Cent. Eur. J. Phys. • 1-4
Author version

Central European Journal of Physics

Search for critical fluctuations of the proton density in central A+A collisions at maximum SPS energy

Research Article

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Abstract: We performed an intermittency analysis of the proton density fluctuations in transverse momentum space for the collisions Si+A (A=Al,Si,P) and C+A (A=C,N) at maximum SPS energy ($\sqrt{s} \approx 17$ GeV). In our analysis we used exclusively proton tracks in the midrapidity region ($|y_{CM}| \leq 0.75$). For the Si+A system we find signature of power-law distributed density fluctuations quantified by the intermittency index ϕ_2 which approaches in size the predictions of critical QCD. This result supports further the recent findings of power-law fluctuations in the density of (π^+, π^-) pairs with invariant mass close to their production threshold for the Si+Si at the same energy, reported in [9].

PACS (2008): 12.38.Mh,25.75.-q,25.75.Gz,25.75.Nq

Keywords: proton density fluctuations • intermittency analysis • QCD critical point

1. Introduction

The detection of the chiral critical point of QCD in experiments with colliding nuclei requires the employment of suitable observables [1–6]. To achieve such a task it is necessary to investigate the fluctuations of the chiral condensate $\langle \bar{q}(x) q(x) \rangle$ which is the order parameter of the chiral transition ($q(x)$ is the quark field). The quantum state which carries the critical properties of the chiral condensate is the sigma-field $\sigma(x)$. In a heavy ion collision the chiral condensate is likely to be formed, however it will be unstable, decaying mainly into pions at time scales characteristic for the strong interaction. The critical properties of the condensate are transferred to (π^+, π^-) pairs with invariant mass just above their production threshold which are experimentally observable [5]. If the baryochemical potential is different from zero then we expect that the sigma-field will induce critical density fluctuations also in the baryonic sector [7, 8]. In particular, as pointed out in [3], the critical fluctuations are transferred directly to the net proton density which is easily experimentally accessible.

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In the present work we calculate the second factorial moment of the proton density in transverse momentum space using data of Si+A (A=Al,Si,P) and C+A (A=C,N) collisions as recorded in the NA49 experiment at maximum energy ($\sqrt{s} \approx 17GeV$) of the SPS (CERN). We will focus on the protons neglecting the antiprotons which are clearly much fewer for the considered systems. Theoretical work done in this direction [6] points out the emergence of intermittency – i.e. power-law behaviour of the second factorial moment as a function of the number of cells in transverse momentum space – with predicted exponent $\phi_{2,cr}^{B} = \frac{5}{6}$ (intermittency index), when the considered system freezes out exactly at the chiral critical point. The critical intermittency index is determined from first principles (universality class arguments) and it is valid for protons produced in the midrapidity region. One expects a gradual suppression of the intermittent behaviour as the distance of the freeze-out state of the considered system to the critical point increases. This suppression should lead to a decrease of the value of ϕ_2 and/or by a modification of the power-law form [5, 9]. Thus calculating ϕ_2 we obtain a signature for the approach to the critical region.

2. The analysed data sets

For the analysis we used data from central collisions of C and Si nuclei at 158A GeV. In addition to symmetric collisions (A+A) there are also data for C+N, Si+Al and Si+P collisions recorded by the NA49 detector. In order to increase statistics as much as possible we merged C+C and C+N events into one dataset. Similarly we combined Si+Si, Si+Al and Si+P events. Thus we obtained 33560 C+A (A = C, N) and 175943 Si+A (A = Si, Al, P) events all with collision centrality $0 - 12.5\%$. The proton identification was performed with purity of 90%. Only protons with center of mass rapidity y_{CM} in the interval $[-0.75, 0.75]$ were selected for the further analysis. Tracks within this interval clearly fulfil the criterion $|y_{CM}| < y_{beam} - 0.5$ necessary for avoiding spectators in the considered datasets ($y_{beam} \approx 2.9$).

3. Proton intermittency analysis at midrapidity

In order to reveal a potentially underlying power-law behaviour of the factorial moments calculated from the data, we have to subtract the background due to uncorrelated and/or misidentified protons. This background contribution does not contain critical fluctuations and can be simulated by mixed events. The critical behaviour is revealed in the correlator $\Delta F_2(M) = F_2^{(d)}(M) - F_2^{(m)}(M)$ obtained from the second factorial moment of the data $F_2^{(d)}(M)$ after subtraction of the corresponding second factorial moment of the mixed events $F_2^{(m)}(M)$. In the presence of critical fluctuations we expect a power-law dependence of $\Delta F_2(M)$ on M which is the number of bins in each transverse momentum space direction.

In Fig. 1(a,b) we show the second factorial moments $F_2(M)$ for the two analysed systems (red circles). In the same figure we also plot the second moments for the corresponding mixed events (black triangles). We observe that the factorial moments of the data are in general larger than those of the mixed events especially in the region of large M values. For the C+A system there are also overlaps between the data and mixed events moments. In addition the errors are quite large which can be attributed to the smaller statistics available for this system. In the Si+A case the statistics is significantly better and the moment of the data is clearly distinguished from that of the mixed events. The distance between the two moments increases with increasing number of cells M^2 a typical characteristic of intermittent behaviour.

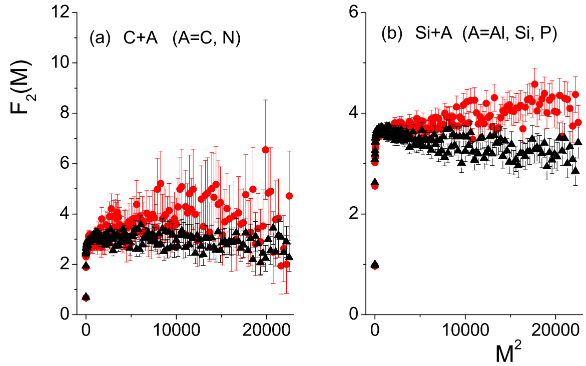

Figure 1. Second factorial moments of proton transverse momentum distribution at midrapidity for data and mixed events using (a) C+A (A=C, N) and (b) Si+A (A=Al, Si, P) central collisions at 158A GeV.

To explore the nature of these correlations we calculate the correlator ΔF_2 as a function of M^2 according to the above definition. The results are given in Fig. 2(a,b). Only the region of large number of bins ($M^2 > 2000$), where the intermittency effect, if present, is expected to show up, is presented. Performing a power-law fit on $\Delta F_2(M)$ we find the values $\phi_2 = 0.38 \pm 0.16$ for the C+A and $\phi_2 = 0.65 \pm 0.12$ for the Si+A collisions. The quality of the power-law fit - measured in terms of the coefficient of determination R^2 [10] - is bad for the C+A system ($R^2 = 0.15$) while it is sufficiently good for the Si+A system ($R^2 = 0.62$). Since the values of ΔF_2 at different binning M are in principle correlated one has to check the impact of these correlations on the obtained fitting results. This has been done using several methods ([11]) and in particular the sparse binning method [12] which converges also for small statistics as it is the case for C+A. We have found that the above fitting results do not change by taking the correlations of the ΔF_2 values into account.

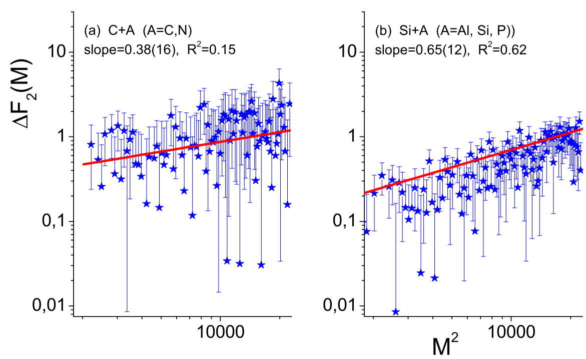

Figure 2. The correlator $\Delta F_2(M)$ for (a) C+A (A=C, N) and (b) Si+A (A=Al, Si, P) central collisions at 158A GeV. The red solid lines in each case are the results of the power-law fit.

4. Concluding remarks

We performed a search for critical fluctuations in NA49 data using intermittency analysis of the transverse momentum distribution of protons at midrapidity. The analysed events were the 0 - 12 % most central ion collisions at 158A GeV from: (i) C+A with A=C, N and (ii) Si+A with A=Si, Al, P collisions. For the dependence of the correlator ΔF_2 on the number of transverse momentum cells (M^2) we found a strong intermittency effect in Si+A collisions. This effect is expressed through the power-law dependence of ΔF_2 on M^2 with a large slope (intermittency index) ϕ_2: $\Delta F_2(M) \sim (M^2)^{\phi_2}$ approaching in size the critical QCD prediction. An analogous effect was found recently [9] in an analysis of central Si+Si collisions at the same energy using dipions with invariant mass close to their production threshold. The analysis presented here further supports these findings providing an additional experimental indication that the Si+A system freezes-out within the critical region, offering this way a signature for the existence and location of the QCD critical point.

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