Recent results from the search for the critical point of strongly interacting matter at the CERN SPS

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Recent searches at the CERN SPS for evidence of the critical point of strongly interacting matter are discussed. Experimental results on theroretically expected signatures, such as event-to-event fluctuations of the particle multiplicity and the average transverse momentum as well as intermittency in particle production are presented.

1. Introduction

Exploration of the phases of strongly interacting matter is the main purpose of the study of high energy heavy-ion collisions. Theoretical considerations [1] suggest that the phase boundary between confined hadrons at low and quasi-free quarks and gluons at high temperature and/or density is of the first order in systems with large net-baryon density (or equivalently baryochemical potential $\mu_B \gg 0$). Lattice QCD calculations [2] can provide quantitative predictions at zero net baryon density ($\mu_B = 0$) and find that the transition is a rapid crossover. Thus a critical point is expected as the endpoint of the first-order transition line. However, lattice QCD is not yet able to cope with $\mu_B > 0$ in a strict way. Predictions of the existence and location of the critical point (CP) in the phase diagram of T versus μ_B have to be obtained from extrapolations which arrive at conflicting results. Some find a CP in a region accessible to experiments at the SPS and the RHIC beam energy scan [3], others locate the CP at high μ_B where heavy-ion experiments are not able to produce the deconfined phase [4] or they find no CP at all [5]. Clearly it is important to address this issue by experimental studies.

At a CP the correlation length ξ diverges leading to a strong increase of suitable correlation measures such as event-to-event fluctuations of the multiplicity and average transverse momentum of produced particles [6] as

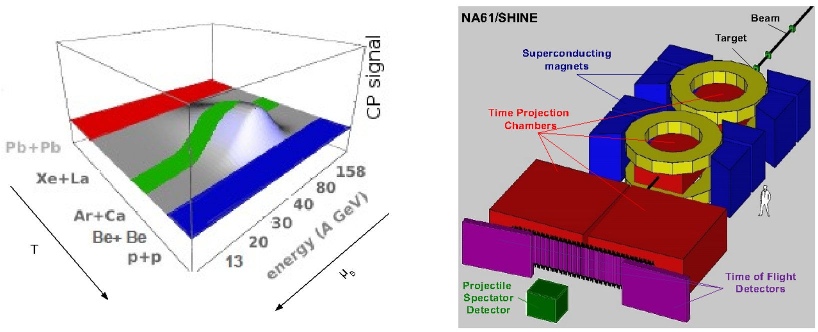

Fig. 1. Left: expected hill of fluctuations in a scan of the phase diagram with a critical point. Right: schematic view of the NA49/NA61 detector

well as local density fluctuations resulting in the appearance of intermittency in particle production [7]. Owing to the finite size and short lifetime of the fireballs produced in collisions of nuclei, ξ is expected not to exceed 3-6 fm in Pb+Pb collisions. Moreover, correlations may be diluted by rescattering of the produced particles before final freezeout.

A scan of the phase diagram by varying the sizes of colliding nuclei (change of rescattering probabilty) and energies of the collisions (change of μ_B) is a promising search strategy (see Fig. 1, left). A coinciding maximum of several fluctuation measures would indicate the existence and the location of the CP. This program was started by the NA49 collaboration [8] and is now pursued systematically by the NA61/SHINE experiment [9].

2. Detector and recorded data

The NA61 experiment, the successor of NA49, uses a fixed target spectrometer with particle identification, covering mainly the forward region in the center-of-mass rapidity. The schemtic view in Fig. 1 (right) shows the system of four large Time Projection Chambers for particle tracking and momentum measurement. The first two are placed inside superconducting magnets with combined bending power of 9 Tm. Particle identification is obtained by measuring the energy loss by ionisation in the gas of the TPCs with precision of about 4 % and the time-of-flight in scintillation counter walls with resolution of 60-80 ps. For the NA61 program the NA49 detector was upgraded by a new cellular zero degree calorimeter (Projectile Spectator Detector) with single beam nucleon energy resolution and a He filled beam pipe trough the TPCs to reduce beam induced δ-ray background. Finally, the digital part of the TPC readout was replaced resulting in a factor 10 increase of the data acquisition rate.

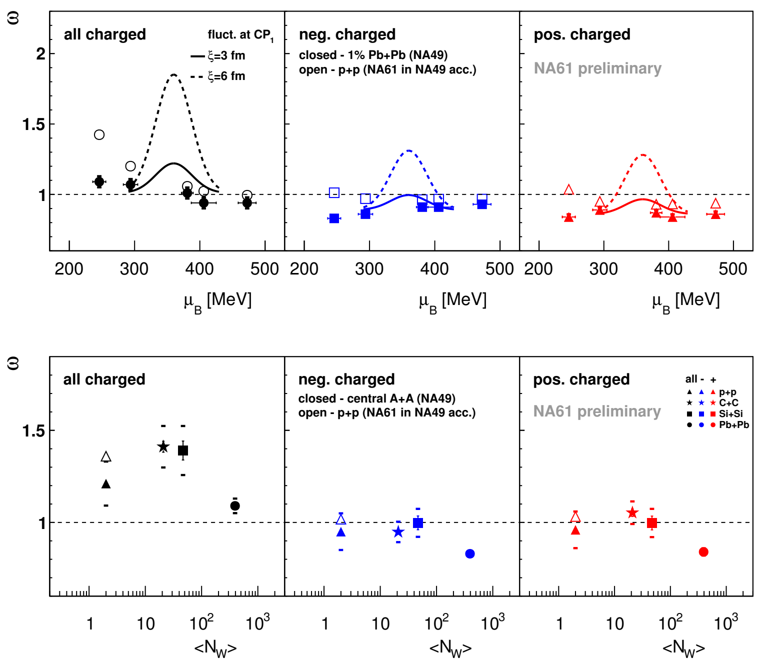

Fig. 2. Scaled variance ω of the multiplicity distribution of charged particles. Top: versus μ_B for the 1% most central Pb+Pb collisions and inelastic p+p reactions for $1.0 < y < y_{beam}$ (assuming the pion mass). Bottom: versus the number of wounded nucleons N_W in inelastic p+p ($1.1 < y < 2.6$) and the 1% most central C+C, Si+Si and Pb+Pb collisions at 158A GeV ($1.0 < y < y_{beam}$). Full symbols show results of NA49 [10], open symbols NA61 (preliminary).

NA49 recorded data on central Pb+Pb collisions at a set of energies (20A, 30A, 40A, 80A and 158A GeV) through the SPS energy range in the period 1994–2002. Additionally a smaller set of data was taken for C+C and Si+Si collisions at 40A and 158A GeV. NA61 expands this program and resumed in 2009 a comrehensive scan of energies (13A GeV + NA49 energies) and nuclear sizes (p+p, Be+Be, Ar+Ca, Xe+La, Pb+Pb) which has been completed for the lightest two systems.

3. Fluctuations of the particle multiplicity

The signature of a CP is expected to be primarily an increase of multiplicity fluctuations [6] which are usually quantified by the scaled variance $\omega = (\langle N^2 \rangle - \langle N \rangle^2)/\langle N \rangle$ of the distribution of particle multiplicities N produced in the collisions. The measure ω is "intensive", i.e., it is independent

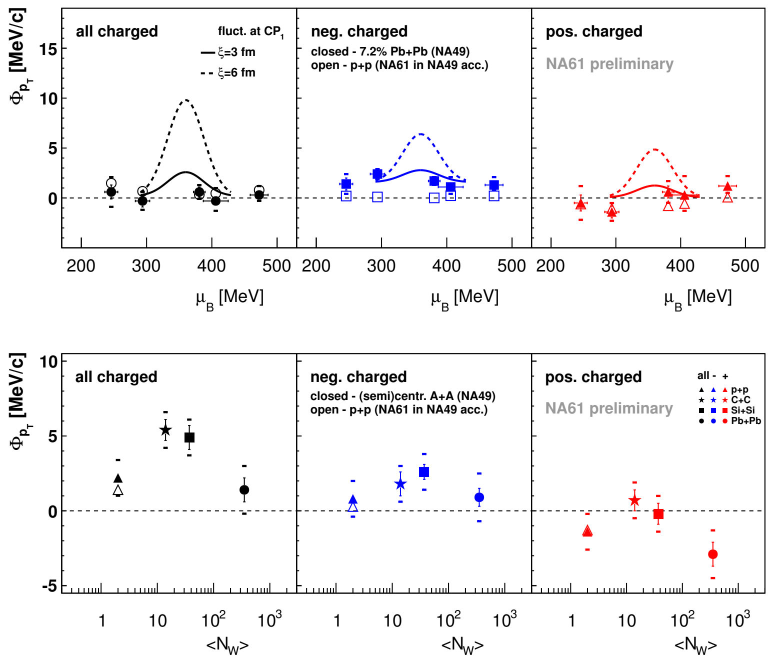

Fig. 3. Fluctuation measure Φ_{p_T} of the average transverse momentum of charged particles. Top: versus μ_B for the 7.2% most central Pb+Pb collisions (full symbols, NA49 [16]) and inelastic p+p reactions (open symbols, NA61 preliminary). Bottom: versus the number of wounded nucleons N_W in central C+C, Si+Si and Pb+Pb collisions at 158A GeV (NA49 [17]) and inelastic p+p reactions (NA61 preliminary). Results are for cms rapidity $1.1 < y < 2.6$ assuming the pion mass.

of the number of wounded nucleons N_W (size or volume) of the system in models which assume nucleus+nucleus collisions to be a superposition of nucleon+nucleon reactions. However, ω is sensitive to the unavoidable fluctuations of N_W [12]. Therefore the measurements were restricted to the 1 % most central collisions. Results for charged particles in Pb+Pb collisions (NA49 [10]) are shown in Fig. 2 (top) versus μ_B (obtained from statistical model fits to yields of different particle types at the various collision energies) and compared to preliminary NA61 results from p+p reactions. The data do not support a maximum as might be expected for a CP (see curves [11]). NA49 also obtained results for different size nuclei at the top SPS energy of 158A GeV (see Fig. 2 (bottom)). Here there may be an indication of a maximum for medium size nuclei. A new identification procedure (identity method [13]) allowed to measure the energy dependence of fluctu-

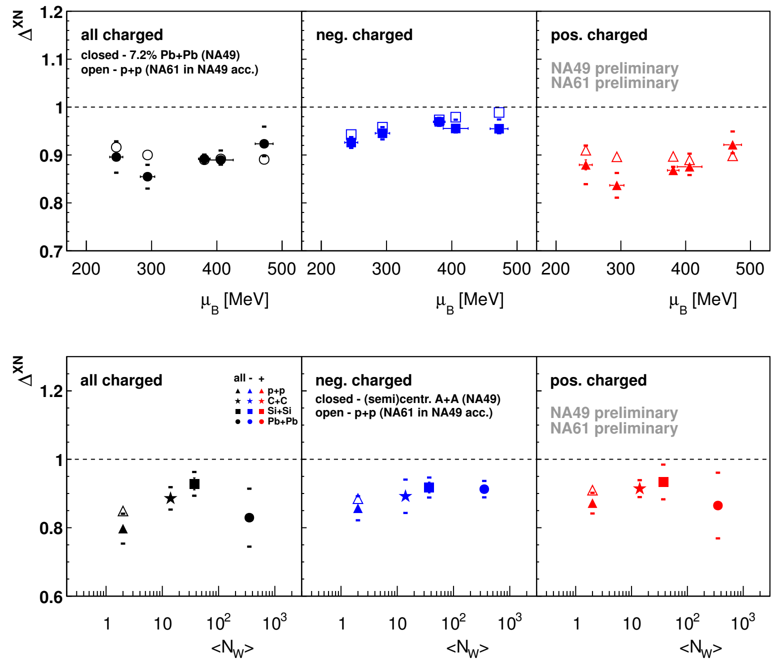

Fig. 4. Fluctuation measure $\Delta^{P_T,N}$ of the average transverse momentum of charged particles. Top: versus μ_B for the 7.2% most central Pb+Pb collisions (full symbols) and inelastic p+p reactions (open symbols). Bottom: versus the number of wounded nucleons N_W in inelastic p+p and central C+C, Si+Si and Pb+Pb collisions at 158A GeV. Results are for cms rapidity $1.1 < y < 2.6$ assuming the pion mass. (NA49 and NA61 preliminary).

ations of identified proton, kaon and pion multiplicities in p+p and Pb+Pb collisions. As in the case of charged particle multiplicities no indication of a CP is found. It was pointed out that higher moments of the multiplicity distributions are more sensitive to effects of the CP [14]. Unfortunately the systematic uncertainties of the measurements in NA49 and NA61 at present do not allow meaningful conclusions.

4. Fluctuations of the average transverse momentum

Enhanced fluctuations are also expected for the average transverse momentum p_T when the freezeout occurs close to the CP [6]. A suitable measure Φ_{p_T} was proposed in [15], which is "strongly intensive", i.e. independent of both N_W and its fluctuations. Results on the dependence of Φ_{p_T} on μ_B in central Pb+Pb (NA49 [16]) and inelastic p+p collisions (NA61

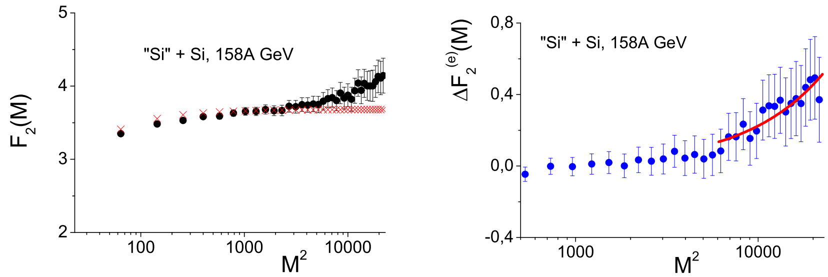

Fig. 5. Scaled factorial moments of protons in rapidity $|y| < 0.75$ for the 12.5% most central Si+Si collisions at 158A GeV (NA49 [20]). Left: $F_2(M)$ versus the number of cells M^2 in transverse momentum space. Dots show data, crosses the mixed event background. Right: $\Delta F_2(M)$ versus M^2; dots show background subtracted data, the curve the result of a power-law fit $\Delta F_2(M) \propto M^{2\Phi_2}$.

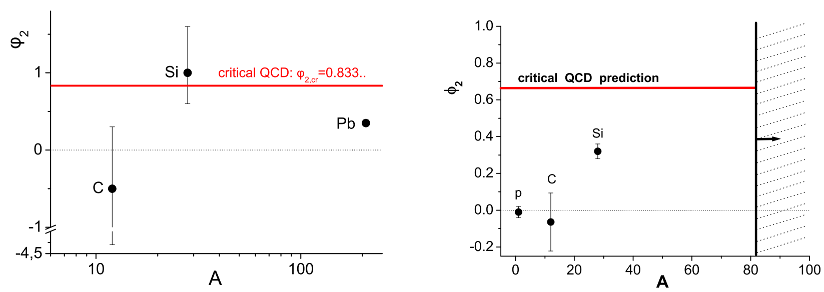

Fig. 6. Exponent Φ_2 obtained from power law fits to second scaled factorial moments of protons [18] (left) and low-mass $\pi^+\pi^-$ pairs [21] (right) for several collision systems at 158A GeV.

preliminary) are plotted in Fig. 3 (top) and compared to expectations for a CP (curves in Fig. 3 (top) [11]). Measurements for different size nuclei at the top SPS energy of 158A GeV are shown in Fig. 3 (bottom). As found for ω there is no evidence for a CP from the dependence of Φ_{p_T} on μ_B, but there may be a maximum for medium-size nuclei.

Recently a new class of strongly intensive measures was proposed in Ref. [12]. Whereas $\Sigma^{P_T,N}$ is closely related to Φ_{p_T} the quantity $\Delta^{P_T,N}$ is sensitive to fluctuations of p_T and N in a different combination. Results shown in Fig. 4 are inconclusive, in particular, as at present there are no predictions for the effect of a CP in this observable.

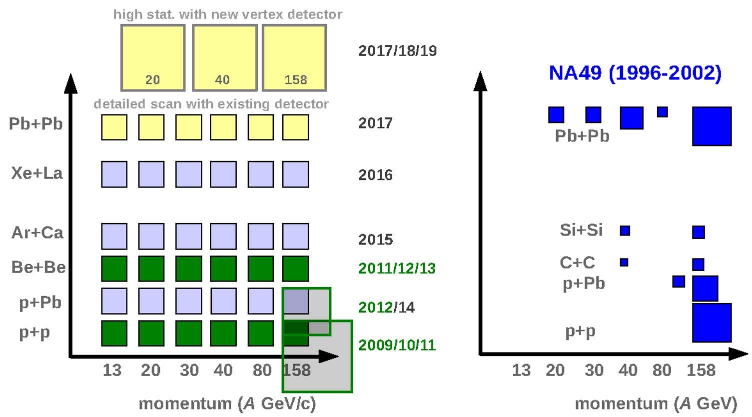

Fig. 7. Reactions and energies of the scan of the phase diagram by NA61 (left, in progress) and systems previously studied by NA49 (right).

5. Local density fluctuations of protons and low-mass $\pi^+\pi^-$ pairs

Theoretical investigations [7] predict near the CP the appearance of local density fluctuation for protons [18] and low-mass $\pi^+\pi^-$ pairs of power-law nature with known critical exponents [19]. These can be studied by the intermittency analysis method in transverse momentum space using second factorial moments $F_2(M)$, where M is the number of subdivisions in each p_T direction. After combinatorial background subtraction the exponents Φ_2 are obtained from a power-law fit to the corrected moments $\Delta F_2(M) \propto M^{2\Phi_2}$. The procedure is illustrated for protons in central Si+Si collisions in Fig. 5. The resulting values of Φ_2 obtained for central C+C, Si+Si and Pb+Pb collisions at 158A GeV [20] are plotted in Fig. 6 (left). Remarkably, Φ_2 seems to reach a maximum for Si+Si collisions which is consistent with the theoretical expectation for the CP. A similar conclusion was reached for low-mass $\pi^+\pi^-$ pairs [21] (see Fig. 6 (right)).

6. Conclusion

The continuing search in nucleus+nucleus collisions for the maximum of fluctuations predicted for a critical point of strongly interacting matter has not yet turned up firm evidence in the CERN SPS energy range. Tantalising hints were found for medium-size nuclei in data from the NA49 experiment which strongly motivate the ongoing scan of the phase diagram by the NA61 experiment (see Fig. 7). A search for the CP is also in progress at the Brookhaven RHIC within the beam energy scan (BES) program.

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