Vol. 10 (2017) *Acta Physica Polonica B Proceedings Supplement* No 3

SEARCHING FOR THE QCD CRITICAL POINT THROUGH POWER-LAW FLUCTUATIONS OF THE PROTON DENSITY IN HEAVY-ION COLLISIONS*

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(Received April 26, 2017)

One of the goals of the NA61/SHINE experiment is to discover the critical point (CP) of QCD, which is an object of much experimental and theoretical interest. To this end, a scan of the 2-dimensional phase diagram $(T, \mu_{\rm B})$ through proton–nucleus and nucleus–nucleus collisions is being performed at the SPS, with varying collision energy and system size. One of the most promising observables that signal the approach to the CP are local power-law fluctuations of the order parameter of the QCD chiral phase transition, subject to universal scaling laws. In particular, fluctuations of the proton density probed through the method of intermittency analysis of scaled factorial moments for a number of NA49 collision data sets provide evidence of power-law fluctuations in the "Si"+Si dataset, consistent with an approach to the critical point, within errors. In this contribution, we expand on previous work by studying the prospects for an intermittency analysis in NA61 Be+Be and Ar+Sc collisions at 150 A GeV, through Monte Carlo simulations of critical protons mixed with a non-critical background.

DOI:10.5506/APhysPolBSupp.10.537

1. Introduction

Experimental observables proposed for the detection of the QCD CP [1] fall into two categories: event-by-event (global) fluctuations of integrated quantities [2–4], as well as local power-law fluctuations [5] of the order

* Presented at the "Critical Point and Onset of Deconfinement" Conference, Wrocław, Poland, May 30–June 4, 2016.

parameter of the QCD chiral phase transition, the chiral condensate $\langle \bar{q}q \rangle$. The critical properties of the chiral condensate are carried by the sigma field $\sigma(\boldsymbol{x})$, and may be probed indirectly through its decay into experimentally observable (π^+, π^-) pairs [6]. At finite baryochemical potential, critical fluctuations are also transferred to the net-proton density, as well as to the proton and antiproton densities separately [7].

At the CP, the fluctuations of the order parameter are self-similar [8], belonging to the 3D-Ising universality class, and can be detected in transverse momentum space within the framework of an intermittency analysis of proton density fluctuations by the use of scaled factorial moments (SFMs). A detailed analysis, augmented by properly adapted statistical techniques, can be found in [9], where we study various heavy-nuclei collision datasets recorded in the NA49 experiment at maximum energy (158 A GeV, $\sqrt{s_{NN}} \approx 17$ GeV) of the SPS (CERN).

2. Method of analysis

In a pure critical system, intermittency in transverse momentum space can be revealed by the scaling of the Second Scaled Factorial Moments (SSFMs) of proton particles as a function of bin size. For that purpose, a region of transverse momentum space is partitioned into $M \times M$ equal-size bins. Consequently, the SSFMs

$$F_2(M) = \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i - 1) \right\rangle \Big/ \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \right\rangle^2 \tag{1}$$

are calculated as an average over bins and events $(\langle \ldots \rangle)$, where n_i is the number of particles in the i^{th} bin and M^2 is the total number of bins. If the system exhibits critical fluctuations, $F_2(M)$ is expected to scale with M, for large values of M, as a power-law

$$F_2(M) \sim M^{2\phi_2}\,, \qquad \phi_2 = \phi_{2,\text{cr}}^B = \tfrac{5}{6}\,, \tag{2}$$

where ϕ_2 is the intermittency index, and provided the freeze-out occurs at exactly the critical point [10].

Noisy experimental data require the subtraction of a background of uncorrelated and misidentified protons, which is achieved through the construction of correlation-free mixed events. The critical behaviour is then expected to be revealed in the correlator, $\Delta F_2(M) = F_2^{(d)}(M) - F_2^{(m)}(M)$, where mixed event (m) moments are subtracted from data (d) moments. $\Delta F_2(M)$ should then scale as a power law, $\Delta F_2(M) \sim M^{2\phi_2}$, in a limited range, with the same intermittency index as the pure critical system[1].

[1] The actual correlator contains a mixed term with the background, which can be shown to be negligible through use of CMC simulation mixed with non-critical background.

Furthermore, calculation of SSFMs is smoothed by averaging over many lattice positions (lattice averaged SSFMs, see [9]). An improved estimation of statistical errors of SSFMs is achieved by the use of the bootstrap method [11–13], whereby the original set of events is resampled with replacement [9].

A proton generating modification of the Critical Monte Carlo (CMC) code [5, 10] is used to simulate a system of critically correlated protons, which are mixed with a non-critical background to study the effects on the quality of intermittency analysis.

3. Overview of proposed NA61 data sets

Following the detection of power-law fluctuations compatible with criticality in the NA49 "Si"+Si dataset [9], we are encouraged to look for intermittency in medium-sized nuclei collisions recorded within the successor NA61 experiment. In order to reliably perform an intermittency analysis, we require large event statistics (a minimum of 100 K events, ideally of the order of 1 M events), reliable particle identification (candidate proton purity of at least 80–90%), and a relatively high mean proton multiplicity density in mid-rapidity for 5–10% most central collisions (typically, $\mathrm{d}N_p/\mathrm{d}y \geq 1.5 \to 2$ for $|y_{\mathrm{CM}}| \leq 0.75$, $p_{\mathrm{T}} \leq 1.5$ GeV/c). Subsequently, our two main candidate NA61 systems for study are ^{7}Be+^{9}Be and ^{40}Ar+^{45}Sc at 150 A GeV.

Pilot analysis of NA61 Be+Be data suggests $\mathrm{d}N_p/\mathrm{d}y|_{|y_{\mathrm{CM}}|\leq 0.75,\, p_{\mathrm{T}}\leq 1.5} \sim 0.75$, a rather low value for the standards of an intermittency analysis. Ar+Sc analysis of NA61 data is still in progress; however, simulations performed with the EPOS event generator [14], for a maximum impact parameter $b \sim 3.5$ fm, suggest $\mathrm{d}N_p/\mathrm{d}y|_{|y_{\mathrm{CM}}|\leq 0.75,\, p_{\mathrm{T}}\leq 1.5} \sim 4$, quite adequate for an intermittency analysis.

4. Results

Based on the pilot analysis of NA61 Be+Be data, we simulate in EPOS a set of 200 K central Be+Be collisions at 150 A GeV. We then calculate $F_2(M)$ and $\Delta F_2(M)$ for these events, as well as extract the mean proton multiplicity and one-particle transverse momentum distributions which are then plugged in as input parameters to a CMC simulation of 500 K critical events and the background proton generator, respectively. The pure CMC critical exponent is adjusted according to Eq. (2). In Fig. 1, left panel, we see that the $F_2(M)$ level of EPOS-generated events can be reproduced by mixing critical protons with 99.5% noise. In the middle panel, it is evident that while the absolute magnitude of $\Delta F_2(M)$ decreases by orders of magnitude with the addition of more noise, its scaling persists for up to 98% noise levels. However, at the 99.5% noise level required to match EPOS with noisy CMC moments, intermittency has been lost, as evidenced by the fact that the intermittency index ϕ_2 fluctuates around zero, $\phi_2 = -0.21^{+0.39}_{-1.13}$ (right panel).

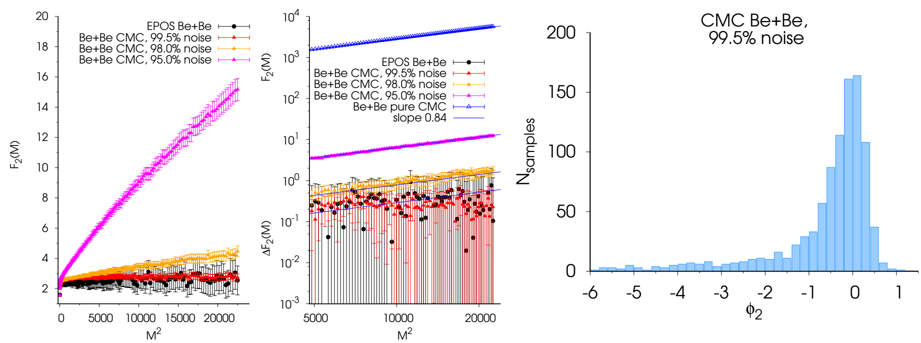

Fig. 1. SSFMs $F_2(M)$ (left) and $\Delta F_2(M)$ (middle) of EPOS and noisy CMC Be+Be simulated collisions (10% most central, 150 A GeV). For comparison, $F_2(M)$ of pure CMC is plotted, along with the theoretically expected slope; (right) distribution of ϕ_2 values, obtained via bootstrap resampling of events.

Similarly as with Be+Be, we simulate 100 K EPOS Ar+Sc events, as well as 500 K critical CMC events with the proper multiplicity. In Fig. 2, left panel, we see that again a 99.5% noise level can reproduce the magnitude of EPOS moments $F_2(M)$. However, in the middle panel, it is evident that in the Ar+Sc case, the correlator $\Delta F_2(M)$ of noisy CMC retains criticality for up to 99.5% noise. In the right panel, the distribution of ϕ_2 gives as a median and error of $\phi_2 = 0.75^{+0.12}_{-0.12}$, which is compatible with $\phi^B_{2,\mathrm{cr}}$ within errors.

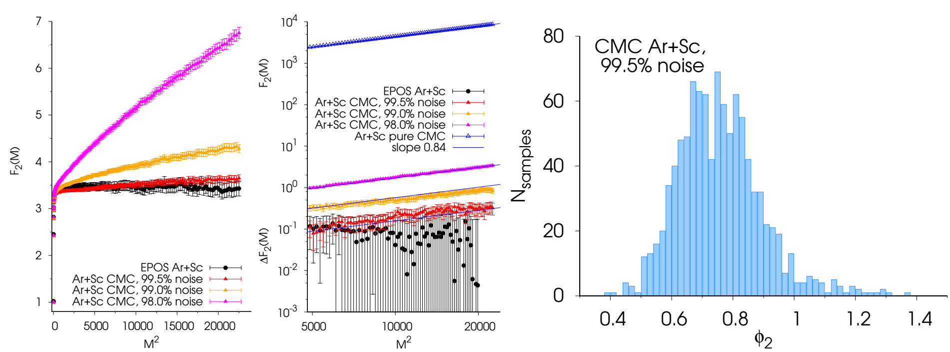

Fig. 2. SSFMs $F_2(M)$ (left) and $\Delta F_2(M)$ (middle) of EPOS and noisy CMC Ar+Sc simulated collisions (10% most central, 150 A GeV). For comparison, $F_2(M)$ of pure CMC is plotted, along with the theoretically expected slope; (right) distribution of ϕ_2 values, obtained via bootstrap resampling of events.

5. Summary and conclusions

The study of self-similar (power-law) fluctuations of the proton density in transverse momentum space through intermittency analysis provides us with a promising set of observables for the detection of the QCD critical point. A preliminary study of light nuclei collisions in the NA61 experiment indicates that an intermittency analysis is feasible for (at least) the Ar+Sc system at maximum SPS energy. Performing a systematic intermittency analysis in this system size region (Be+Be, Ar+Sc, Xe+La) will hopefully lead to an accurate determination of the critical point location.

This work was supported by the National Science Centre, Poland (NCN) (grant No. 2014/14/E/ST2/00018).

REFERENCES

[1] K. Fukushima, T. Hatsuda, *Rep. Prog. Phys.* **74**, 014001 (2011).
[2] C. Alt *et al.*, *Phys. Rev. C* **75**, 064904 (2007); **78**, 034914 (2008).
[3] L. Adamczyk *et al.*, *Phys. Rev. Lett.* **112**, 032302 (2014).
[4] T. Anticic *et al.*, *Phys. Rev. C* **70**, 034902 (2004); **79**, 044904 (2009).
[5] N.G. Antoniou *et al.*, *Nucl. Phys. A* **693**, 799 (2001).
[6] N.G. Antoniou, Y.F. Contoyiannis, F.K. Diakonos, G. Mavromanolakis, *Nucl. Phys. A* **761**, 149 (2005).
[7] Y. Hatta, M.A. Stephanov, *Phys. Rev. Lett.* **91**, 102003 (2003).
[8] T. Vicsek, *Fractal Growth Phenomena*, World Scientific, Singapore, 1989, ISBN 9971-50-830-3.
[9] T. Anticic *et al.*, *Eur. Phys. J. C* **75**, 587 (2015).
[10] N.G. Antoniou, F.K. Diakonos, A.S. Kapoyannis, K.S. Kousouris, *Phys. Rev. Lett.* **97**, 032002 (2006).
[11] W.J. Metzger, *Estimating the Uncertainties of Factorial Moments*, HEN-455, 2004.
[12] B. Efron, *Ann. Stat.* **7**, 1 (1979).
[13] T. Hesterberg *et al.*, *Bootstrap Method and Permutation Tests*, W.H. Freeman and Co., USA, 2003, ISBN-10:0716757265.
[14] K. Werner, F. Liu, T. Pierog, *Phys. Rev. C* **74**, 044902 (2006).