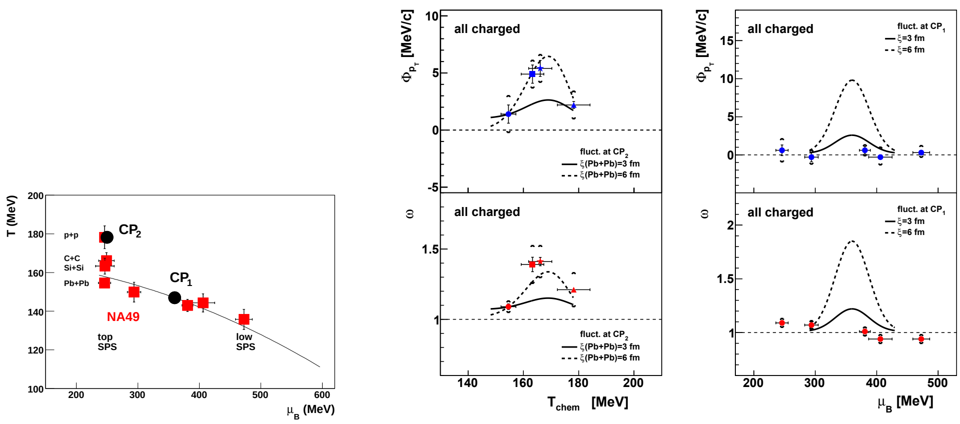

Fig. 2. Left: Chemical freeze-out points in NA49 (squares) and two possible locations of the critical point (circles). Center: System size dependence of the Φ_{pT} measure of transverse momentum fluctuations (top) and scaled variance of multiplicity fluctuations (bottom) for charged hadrons in central collisions of two identical nuclei. Right: Results for central Pb+Pb collisions at $20A$-$158A$ GeV plotted as a function of baryonic chemical potential at chemical freeze-out.

The presence of the predicted critical point is expected to lead to an increase of event-by-event fluctuations of many observables provided that the freeze-out of the measured hadrons occurs close to its location in the phase diagram and that the evolution of the hadron phase does not erase the fluctuation signal. Particle multiplicity fluctuations are characterized by the scaled variance ω of the multiplicity distribution while $\langle p_T \rangle$ fluctuations can be quantified by the Φ_{p_T} measure. Example results on the dependence of these fluctuations on system size at $158A$ GeV and on energy in central Pb+Pb collisions are shown in Fig. 2. They suggest that signals of the critical point are visible in C+C and Si+Si collisions at 158A GeV[2)].

Theoretical studies predict density fluctuations of zero mass σ particles produced abundantly in nuclear collisions at the critical point [3)] . These fluctuations should obey a power law which reflects the critical nature of density fluctuations. The sigma states can be identified with $\pi^+\pi^-$ pairs of invariant mass distributed near the two-pion threshold. The second factorial moment of the number of pion pairs (above Coulomb correlation region) with increasing number of 2-dim cells M^2 in transverse momentum space was analysed for real data and mixed events [4)] . The results in Fig. 3(right) indicate the presence of power-law fluctuations in the freeze-out state of Si+Si approaching in size the prediction of critical QCD.

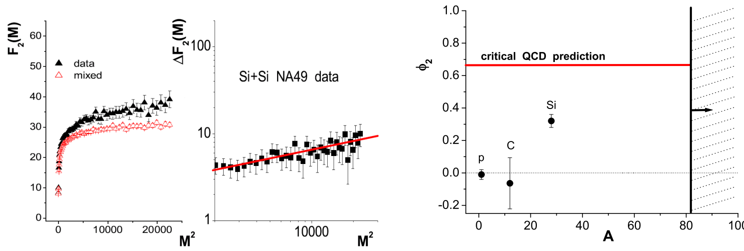

Fig. 3. Left: The second factorial moment in transverse momentum space for central Si+Si collisions at 158A GeV. Center: The correlator ΔF_2 after subraction of the combinatorial background (mixed events). Right: The fitted values of the intermittency index (ϕ_2) for the A+A systems (A = p, C, Si) studied by NA49 as a function of the size A. The upper horizontal line presents the theoretically expected value (2/3) for a system freezing out at the QCD critical point.

§4. Event-by-event particle ratio fluctuations

In the vicinity of the phase transition, where the underlying degrees of freedom change, distinct fluctuations patterns of particle ratios are expected. Such fluctuations can be sensitive to the critical point of strongly interacting matter. Additional motivation for the study of particle ratio fluctuations is the predicted change of the baryon-strangeness correlation at the deconfinement phase transition. This change might be reflected in the kaon to proton ratio as they are major carriers of strangeness and baryon number, respectively.

The "dynamical" fluctuations, arising only from the physics correlations, were calculated as

$$\sigma_{\rm dyn} = {\rm sign}\left(\sigma^2_{\rm data} - \sigma^2_{\rm mix}\right)\sqrt{\left|\sigma^2_{\rm data} - \sigma^2_{\rm mix}\right|}. \qquad (4{\cdot}1)$$

The centrality dependence of $(\mathrm{p}+\bar{\mathrm{p}})/(\pi^+ + \pi^-)$, $(\mathrm{K}^+ + \mathrm{K}^-)/(\pi^+ + \pi^-)$ and $(\mathrm{K}^+ + \mathrm{K}^-)/(\mathrm{p}+\bar{\mathrm{p}})$ fluctuations in Pb+Pb collisions at the top SPS energy was studied [5)]and is presented in Fig. 4. All three ratios studied by NA49 show a similar increase of the magnitude of $\sigma_{\rm dyn}$ when going to peripheral collisions. The hadronic transport model UrQMD predicts a similar behaviour here, and the scaling with multiplicity suggested in [6] is consistent with the data. This result is compatible with the hypothesis that at constant energy the underlying correlations are not significantly changed by a variation of the system size.

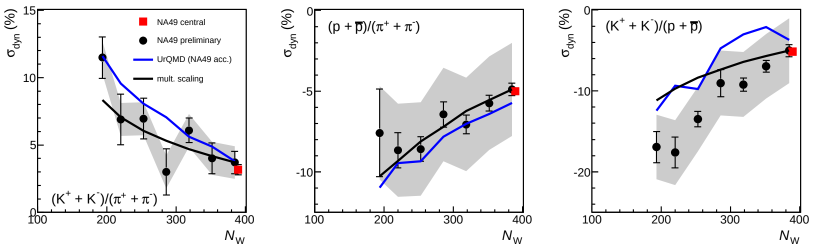

Fig. 4. Centrality dependence of $(K^+ + K^-)/(\pi^+ + \pi^-)$, $(p + \bar{p})/(\pi^+ + \pi^-)$ and $(K^+ + K^-)/(p + \bar{p})$ fluctuations in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The centrality is expressed in terms of N_W, the number of "wounded" or participating nucleons.

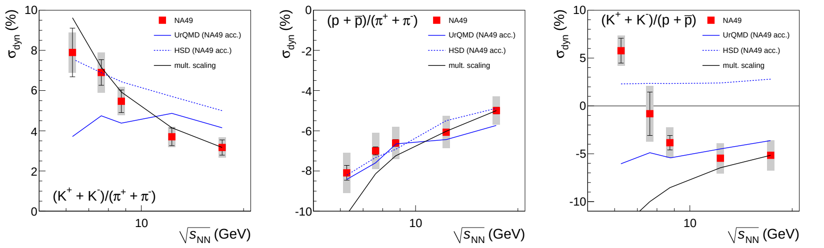

Fig. 5. Energy dependence of σ_{dyn} for $(K^+ + K^-)/(\pi^+ + \pi^-)$, $(p + \bar{p})/(\pi^+ + \pi^-)$ and $(K^+ + K^-)/(p + \bar{p})$ in central Pb+Pb collisions, compared to results from the transport models UrQMD and HSD, as well as to the multiplicity scaling proposed in [6]

The fluctuation measure σ_{dyn} of particle ratios was also studied in central Pb+Pb collisions at five SPS energies [5),7] and the results are shown in Fig. 5. For $(p + \bar{p})/(\pi^+ + \pi^-)$ negative values of σ_{dyn} are observed, indicating a correlated production. For $(K^+ + K^-)/(\pi^+ + \pi^-)$ fluctuations positive values of σ_{dyn} and a rise towards low energies is observed. The hadronic transport models UrQMD and HSD with the production and strong decay of nucleon resonances as the dominating process correlating proton and pion numbers closely match the energy dependence of $(p + \bar{p})/(\pi^+ + \pi^-)$ ratio fluctuations but fail to reproduce the increase of $(K^+ + K^-)/(p + \bar{p})$ ratio fluctuations.

The fluctuations in the kaon to proton ratio were also investigated [8] , motivated by their conjectured connection to the baryon-strangeness correlation. The results are shown in Fig. 5(right) for the combined charges ratio $((K^+ + K^-)/(p + \bar{p}))$. σ_{dyn} shows a strong dependence on $\sqrt{s_{NN}}$, going from positive values at low energies to $\sigma_{dyn} < 0$ at high energies. HSD and UrQMD show practically no energy dependence in strong contrast to the data. The simple scaling model mentioned before fails to decribe these data which might indicate that the underlying correlations between kaons and protons is changing with energy.

Acknowledgements

This work was supported by the Polish Ministry of Science and Higher Education grant N N202 204638.

References

1) C. Alt *et al.* [NA49 Collaboration], Phys. Rev. **C77** , 024903 (2008).
2) T. Anticic *et al.* [NA49, NA61/SHINE Collaborations], PoS **EPS-HEP2009**, 030 (2009).
3) N. G. Antoniou, Y. F. Contoyiannis, F. K. Diakonos, A. I. Karanikas, C. N. Ktorides, Nucl. Phys. **A693**, 799 (2001); N. G. Antoniou, Y. F. Contoyiannis, F. K. Diakonos, G. Mavromanolakis, Nucl. Phys. **A761**, 149 (2005).
4) T. Anticic *et al.* [NA49 Collaboration], Phys. Rev. **C81**, 064907 (2010).
5) T. Schuster *et al.* [NA49 Collaboration], [arXiv:1107.1579 [nucl-ex]].
6) V. Koch and T. Schuster, Phys. Rev. **C81**, 034910 (2010)
7) C. Alt *et al.* [NA49 Collaboration], Phys. Rev. **C79**, 044910 (2009)
8) T. Anticic *et al.* [NA49 Collaboration], Phys. Rev. **C83** (2011) 061902.