

Search for the Critical Point of Strongly Interacting Matter in Heavy-Ion Collisions

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Abstract. Results obtained from the search for the critical point of strongly interacting matter in relativistic heavy-ion collisions at the CERN-SPS (experiments NA49 and NA61/SHINE) and the RHIC beam energy scan program (experiments STAR and PHENIX) are discussed. Although some intriguing signals were found, establishing firm evidence for the critical point remains a challenging enterprise.

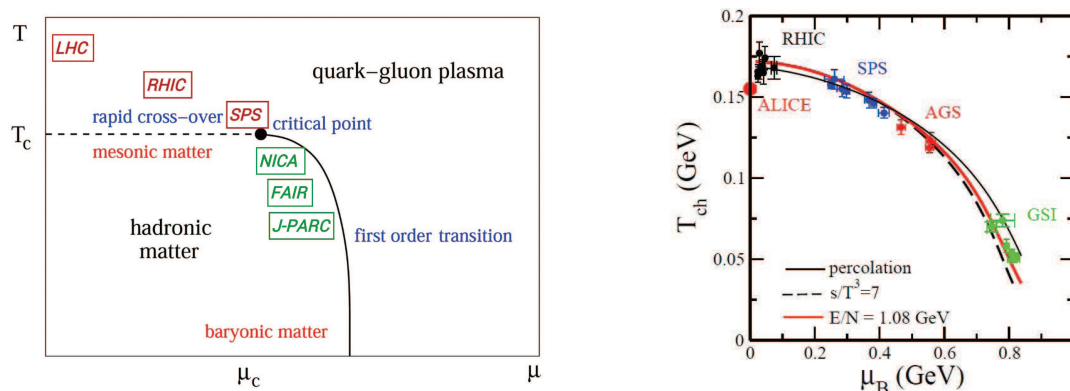


Figure 1. *Left:* Sketch of the phase diagram of strongly interacting matter. Italic labels added to the sketch show regions probed by the early stage of heavy-ion collisions studied in current (in red: CERN SPS, RHIC, LHC) and future (in green: NICA, FAIR, J-PARC) experimental programmes. *Right:* Compilation of chemical freeze-out points of central Pb+Pb (Au+Au) collisions [8].

1. Introduction

The structure of the phase diagram of strongly interacting matter is an important aspect of QCD in the non-perturbative sector. The most popular suggestion is shown schematically in Fig. 1 *left* (see e.g. Ref. [1]). The deconfinement transition at low temperature T and high baryochemical potential μ_B is believed to be of the first order and happen along a line which



ends with decreasing μ_B in a critical point CP (of the second order) and then turns into a crossover region. Present lattice QCD calculations can neither provide consistent estimates of the location of the CP [2, 3, 4] nor a definitive answer to the question of its existence [5, 6] due to the so-called sign problem encountered in calculations for finite μ_B values. Experimentally the structure of the phase diagram is explored by studying the final states produced in relativistic nucleus-nucleus collisions. By varying collision energy and size of colliding nuclei one changes temperature T and chemical potentials μ_B of the matter at the freeze-out stage. The values of T and μ_B for the system are obtained from fits of the statistical model of hadronisation [7, 8] to the composition of the observed hadrons (see Fig. 1 *right*). Model calculations suggest [9] that at high collision energies these values are close to those of the deconfinement transition (hadronisation) of the system in the phase diagram. Of course, effects of the phase transition and the CP can only be seen if the matter droplet initially reaches deconfinement. Rapid changes found in the freeze-out properties indicate that this happens for collision energies above about $E_{LAB} \approx 30A$ GeV ($\sqrt{s_{NN}} = 8$ GeV) [14].

At the CP the correlation length ξ diverges resulting in a maximum of fluctuations of the multiplicity of produced particles. This leads to scale invariance, the effect of intermittency [10] as well as to a large increase of the moments of the distributions of event-by-event multiplicities, net charge or transverse momentum [11]. However, the growth of ξ is limited by the small size and short lifetime of the system [12] to estimated values of about 3 fm in collisions of heavy nuclei. Moreover, the CP signal might be weakened or erased during the evolution of the hadron phase.

This contribution discusses results obtained from the search for the CP from experiments NA49 and NA61/SHINE at the CERN-SPS [13] and experiments STAR and PHENIX in the RHIC beam energy scan program. Emphasis is put on showing the experimental results. For more details on the experiments and the analysis procedure the given references should be consulted.

2. Intermittency studies

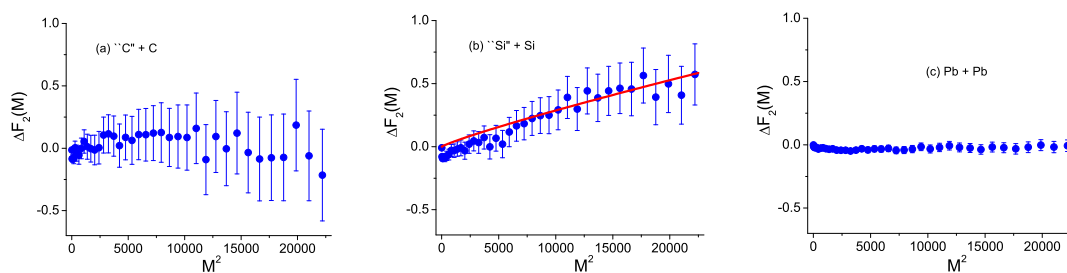


Figure 2. NA49 collaboration: combinatorial background subtracted second scaled factorial moments $\Delta F_2^{(e)}(M)$ in transverse momentum space [21] for the most central collisions of (a) “C”+C (centrality 12 %), (b) “Si”+Si (centrality 12 %) and (c) Pb+Pb (centrality 10 %) at $\sqrt{s_{NN}} = 17.3$ GeV. The line in the middle plot shows the result of a power-law fit for $M^2 > 6000$ with exponent 0.96.

Scale invariance of the produced particle system can be exposed by the power law behaviour of scaled factorial moments $F_r(\delta)$ of the particle multiplicity N on the selected phase-space bin size δ :

$$F_r(\delta) = \left\langle \frac{1}{M} \sum_{i=1}^M N_i(N_i - 1) \dots (N_i - r + 1) \right\rangle / \left\langle \frac{1}{M} \sum_{i=1}^M N_i \right\rangle^r, \quad (1)$$

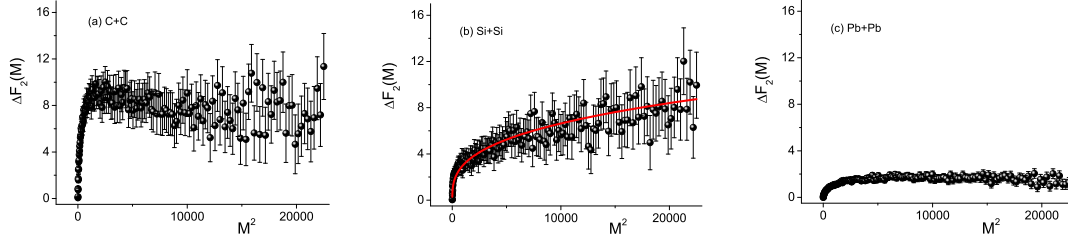


Figure 3. NA49 collaboration: combinatorial background subtracted second scaled factorial moments ΔF_2 in transverse momentum space [22] for: (a) C+C, (b) Si+Si and (c) Pb+Pb systems. The line in (b) shows the result of a power-law fit for $M^2 > 2000$ with exponent 0.33.

where r is the rank of the moment, δ the size of the subdivision intervals of the momentum phase space region Δ and $M = \Delta/\delta$ the number of intervals. N_i refers to particle multiplicity in the interval i and $\langle \dots \rangle$ indicates averaging over the analyzed collisions. Scale invariance implies the relation:

$$F_r(\delta) = F_r(\Delta) \cdot (\Delta/\delta)^{\phi_r}, \quad \phi_r = (r-1) \cdot d, \quad (2)$$

with a rank independent anomalous fractal dimension d .

Early searches for critical fluctuations in nucleus-nucleus collisions investigated scaled factorial moments from charged particle production [10]. However, the observed effects were small and inconclusive [17, 18, 19]. More recent QCD considerations suggested [1] that the order parameter of the phase transition is the chiral condensate $\langle \bar{q}q \rangle$ (q is the quark field), which at the hadronisation stage transforms into σ mesons. The critical fluctuations at the CP were predicted to be observable via the intermittent behaviour of $\pi^+\pi^-$ pairs from the decay of the σ mesons with invariant mass just above twice the pion mass [15] or of protons which also couple to the chiral condensate [16]. The corresponding power law indices were predicted to have the values $\phi_2 = 2/3$ [15] for $\pi^+\pi^-$ pairs and $\phi_2 = 5/6$ [20] for protons respectively.

The NA49 collaboration searched for intermittency in central nucleus-nucleus collisions at the highest SPS energy of 17.3 GeV. The resulting combinatorial background subtracted second scaled factorial moments $\Delta F_2(M)$ are plotted versus M^2 in Figs. 2 and 3 for protons and for $\pi^+\pi^-$ pairs near mass threshold, respectively. One observes power law behavior at large M^2 for central Si+Si collisions (freeze-out at $T \approx 162$ MeV, $\mu_B \approx 260$ MeV [7]) with exponents $\phi_2 = 0.96^{+0.38}_{-0.25}(\text{stat}) \pm 0.16(\text{syst})$ and $\phi_2 = 0.33 \pm 0.04$. The result for protons agrees with the CP prediction whereas that for $\pi^+\pi^-$ pairs is smaller, probably as a consequence of the difficulty of isolating the pairs from σ decay. Although the freeze-out states of C+C and Pb+Pb are close to that of Si+Si the critical fluctuation pattern probably cannot develop in C+C due to the small size of the system and may be erased in Pb+Pb during the longer evolution of the hadron phase.

3. Finite size scaling in collisions of heavy nuclei

An interesting non-monotonic behaviour was observed by R. Lacey [23] for the difference of matter droplet radius parameters $R_{out}^2 - R_{side}^2$ as obtained from pion Bose-Einstein correlation analysis of Au+Au and Pb+Pb collisions (see Fig.4 *left*). A maximum appears at RHIC energies which might be related to a minimum of the compressibility as expected at the CP. Finite size scaling is then predicted [24] when changing the radius \bar{R} of the system by selecting different collision centralities. As seen in Fig.4 *right* this is indeed observed with suitable scaling parameters and suggests the existence of the CP at $\mu_B \approx 95$ MeV and $T \approx 165$ MeV.

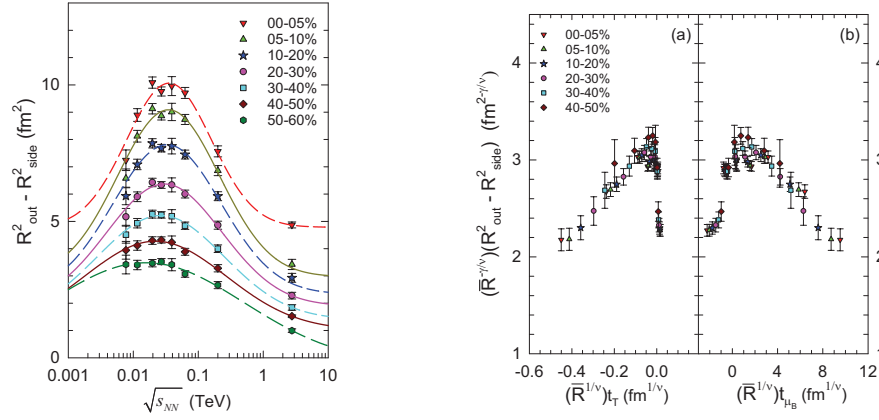


Figure 4. Figures from Ref. [23]. *Left:* difference $R_{out}^2 - R_{side}^2$ of radius parameters in Au+Au and Pb+Pb collisions versus collision energy for various centralities. *Right:* demonstration of finite size scaling of the radius parameter difference with system radius \bar{R} .

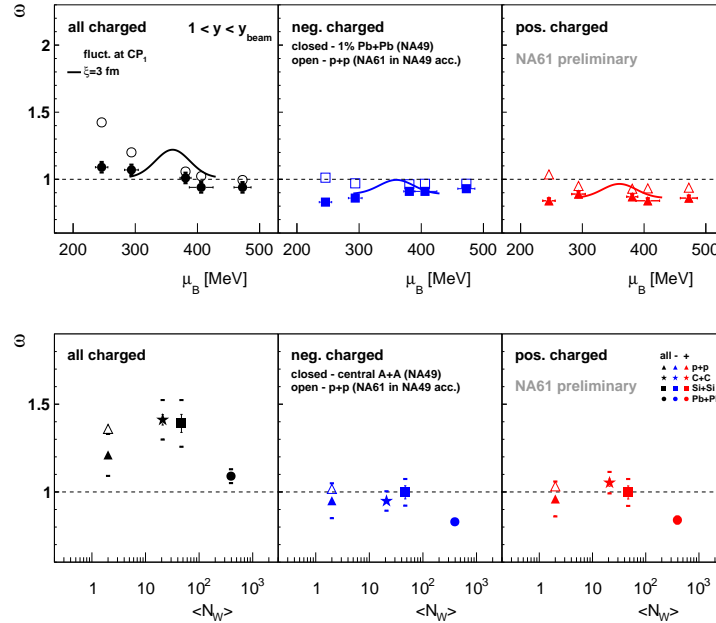


Figure 5. NA49 and NA61/SHINE collaborations: scaled variance ω of the multiplicity distribution of charged particles for the 1 % most central Pb+Pb collisions and inelastic p+p reactions for $1.0 < y < y_{beam}$ (assuming the pion mass). *Top:* versus μ_B . *Bottom:* versus the number of wounded nucleons N_W . Full symbols show results of NA49 [25], open symbols preliminary measurements of NA61/SHINE [26]. Curves illustrate the effect of a critical point [27].

4. Multiplicity and transverse momentum fluctuations

Multiplicity and net-charge fluctuations in nucleus-nucleus collisions have most often been studied via the moments of their distributions. Cumulants of the distribution $P(N)$ (here N

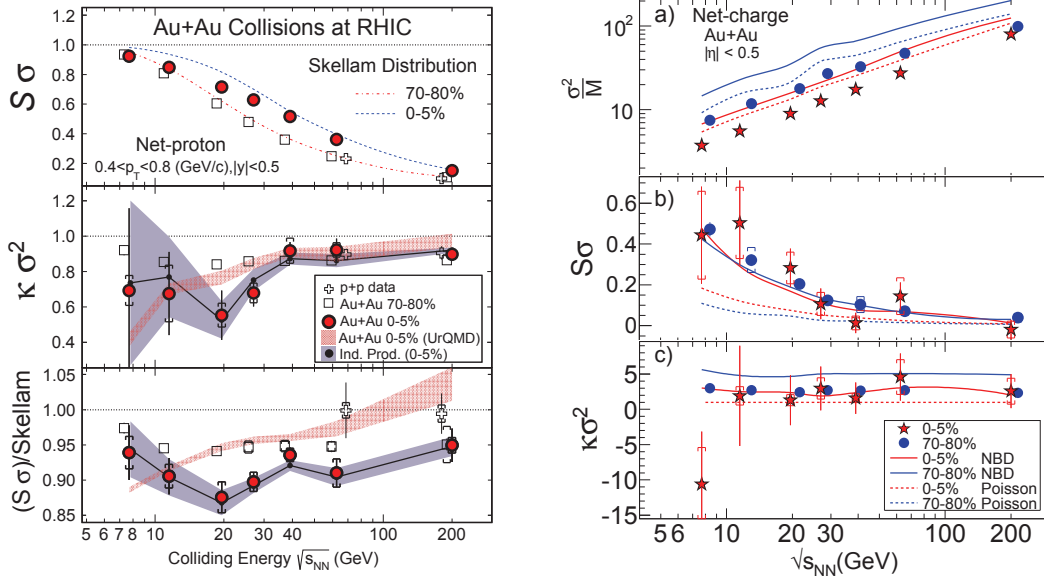


Figure 6. STAR collaboration: fluctuations of net-proton multiplicity (*left*) [29] and net-charge (*right*) [30] in central Au+Au collisions measured by the width σ , mean M , skewness S and kurtosis κ of the distributions. (Rapidity range $|y| < 0.5$ and $|\eta| < 0.5$ respectively)

can be e.g. the multiplicity or the net charge in the event) are defined as follows:

$$\kappa_2 = \langle (\delta N)^2 \rangle, \quad \kappa_3 = \langle (\delta N)^3 \rangle, \quad \kappa_4 = \langle (\delta N)^4 \rangle - 3\kappa_2^2, \quad \text{and} \quad \delta N := N - \langle N \rangle \quad (3)$$

Cumulants are extensive quantities, proportional to the size of the system as given e.g. by the number of participant nucleons in the collision. Since the latter cannot be tightly controlled or measured in nucleus-nucleus collisions one prefers to use size independent normalised cumulants $\omega_k = \kappa_k / \langle N \rangle$. For independent particle production one expects $\omega_2 = 1$ and $\omega_{k>2} = 0$. Moreover the cumulant ratios $S\sigma = \kappa_3 / \kappa_2$ and $\kappa\sigma^2 = \kappa_4 / \kappa_2$ (σ , S and κ denote the variance, skewness and kurtosis of the distribution, respectively) are of special interest since they are related to susceptibilities of conserved charges calculable in lattice QCD.

The simplest non-trivial normalised cumulant is the widely used scaled variance ω , an intensive quantity, i.e. independent of the size of the system, but not of the inevitable fluctuations thereof. In order to minimise their effect NA49 [25] selected the 1 % most central collisions. The obtained results on ω for charged particles are plotted in Fig. 5 *top* for the energy dependence in Pb+Pb reactions and in Fig. 5 *bottom* for the nuclear size dependence at highest SPS energy. Clearly no significant maximum is observed in the energy scan, while there may be a bump for medium-size nuclei (Si+Si).

Higher moments have been shown to be more divergent near the CP. This applies in particular to the net proton multiplicity [28] which was investigated by the STAR collaboration [29] in central Au+Au collisions at RHIC. The energy dependence of combinations of moments and cumulants (width σ , skewness S and kurtosis κ) is plotted in Fig. 6 *left*. The results are close to expectations for independent particle production (Skellam distribution for a difference of

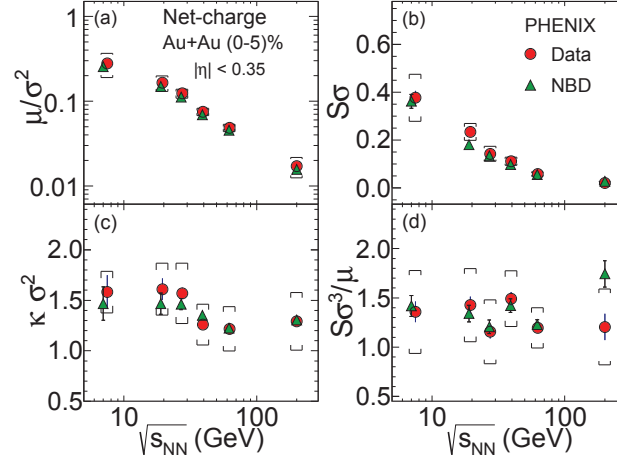


Figure 7. PHENIX collaboration: fluctuations of net-charge [31] in central Au+Au collisions at RHIC measured by the width σ , mean μ , skewness S and kurtosis κ of the distribution. (Pseudo-rapidity range $|\eta| < 0.35$)

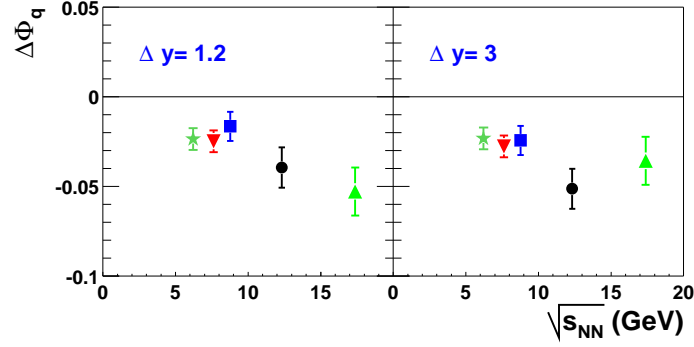


Figure 8. NA49 collaboration: energy dependence of $\Delta\Phi_q$ measured in central Pb+Pb collisions at 20A, 30A, 40A, 80A and 158A GeV [33] for a narrow rapidity interval $\Delta y = 1.2$ (left) and a broad rapidity interval $\Delta y = 3$ (right).

multilicities) and the trend with collision energy is similar in the microscopic model UrQMD. Thus no structure was found which might be attributable to the CP.

Charge fluctuations are also expected to show a non-monotonic dependence in a collision energy scan when the system passes near the CP in the phase diagram. The results from STAR [30] for the energy dependence of combinations of moments and cumulants of the net-charge multiplicity distribution in central Au+Au collisions is presented in Fig. 6 *right*. The observed smooth behaviour does not provide evidence for the CP. A similar analysis was performed by the PHENIX collaboration [31]. The measurements shown in Fig. 7 likewise do not find indications for the CP.

Some years back NA49 studied charge fluctuations in central Pb+Pb collisions at the SPS [33] and employed the strongly intensive measure Φ_x [32, 34]:

$$\Phi_x = \sqrt{\langle Z^2 \rangle / \langle N \rangle} - \sqrt{(x - \bar{x})^2} \quad , \quad Z = \sum_{i=1}^N (x_i - \bar{x}) \quad , \quad (4)$$

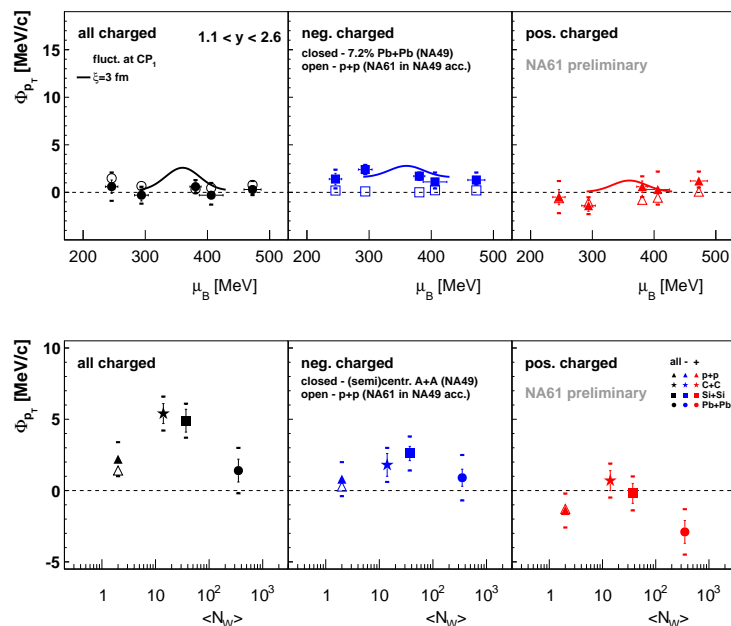


Figure 9. NA49 and NA61 collaborations: measure Φ_{p_T} of transverse momentum - multiplicity fluctuations of charged particles. *Top:* versus μ_B for the 7.2 % most central Pb+Pb collisions (full symbols, NA49 [35]) and inelastic p+p reactions (open symbols, NA61 preliminary). *Bottom:* versus the number of wounded nucleons N_W in central C+C, Si+Si and Pb+Pb collisions at 158A GeV (NA49 [36]) and inelastic p+p reactions (NA61/SHINE preliminary [26]). Results are for cms rapidity $1.1 < y < 2.6$ assuming the pion mass. Curves illustrate the effect of a critical point [27].

where x is a particle observable and the bar and brackets denote the inclusive average and averaging over events, respectively. Φ_x is independent of both the system volume and its fluctuations. For the study of charge fluctuations the observable x is taken to be the charge q of the particle. It was found that there were large contributions from global charge conservation which were calculated and subtracted. The resulting values of $\Delta\Phi_q$ are plotted in Fig. 8 as function of collision energy. Again no structure due to a CP is seen.

A maximum of fluctuations of the transverse momentum p_T of produced particles was also proposed as a signature of the CP [11]. Such fluctuations were measured for nucleus-nucleus and p+p collisions at the SPS by experiments NA49 and NA61, respectively, again using the quantity Φ_x now with $x = p_T$. The results for charged particles are shown in Fig. 9 as function of energy (*top*) and size of the interacting nuclei (*bottom*). Similar to the measurements of charged particle multiplicity fluctuations (see Fig. 5) one finds no peak in the energy dependence but perhaps a weak indication of a maximum in the system size study.

5. Summary and conclusion

A search for evidence of the critical point of strongly interacting matter has been performed by pilot scans of the phase diagram with measurements of fluctuations in nucleus-nucleus collisions in the most promising energy region, i.e at the CERN SPS and in the RHIC beam energy scan program. While some intriguing effects were found in studies of intermittency and multiplicity fluctuations in the medium size Si+Si system as well as of finite size scaling as function of centrality in Au+Au collisions no definitive evidence of the critical point has yet emerged.

Further more systematic and precise studies are ongoing by the NA61/SHINE collaboration, are scheduled for the second beam energy scan at RHIC and are planned by future experiments at NICA, FAIR and J-PARC. Exploration of the phase diagram and discovering the critical point remains a challenging and exciting enterprise.

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