



XXVIIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2019)

NA61/SHINE results on fluctuations and correlations at CERN SPS energies

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Abstract

The aim of the NA61/SHINE strong interaction programme is to explore the phase diagram of strongly interacting matter. The main physics goals are the study of the onset of deconfinement and the search for the critical point of strongly interacting matter. These goals are pursued by performing a beam momentum (13A – 150/158A GeV/c) and system size (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) scan. This contribution presents new results from NA61/SHINE on fluctuations and correlations which include in particular quantum correlations, as well as multiplicity and net-charge fluctuations, proton density fluctuations and anisotropic collective flow. Obtained results are compared with other experiments and with model predictions.

Keywords: critical point, onset of deconfinement, fluctuations, intermittency, femtoscopy, flow

1. Introduction

NA61/SHINE [1] at the CERN Super Proton Synchrotron (SPS) is a fixed-target experiment pursuing a rich physics program including measurements for strong interactions, neutrino, and cosmic ray physics.

The strong interactions program focuses on search for the critical point (CP) and study of the onset of deconfinement (OD) of strongly interacting matter. NA61/SHINE is the first experiment to perform a two-dimensional scan, in beam momentum (13A – 150/158A GeV/c) and system size (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) of colliding nuclei.

2. Search for the critical point

The expected signal of a critical point is a non-monotonic dependence of various fluctuation/correlation measures in such a scan. A specific property of the CP - the increase in the correlation length - makes fluctuations its basic signal. Special interest is devoted to fluctuations of conserved charges (electric, strangeness or baryon number) [2].

<https://doi.org/10.1016/j.nuclphysa.2020.121753>

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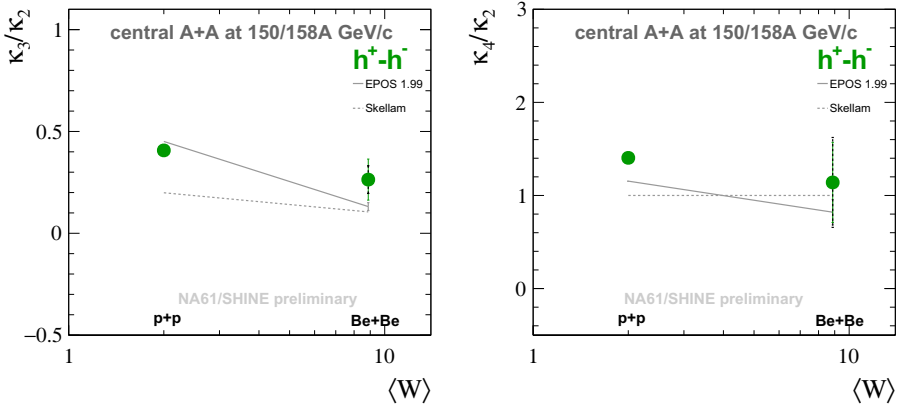


Fig. 1. Preliminary NA61/SHINE results on the system size dependence of $\kappa_3/\kappa_2[h^+ - h^-]$ and $\kappa_4/\kappa_2[h^+ - h^-]$ at 150/158A GeV/c as a function of the mean number of wounded nucleons, $\langle W \rangle$. Statistical uncertainty is indicated with green bars. Statistical uncertainty was obtained with the bootstrap method and it is indicated as a dashed black bar. Systematic uncertainty/bias: p+p - corrected data with estimate on systematic uncertainty; Be+Be - uncorrected data with estimate of systematic bias. Systematic uncertainty/bias is indicated with a green bar.

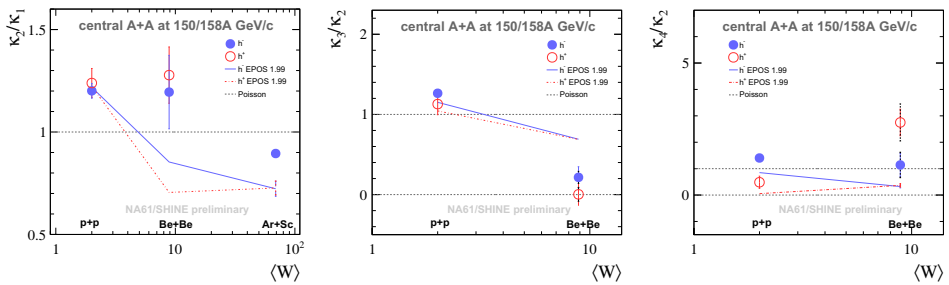


Fig. 2. Preliminary NA61/SHINE results on the system size dependence of multiplicity fluctuations of h^+ and h^- at 150/158A GeV/c as a function of the mean number of wounded nucleons, $\langle W \rangle$. Statistical uncertainty was obtained with the bootstrap method and it is indicated as a dashed black bar. Systematic uncertainty/bias: p+p and Ar+Sc - corrected data with estimate on systematic uncertainty (except published $\omega[h^-]$ and $\omega[h^+]$ [3]); Be+Be - uncorrected data with estimate of systematic bias. Systematic uncertainty/bias is indicated with a blue/red bar.

In order to compare fluctuations in systems of different sizes one should use intensive quantities, i.e. quantities insensitive to system volume. Such quantities are constructed by division of cumulants κ_i of the measured distribution (up to fourth order), where i is the order of the cumulant. For second, third and fourth order cumulants intensive quantities are defined as: κ_2/κ_1 , κ_3/κ_2 and κ_4/κ_2 .

Figure 1 shows the system size dependence of third and fourth order cumulant ratio of net-charge at 150/158A GeV/c. Measured data are in agreement with EPOS 1.99 model [4, 5] predictions. More detailed examination of system size dependence of the same quantities for negatively and positively charged hadrons (Fig. 2) shows very different system size dependence. Moreover, none of the measured quantities of h^+ and h^- are reproduced by the EPOS 1.99 model. This disagreement indicates that we do not fully understand the underlying physics how fluctuations are induced. Thus, more detailed studies are needed.

In search of CP a possible tool is proton intermittency which should follow power-law fluctuations near CP. It can be checked by studying the scaling behavior of 2^{nd} factorial moments $F_2(M)$ with the cell size or, equivalently, with the number of cells in (p_x, p_y) space of protons at mid-rapidity (see Refs. [6, 7, 8]). For experimental data a non-critical background must be subtracted with mixed events. After subtraction, the second factorial moments $\Delta F_2(M)$ should scale according to power-law for $M \gg 1$ with resulting critical

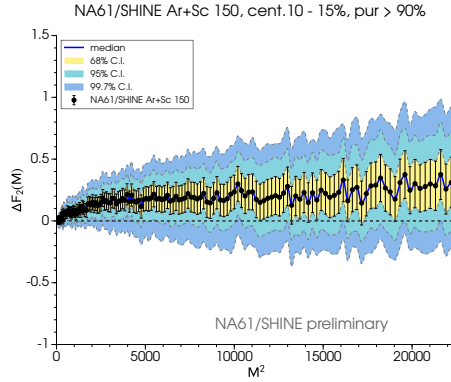


Fig. 3. Preliminary NA61/SHINE results on proton intermittency signal with total available statistics of Ar+Sc interactions. Only statistical uncertainty shown. For details see text.

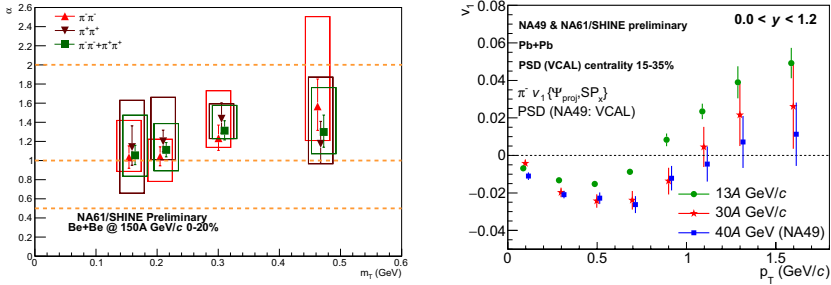


Fig. 4. Left: Preliminary NA61/SHINE results on α parameter in Be+Be collisions at 150A GeV/c. Static and systematic uncertainties indicated with a bar and a box, respectively. Right: NA49 [18] and NA61/SHINE [21] preliminary results on energy dependence of v_1 in Pb+Pb collisions. Only statistical uncertainty indicated.

exponent ϕ_2 comparable to theoretical predictions [9]. Figure 3 shows $\Delta F_2(M)$ in semi-central Ar+Sc interactions at 150A GeV/c with higher considered statistics then results released in 2018 [10]. These results indicated positive values of ΔF_2 which may be connected with the CP. Current results obtained on higher statistics (208k events vs 143k events) indicate weaker ΔF_2 signal.

At the CP, the spatial correlation function becomes a power-law $\sim r^{-(d-2+\eta)}$, where d represents the number of dimensions. One can predict a critical exponent η (related to spatial correlations) for the QCD universality class, which is the 3D-Ising model for QCD [11, 12]. The predicted value of η at the CP is 0.03631 [13]. For the random field 3D Ising $\eta = 0.50 \pm 0.05$ [14]. In the HBT analysis the momentum correlation function $C(q)$ of produced particles is directly related to the normalized source distribution $S(r)$ via $C(q) = 1 + |\tilde{S}|^2$, where \tilde{S} is the Fourier transformation of $S(r)$. The data analysis was done by using a Levy distributed source function [15]. Since, it leads to the same power-law tails, the Levy exponent α was assumed to be identical to the spatial correlation exponent η [16]. In the vicinity of the critical point, very low α values (around 0.5) may be expected and this can be measured by investigating the Bose-Einstein correlation function $C(q) = 1 + \lambda e^{-(qR)^\alpha}$. Figure 4 (left) shows measured values of α parameter for pion pairs ($\pi^-\pi^+$, $\pi^+\pi^+$ and $\pi^-\pi^- + \pi^+\pi^+$) in 20% most central Be+Be collisions at 150A GeV/c.

All measured combinations indicate $1 < \alpha < 2$ which is far from the CP value. In addition to the CP, α values lower than 2 can be caused by anomalous diffusion, QCD fractal structured jet fragmentation, and also to some extent by the averaging over broad event class (e.g. centrality) [17].

3. Bulk matter properties

Spatial asymmetry of the initial energy density in the overlapping region of the colliding relativistic nuclei is converted, via interactions between produced particles, to the asymmetry of momentum distribution of particles in the final state. The resulting asymmetry encodes important information about the transport properties of the QCD matter created during the collision. Asymmetry is usually quantified with the coefficients v_n in a Fourier decomposition of the azimuthal distribution of produced particles relative to the reaction plane. The NA61/SHINE has a unique way to estimate the reaction plane with the Projectile Spectator Detector (for details see Refs. [18, 19]).

The energy dependence of flow coefficients is of particular importance. At the energies of SPS and Beam Energy Scan Program at RHIC it is expected that the slope of proton directed flow at mid-rapidity, dv_1/dy , changes its sign [20]. Directed flow of π^- for Pb+Pb collisions at different energies is presented in Fig. 4 (right). The NA49 results [18] for 40A GeV/c were obtained using spectator plane estimated with Veto calorimeter (VCAL). Directed flow of π^- , in particular the p_T dependence where v_1 changes its sign, shows collision energy dependence.

4. Summary

Presented experimental results show no indications of the CP in Be+Be collisions at 150A GeV/c. Enlarged statistics of Ar+Sc interactions has not improved the significance of the proton intermittency signal, making it inconclusive. In order to qualitatively measure the CP signal, the background phenomena should be studied in details. Measured system size dependences of multiplicity fluctuations show clear disagreement with model predictions.

The measured directed flow of pions shows energy dependence, with the slope of negatively charged pions changing sign at different collision centralities in Pb+Pb collisions (for details see Ref. [19]).

Acknowledgements: This work was supported by the National Science Centre, Poland under grants no. 2016/21/D/ST2/01983 and 2014/14/E/ST2/00018.

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