Searching for the QCD critical point in AA collisions at CERN SPS

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We investigate the transverse momentum correlations of pairs of opposite charged pions near their production threshold. Through intermittency analysis, we search for power-law dependence on observation scale, as dictated by critical QCD. We analyse the data of the most central collisions in four A systems (A = p, C, Si, Pb) at maximum SPS energy. We find a significant effect for the SiSi system approaching in size the critical QCD predictions as measured by the intermittency index ϕ_2. Absence of this effect in the (π^-, π^-) sector of the SiSi system gives further support that the observed behaviour in the isoscalar mode is of critical origin.

The recent experiments with ultrarelativistic nuclei are dedicated to the search for experimental signatures of a deconfined state of quarks and gluons separated from conventional hadronic matter by a line of first order transitions ending up at a second order critical endpoint in the two-dimensional phase diagram (μ_{B}, T). The order parameter signaling the transition from quark to hadronic degrees of freedom is the condensate $\langle \bar{q} q \rangle$, remnant of the chiral phase transition for quarks with vanishing current mass. Non-monotonic dependence on (μ_{B}, T) of global order parameter fluctuation measures, can be used to identify traces of the first order transitions in data originating from AA collisions [1]. However, the second order critical behavior is distinguished through local self-similar fluctuations of the order parameter, a property which should inevitably be the basis of the experimental detection of the critical endpoint. In fact one can argue, in a model independent way, that the local fluctuations of the $\langle \bar{q} q \rangle$ condensate are related to the density fluctuations of zero-mass σ-particles which can be abundantly produced in a nuclear collision at the critical point [2–10]. During the freeze-out, the mass of the σ-particles increases reaching the two pion threshold when the sigmas start to decay into pions. Recently it has been suggested that the critical density

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fluctuations of the σ-particles in momentum space can be reconstructed using the momenta of pion pairs with opposite charge produced with invariant mass just above the two pion threshold [10]. The critical behaviour of the reconstructed isoscalar density fluctuations can then be revealed through intermittency analysis in transverse momentum [10]. This is clearly demonstrated using events generated by the Critical Monte Carlo (CMC) algorithm [11] capturing the main ingredients characterizing the critical σ-state and its subsequent decay into pions:

- sigma particles with power-law density-density correlations (self-similarity) in configuration and momentum space [11]
- spectral density of the sigma particles with square-root threshold singularity (partial chiral symmetry restoration [12])

The combinatorial background introduced by the reconstruction procedure can be simulated through mixed events and removed in the intermittency analysis by calculating the correlator $\Delta F_2(M)$ given as:

$$\Delta F_2(M) = F_2(M) - x_M^2 F_2^{(m)}(M) - 2x_M(1-x_M)\,, \quad x_M = \frac{\langle n^{(m)}\rangle_M}{\langle n\rangle_M}, \tag{1}$$

where $F_2(M)$, $F_2^{(m)}(M)$ are the second factorial moments in transverse momentum space while $\langle n\rangle_M$ and $\langle n^{(m)}\rangle_M$ are the mean numbers of reconstructed dipions per cell obtained from data and mixed events, respectively. M is the number of elementary cells in transverse momentum space used in the calculation of the factorial moments [13]. At the QCD critical endpoint we expect a power-law behaviour of the correlator $\Delta F_2(M) \sim M^{2\phi_2}$ with $\phi_2 = \frac{2}{3}$ [11] as determined by the corresponding universality class (3D Ising [2–9]).

We have analysed four data sets of the NA49 experiment at CERN SPS containing charged pions produced in AA collisions (A $= p$, C, Si, Pb) at 158 AGeV. Only events with centralities 0–12.5% have been used in a search for traces of critical fluctuations, i.e. power-law dependence of ΔF_2 on the number of cells M. A detailed description of the used data sets as well as the cuts applied for their production can be found in [13]. The invariant mass window used in the reconstruction of dipions was close to the two-pion threshold and beyond the region of [280, 285] MeV in order to avoid the presence of Coulomb correlations. The results of our analysis are summarized in Fig. 1. A significant intermittency effect ($\phi_2 \approx 0.33 \pm 0.08$) has been found in the isoscalar mode of the SiSi system for the invariant mass window [302, 305] MeV [13]. In the other systems (p, C) no intermittency effect is observed while the analysis in the PbPb system is not conclusive since, due to the large multiplicity, the combinatorial background is very large and cannot be efficiently removed using the correlator, Eq. (1). As shown in Fig. 2, the effect in the SiSi system (Fig. 2a) tends to approach the CMC result (Fig. 2b) and cannot be reproduced by events generated by conventional Monte Carlo generators like HIJING (see Fig. 2c).

In fact the intermittency result presented in [13] becomes stronger by considering only SiSi collisions in the centrality bin 5–12.5%. A possible explanation of this behavior is that the distance to the critical point depends not only on (μ_{B}, T) but also on the net-baryon density at midrapidity acting as a third dimension in the QCD phase diagram [15]. Clearly the net-baryon density differs in the two centrality bins. In addition, an improvement of the intermittency analysis can be achieved by applying more strict criteria in the pion identification. In Fig. 3a we present $\Delta F_2(M)$ for SiSi calculated using isoscalar dipions with invariant mass in [302, 305] MeV originating from events with centrality 5–12.5% and containing exclusively pion tracks with total momentum in [3.5, 31] GeV or less than 0.63 GeV. The latter cut excludes tracks in the regions with large overlap between the pion, kaon and proton $\frac{dE}{dx}$ distributions used for particle identification increasing this way the purity of pions. We observe a large slope $\phi_2 = 0.55 \pm 0.04$ with very good linearity ($R^2 = 0.88$). In contrast to the (π^+, π^-) case the correlator in the (π^-, π^-) mode for the same invariant mass window does not possess power-law behavior as shown in Fig. 3b. This is in agreement with critical QCD predicting power-law correlations only in the isoscalar sector. The same behavior is expected also for the (π^+, π^+) sector, however the contamination with protons does not allow a conclusive result in this case.

Summarizing, we have found indication of approaching the QCD critical endpoint in the freeze out state of the SiSi system at maximum SPS energy. Our conclusion is based on intermittency analysis in transverse momentum space of isoscalar dipions with invariant mass close to the two-pion threshold as recorded in the NA49 experiment. A complementary analysis in the net-baryon sector, where a stronger intermittency effect is expected [14], may provide further evidence for this observation making feasible the detection of the critical endpoint at SPS.

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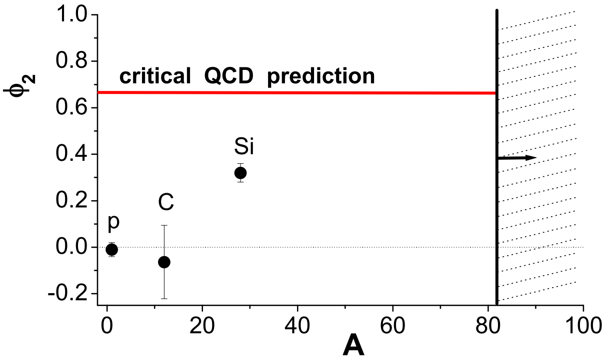

Figure 1. The fitted values of ϕ_2 for the different AA systems studied by NA49. For the shaded region of A-values the reconstruction of the critical fluctuations is not conclusive.

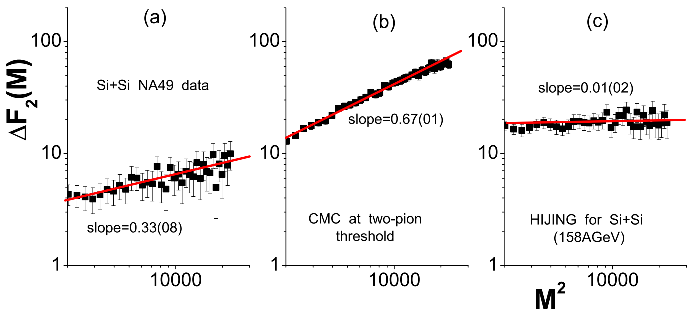

Figure 2. The correlator ΔF_2 corresponding to the best solution for SiSi at 158 AGeV using: (a) NA49 data, (b) CMC generated events and (c) HIJING events. The lines display the corresponding linear fit in log-log scale.

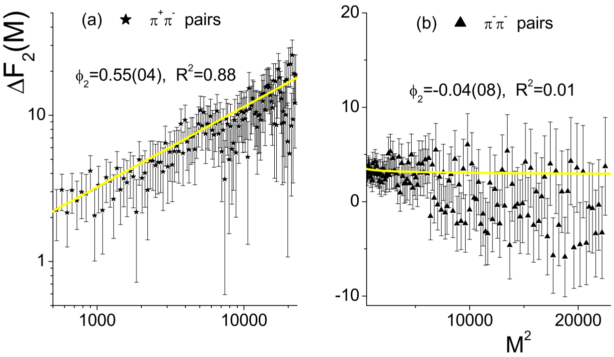

Figure 3. The correlator ΔF_2 for (a) the (π^+, π^-) and (b) the (π^-, π^-) sector of the SiSi system at 158 AGeV using NA49 data (centrality bin 5–12.5%). The lines are the power-law fit results.

FIGURE CAPTIONS

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