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

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The exploration of the QCD phase diagram particularly the search for a phase transition from hadronic to partonic degrees of freedom and possibly a critical endpoint, is one of the most challenging tasks in present heavy-ion physics. As observed by the NA49 experiment, several hadronic observables in central Pb+Pb collisions at the CERN SPS show qualitative changes in their energy dependence. These features are not observed in elementary interactions and indicate the onset of a phase transition in the SPS energy range. The existence of a critical point is expected to result in the increase of event-by-event fluctuations of various hadronic observables provided that the freeze-out of the measured hadrons occurs close to its location in the phase diagram and the evolution of the final hadron phase does not erase the fluctuations signals. Further information about the existence and nature of a phase transition in the SPS energy range can be gained from the studies of event-by-event fluctuations of final state hadron distributions and yields performed by NA61/SHINE, the successor of the NA49 experiment. Experimental results from both experiments on event-by-event fluctuations of transverse-momentum, multiplicity as well as low mass pion pair and proton number fluctuations are shown as a function of beam energy and system size.

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1. Introduction

In 1999, the NA49 experiment at the CERN Super Proton Synchrotron started a search for the onset of quark-gluon plasma (QGP) [1] creation with data taking for central Pb+Pb collisions at 40A GeV. Runs at 80A and 20A, 30A GeV followed in 2000 and 2002, respectively. This search was motivated by the predictions of a statistical model of the early stage of nucleus-nucleus collisions (SMES) [2] that the onset of deconfinement should lead to rapid changes of the energy dependence of several hadron production properties, all appearing in a common energy domain. Conjectured features were observed [3, 4] around 30A GeV and dedicated experiments, NA61/SHINE at the CERN SPS and the beam energy scan at BNL RHIC, continue detailed studies in the energy region of the onset of deconfinement.

2. Onset of deconfinement

Several structures in excitation functions were expected within the SMES: a kink in the increase of the pion yield per participant nucleon (change of slope due to increased entropy production as a consequence of the activation of partonic degrees of freedom), a sharp peak (horn) in the strangeness to entropy ratio, and a step in the inverse slope parameter of transverse mass spectra (constant temperature and pressure in a mixed phase). Such signatures were indeed observed in A + A collisions by the NA49 experiment [3], thus locating the onset of deconfinement energy around 30A GeV ($\sqrt{s_{NN}} \approx 7.6$ GeV).

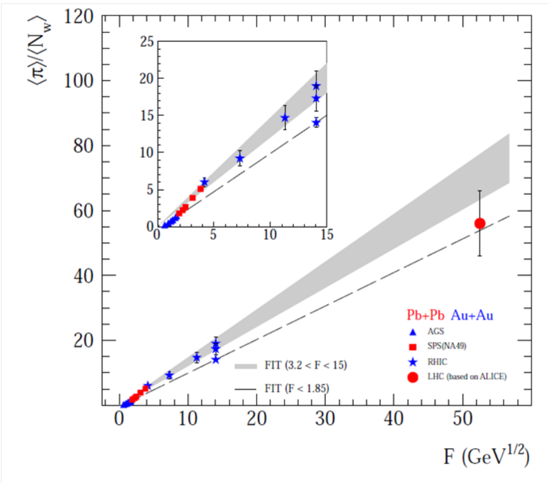

Figure 1: (Color online) Mean pion multiplicity per participant nucleon.

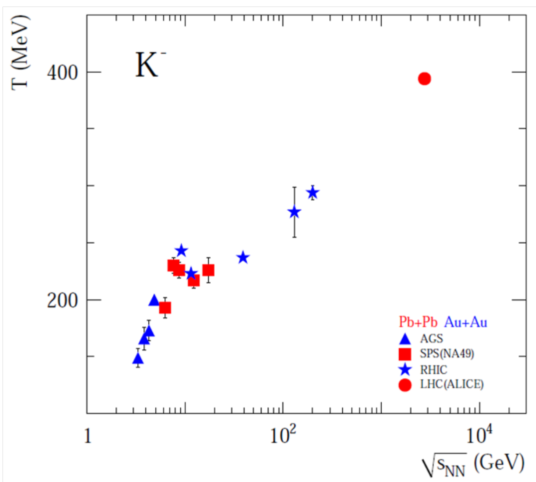

Figure 2: (Color online) Inverse slope parameter of negative kaon m_T spectra.

2.1 Verification of NA49 results and their interpretation by STAR and ALICE

Until recently the evidence of onset of deconfinement was based on the results of a single experiment. Recently new results on central Pb+Pb collisions at the LHC [5] and data on central Au+Au collisions from the RHIC BES program [6] were released. Figure 1 shows an update of

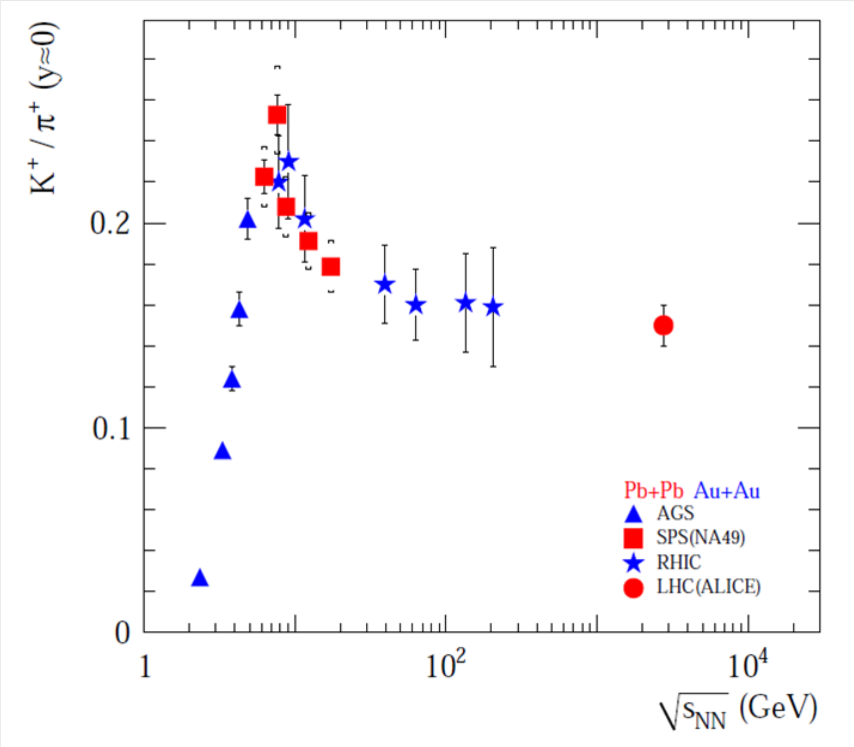

Figure 3: Kaon to pion yield (near midrapidity).

the kink plot, where BES points follow the line for A+A collisions and the LHC point[1], within its large uncertainty, does not contradict extrapolations from high SPS and RHIC energies.

Figure 2 shows the inverse slope parameter of negative kaon transverse mass spectra. The LHC point and the RHIC BES points confirm the step structure expected for the onset of deconfinement. The K^+/π^+ yield (near midrapidity) is presented in Fig. 3.

As seen, RHIC results confirm NA49 measurements at the onset of deconfinement. Moreover, LHC (ALICE) data demonstrate that the energy dependence of hadron production properties shows rapid changes only at low SPS energies, and a smooth evolution is observed between the top SPS (17.3 GeV) and the current LHC (2.76 TeV) energies. All three structures confirm that results agree with the interpretation of the NA49 structures as due to onset of deconfinement. Above the onset energy only a smooth change of QGP properties with increasing energy is expected.

3. New results on fluctuations

Fluctuations and correlations may serve as a signature of the onset of deconfinement. Close to the phase transition the equation of state changes rapidly which can impact the energy dependence of fluctuations. Moreover, fluctuations and correlations can help to locate the critical point of strongly interacting matter. This is in analogy to critical opalescence, where we expect enlarged fluctuations close to the critical point. For strongly interacting matter a maximum of fluctuations

[1] The mean pion multiplicity at LHC was estimated based on the ALICE measurement of charged particle multiplicity, see [7] for details.

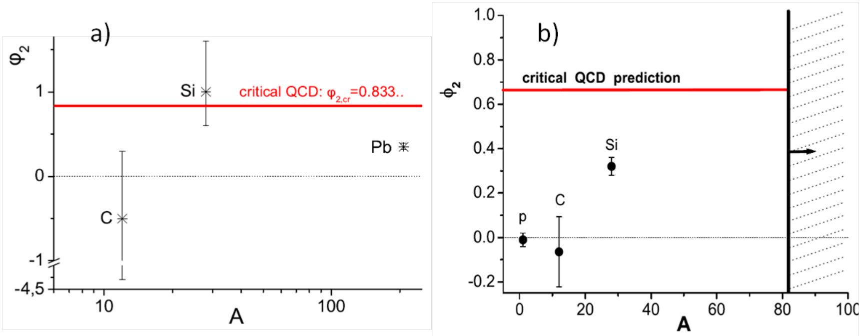

Figure 4: Power law exponents Φ_2 from intermittency analysis: (a) for protons in the 10% most central C+C, Si+Si and Pb+Pb interactions at 158A GeV: (b) for di-pions in p+p, and the 10% most central C+C and Si+Si interactions at 158A GeV.

is expected when freeze-out happens near the critical point. A prerequisite for the appearance of these fluctuations is that the system has first reached deconfinement. Therefore the critical point should be searched for above the onset of deconfinement energy, found by NA49 to be 30A GeV ($\sqrt{s_{NN}} \approx 7.6$ GeV).

3.1 Proton and pion intermittency signals

It was suggested that the analogue of critical opalescence may be detectable through intermittency analysis in p_T space. Significant $\sigma-$field fluctuations are expected at the critical point (density fluctuations of zero mass $\sigma-$particles produced in abundance at the critical point) [8]. This critical point is the endpoint of a line of first order transitions associated with the partial restoration of the chiral symmetry when the temperature T, for given baryochemical potential μ_B, increases beyond a critical value T_c. σ particles at $T < T_c$ may reach the two-pion threshold ($2m_\pi$) and then decay into two pions, therefore density fluctuations of di-pions with $m_{\pi^+\pi^-}$ close to the two pion mass incorporate $\sigma-$field fluctuations at the critical point. Local density fluctuations are expected both in configuration and momentum space. In a finite-density medium there is a mixing between the chiral condensate and the baryon density. Thus the critical fluctuations of the $\sigma-$field are also transferred to the baryon density [9]. Furthermore, as pointed out in [10] the critical fluctuations of the chiral condensate are also directly transferred to the net proton density through the coupling of the protons with the isospin zero $\sigma-$field. Since protons are easier to detect than neutrons the perspective of detecting the QCD critical point through fluctuations of the net proton density is very promising.

The NA49 experiment searched for an intermittency signal in transverse momentum space of reconstructed di-pions ($\pi^+\pi^-$ pairs) with invariant mass just above $2m_\pi$ [11] and protons. The analysis was performed for p+p, C+C and Si+Si interactions (pion intermittency) and C+C, Si+Si and Pb+Pb (proton intermittency) both at 158A GeV. The second factorial moments $F_2(M)$ (with M being the bin size in each transverse momentum space direction) of di-pion and proton densities in transverse momentum space were computed for real data and for artificially produced mixed events where only statistical fluctuations are present. The combinatorial background subtracted (by use of mixed events) moments ΔF_2 in transverse momentum space are expected to follow a power-law behavior $\Delta F_2 \sim (M^2)^{\phi_2}$, with $\phi_2 = 2/3$ (di-pions), and $\phi_2 = 5/6$ protons for systems freezing-out at critical point [8].

Figure 4 shows that the power law exponent Φ_2 fitted to ΔF_2 at the top SPS energy indicates fluctuations approach in size the prediction of critical QCD for Si+Si collisions. The remaining difference may be due to freezing out at a distance from the critical point.

3.2 Multiplicity and transverse momentum fluctuations in Pb+Pb and p+p collisions

The value of $\mathrm{d}E/\mathrm{d}x$ does not allow to identify each particle uniquely as the $\mathrm{d}E/\mathrm{d}x$ distributions overlap. The identity method [12] was developed to extract second and third moments (pure and mixed) of identified particle multiplicity distributions corrected for this imperfect identification. First fluctuation measurements by NA61 in p+p reactions give the unique opportunity to compare Pb+Pb and p+p results at the SPS energies.

Preliminary NA61/SHINE results on multiplicity fluctuations of $\pi = \pi^+ + \pi^-$, $K = K^+ + K^-$, and $p = p + \bar{p}$ were obtained for p+p interactions at 31, 40, 80 and 158 GeV/c. From the first and second corrected moments of the multiplicity distributions, N_i and N_i^2, $(i = \pi, K, p)$, the scaled variance

$$\omega_i = \frac{\langle N_i^2 \rangle - \langle N_i \rangle^2}{\langle N_i \rangle} \tag{3.1}$$

was computed. For Poisson multiplicity distributions $\omega_i = 1$ independent of the number of wounded nucleons in the collisions. However, ω is sensitive to the fluctuations of the number of wounded nucleons. This may distort the comparison of p+p data with results from nucleus+nucleus collisions.

All studied scaled variances increase with increasing collision energy (Figure 5). For kaons $\omega > 1$ for higher energies in agreement with predictions of the EPOS, HSD and UrQMD models. This may be caused by the correlation in K^+ and K^- production due to strangeness conservation. For protons ω is below 1, probably related to baryon number conservation. A comparison of NA61/SHINE results on multiplicity fluctuations (i.e. ω_π) with the magnitude of fluctuations expected at the critical point [13] suggests that the systematic and statistical errors are small enough for a sensitive search of the critical point in NA61/SHINE.

In order to compare results for p+p and central Pb+Pb collisions, the strongly intensive measure Φ_{ij} [14, 15] defined for two hadron types, i and j, was chosen. It is defined as:

$$\Phi_{ij} = \frac{\sqrt{\langle N_i \rangle \langle N_j \rangle}}{\langle N_i + N_j \rangle} \cdot \left(\sqrt{\Sigma^{ij}} - 1 \right) \tag{3.2}$$

where $\Sigma^{ij} = [\langle N_i \rangle \omega_j + \langle N_j \rangle \omega_i - 2 \left(\langle N_i N_j \rangle - \langle N_i \rangle \langle N_j \rangle \right)] / \langle N_i + N_j \rangle$. As a strongly intensive measure, Φ_{ij} is not only independent of the number of wounded nucleons or volume but also of their fluctuations. Figure 6 shows the energy dependence of Φ_{ij} for combinations of two hadron types: πp, πK, and pK. When no inter-particle correlations are present $\Phi_{ij} = 0$. For πK and pK the values of Φ_{ij} increase with increasing energy. There is a minimum for $\Phi_{\pi p}$ between 7.3 and 8.7 GeV. A similar but weaker effect is visible in Pb+Pb interactions. It also appears in the EPOS and UrQMD models. The increase of $\Phi_{\pi K}$ for p+p interactions is not visible in Pb+Pb collisions. Φ_{pK} shows a clear difference between results for p+p, which increase with increasing energy, and for

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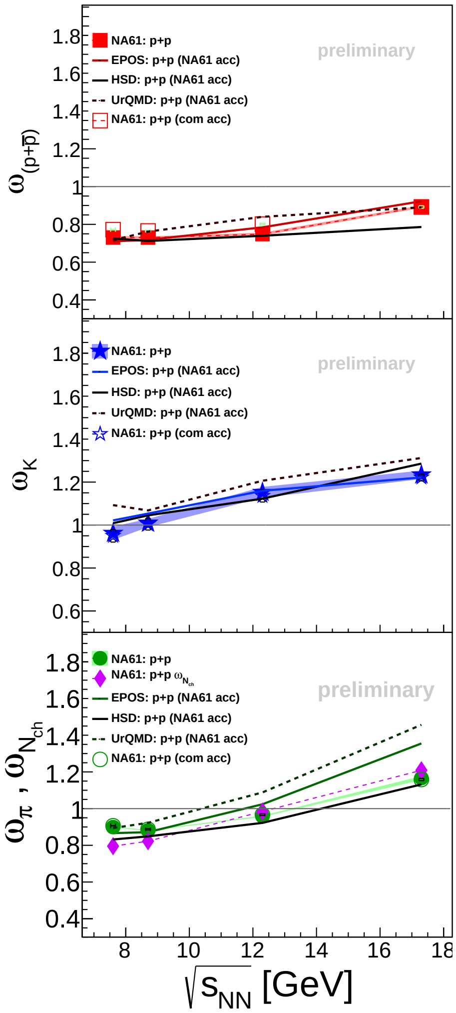

Figure 5: (Color online) Scaled variance for $p+\bar{p}$ (upper panel), $K^{+}+K^{-}$ (middle panel) and $\pi^{+}+\pi^{-}$ (bottom panel) multiplicity distributions for p+p collisions as a function of center-of-mass energy. The NA61/SHINE results are shown by symbols and are compared to EPOS, HSD and UrQMD model calculations depicted by lines.

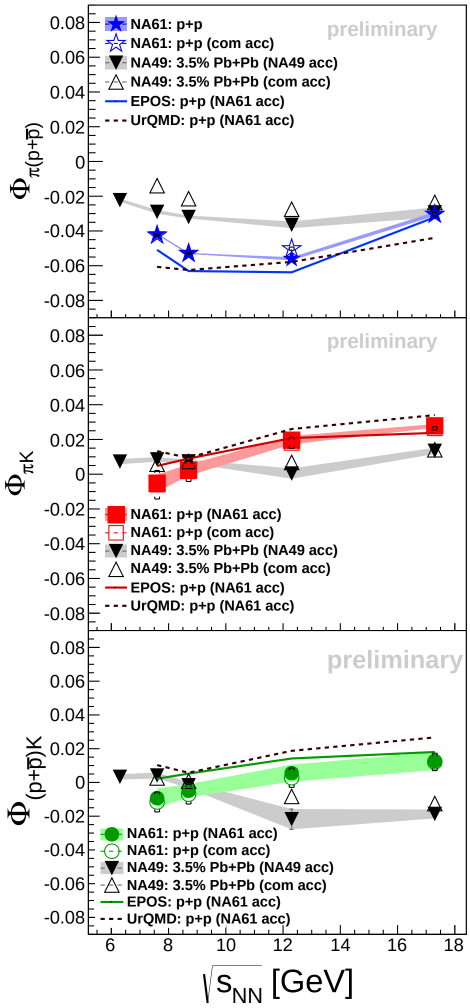

Figure 6: (Color online) Φ_{ij} as a function of center-of-mass energy for p+p (NA61/SHINE) and central Pb+Pb (NA49) collisions. The p+p data are compared with the EPOS and UrQMD model predictions (lines).

Pb+Pb which decrease with increasing energy. Both dependences cross zero at the same energy $\sqrt{s_{NN}} \approx 8.7$ GeV.

4. Summary

The NA49 discovery of the energy threshold for deconfinement is now confirmed. The results from the RHIC Beam Energy Scan agree with NA49 measurements on the onset of deconfinement. LHC data confirm the interpretation of the structures observed at low SPS energies as due to onset of deconfinement. For central A+A collisions fluctuations of pion and proton densities tend to a maximum in Si+Si collisions at 158A GeV. Thus the critical point may be accessible at SPS energies. This result is a strong motivation for future experiments and in fact, the NA49 efforts will be continued by the ion program of the NA61/SHINE experiment [16].

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