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Search for the critical point in NA61/SHINE

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The NA61/SHINE experiment at the CERN SPS is a multipurpose fixed-target spectrometer for charged and neutral hadron measurements. Its research program includes studies of strong interactions as well as reference measurements for neutrino and cosmic-ray physics. One major goal of its strong interaction program is to determine the existence and pinpoint the location of the QCD critical point, an object of both experimental and theoretical studies.

This contribution will summarize the current status of NA61/SHINE critical point searches in nucleus-nucleus collisions, in the collision energy range $\sqrt{s_{NN}} = 5 - 17$ GeV. The review includes studies of fluctuations of net-electric charge, femtoscopy analysis of $\pi\pi$ pairs, as well as intermittency of protons and negatively charged hadrons. No clear indication of the critical point has been observed so far. Finally, we report on the development of novel methods aimed at solving the long-standing problem of bin-by-bin correlations in experimental intermittency analysis, and for a more accurate handling of systematics and uncertainties.

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[1] For the NA61/SHINE collaboration
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1. Introduction

NA61/SHINE [1] is the second largest fixed target experiment at CERN. As a direct, upgraded continuation of its predecessor NA49, the detector offers a nearly continuous experimental data flow for three decades. Its research program includes heavy-ion physics as well as measurements for neutrino (J-PARC, Fermilab) and cosmic-ray studies (Pierre-Auger, KASCADE, satellite experiments). In this paper, only a selected set of most recent results related to the NA61/SHINE critical point search program will be addressed.

A key question in the study of non-perturbative QCD is to determine the structure of the QCD Phase Diagram, that is, the location and type of phase transition boundaries between the various states of strongly interacting matter, as a function of temperature T and baryochemical potential μ_B (or nuclear density, n_B). Evidence from Lattice QCD and effective models indicates a smooth cross-over between hadronic matter and quark-gluon plasma at high T and low μ_B, and a 1^{st} order transition at low T and high μ_B, ending at a critical point (CP), in the vicinity of which a 2^{nd} order transition is widely expected to occur.

At the vicinity of the CP, enhanced, non-monotonic fluctuations of various observables [2], as well as scale-invariant (power-law) particle correlations [3–5] are expected to occur. Correlations in configuration space are projected to momentum space via quantum statistics and collective flow, where they can be observed by collision experiments. In order to do so, one must perform a carefully stepped scan in parameters that can be controlled experimentally, such as collision energy, nuclear mass number, centrality, and others. By varying such parameters, the freeze-out conditions of the colliding systems in (T, μ_B) vary accordingly. NA61/SHINE has completed a two-dimensional scan in collision energy ($13A - 150A$ GeV/c) and system size (p+p, Be+Be, Ar+Sc, Xe+La, Pb+Pb); it is therefore in a unique position to pursue the search for critical point signatures in nuclear collisions.

2. Net charge fluctuations

Fluctuations of conserved charges (electric, strangeness or baryon number) are of particular interest in the NA61/SHINE energy-system size scan [7].

To compare fluctuations in systems of different sizes, one should use quantities insensitive to system volume, i.e. intensive quantities. They are constructed by division of cumulants κ_i of the measured multiplicity distribution (up to fourth order), where i is the order of the cumulant. In case of net-charge, cumulant ratios are defined to be $\kappa_2[h^+ - h^-]/(\kappa_1[h^+] + \kappa_1[h^-])$, $\kappa_3/\kappa_1[h^+ - h^-]$ and $\kappa_4/\kappa_2[h^+ - h^-]$. Reference values are 0 for no fluctuations and 1 for independent particle production.

Figure 1 shows the system size and energy dependence of second, third and fourth order cumulant ratio of net-electric charge in p+p as well as central Be+Be and Ar+Sc interactions. So far, no significant non-monotonic signal is observed; more detailed studies are needed.

3. Femtoscopy analysis

The study of Bose-Einstein correlations (femtoscopy) in pairs of bosons (e.g. pions) produced in an ion collision can reveal the space-time structure of the hadron emitting source [8]. In particular, for small to intermediate systems, we compare measurements with source calculations

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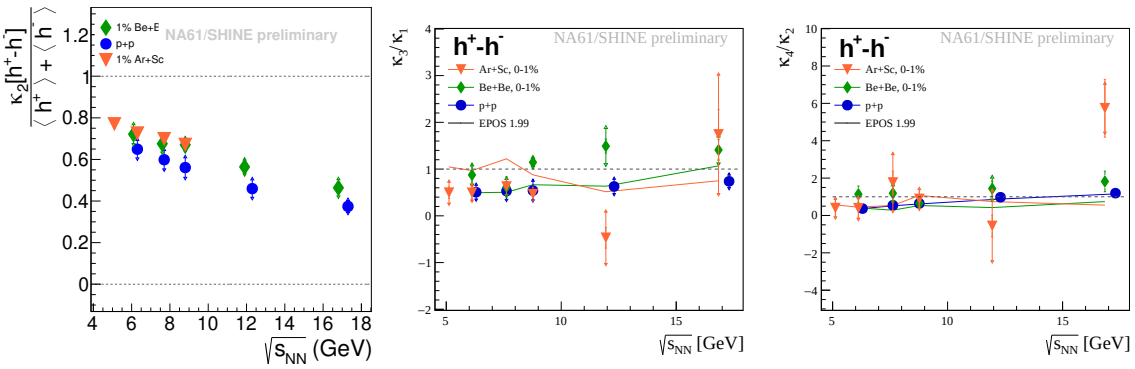

Figure 1: System size and energy dependence of $\kappa_2\,[h^+ - h^-]\,/(\langle h^+\rangle + \langle h^-\rangle)$, $\kappa_3/\kappa_1\,[h^+ - h^-]$, and $\kappa_4/\kappa_2\,[h^+ - h^-]$. Statistical uncertainty was obtained with the bootstrap method and is indicated as a black bar. Systematic uncertainty/bias (indicated with arrows): p+p – corrected data with estimate on systematic uncertainty; Be+Be/Ar+Sc – uncorrected data with estimate of systematic bias. The experimental results are compared with `EPOS1.99` model predictions. Figure adapted from Ref. [6].

based on Lévy-distributed sources, to explore the pair transverse mass dependence of the Lévy source parameters. The Lévy exponent α is of particular significance, as it characterizes the shape of the source and is sensitive to the system freezing out in the vicinity of the CP.

The femtoscopic correlation function fit to the data takes the form:

$$C(q) = 1 + \lambda \cdot e^{-|qR|^{\alpha}}, \tag{1}$$

where $q = |\mathbf{p}_1 - \mathbf{p}_2|$ is the momentum difference between bosons in the pair (Figure 2 *(left)*), R is the Lévy scale parameter, λ is the correlation strength, and α is the Lévy exponent (index) which is a shape parameter of the distribution (for $\alpha = 2$, we get a Gaussian distribution).

Figure 2 *(right)* shows the Lévy index α values fitted to $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs produced at different SPS collision energies, for Be+Be and Ar+Sc collisions observed by the NA61/SHINE experiment. The recent Ar+Sc results are close to Gaussian, and far from the CP predicted value. No indication of the critical point is observed at any of the investigated energies.

4. Intermittency analysis

A characteristic feature of a second order phase transition is the divergence of the correlation length of the physical system, leading to a scale-invariant system with long-range correlations. The density-density correlation function of the phase transition order parameter (for example, the chiral σ-condensate or the net baryon density n_B [10]) assumes a power-law form, with critical exponents determined by the 3D Ising universality class [3–5]. An observable tailored for probing such power-law behaviour are the scaled factorial moments $F_r(M)$ in transverse momentum space,

$$F_r(M) \equiv \left\langle \frac{1}{M^2}\sum_{m=1}^{M^2} n_m(n_m-1)\ldots(n_m-r+1)\right\rangle \Big/ \left\langle \frac{1}{M^2}\sum_{m=1}^{M^2} n_m\right\rangle^r, \tag{2}$$

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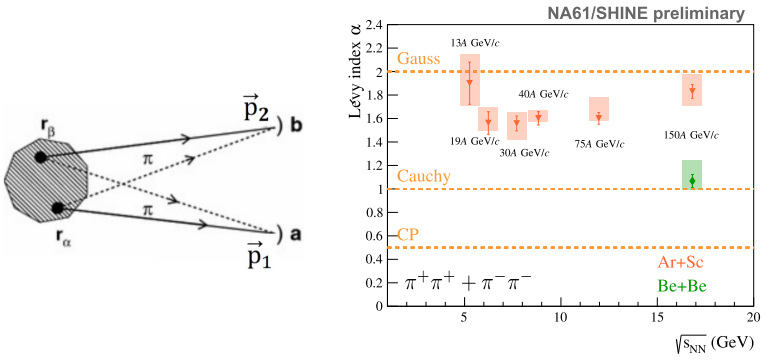

Figure 2: *(left)* Schematic representation of a correlated pair of pions emitted from a source; *(right)* Values of α obtained by fitting the pion pair correlation function, Eq.(1), for pions produced in 0-20% central Be+Be at 150A GeV/c and 0-10% central Ar+Sc collisions at all available energies, as a function of $\sqrt{s_{NN}}$. Special cases corresponding to a Gaussian ($\alpha = 2$) or a Cauchy ($\alpha = 1$) source are shown, as well as $\alpha = 0.5$, which corresponds to the critical point. Boxes denote systematic uncertainties, bars represent statistical uncertainties. Figure adapted from [9].

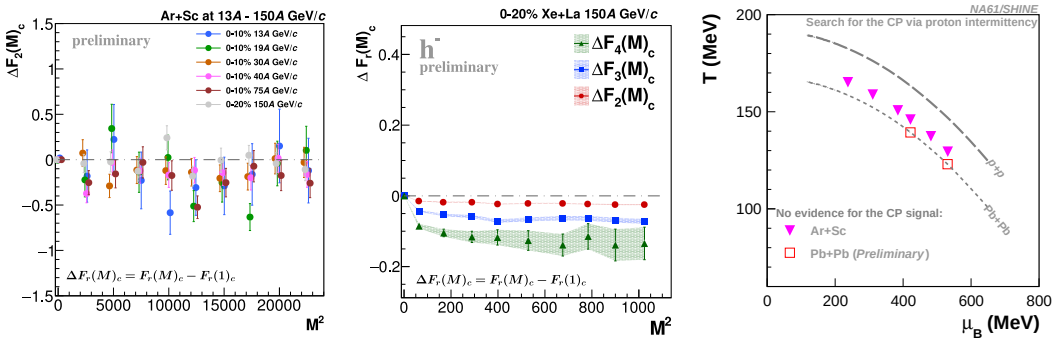

Figure 3: *(left)* Results on the proton multiplicity 2nd-order SFMs $\Delta F_2(M)$ for NA61/SHINE Ar+Sc collisions in the energy range 13 – 150A GeV/c [14, 15]; *(middle)* 2nd through 4th-order SFMs for NA61/SHINE negatively charged hadrons in Xe+La collisions at 150A GeV/c [16]; cumulative variables [12] and independent bins are used; *(right)* Status of NA61/SHINE CP search via proton intermittency [15]. Points indicate freeze-out conditions of respective reactions in (T, μ_B), as extrapolated from [17].

where n_m is the number of particles in a transverse momentum (p_x, p_y) bin in an event, M^2 is the total number of 2D bins, and $\langle \ldots \rangle$ denotes averaging over events. Intermittency is defined as a power-law scaling of $F_r(M)$ with the number of bins, or equivalently bin size: $F_r(M) \sim \left(M^2\right)^{\phi_r}$, with ϕ_r being the r-th order intermittency index [5, 11]. For protons[1] and $r = 2$, $\phi_2 = 5/6$ is expected [5]. When probing intermittent behaviour, baseline correlations have to be subtracted; this can be done either through the cumulative variable transform [12], or by subtracting mixed event moments from those of data [13]; the resulting subtracted 2nd-order scaled factorial moments (SFMs) carrying the critical signal are denoted by $\Delta F_2(M)$.

[1]Protons substitute for net baryons [10], an approximation that is valid when antiprotons are much fewer than protons in events.

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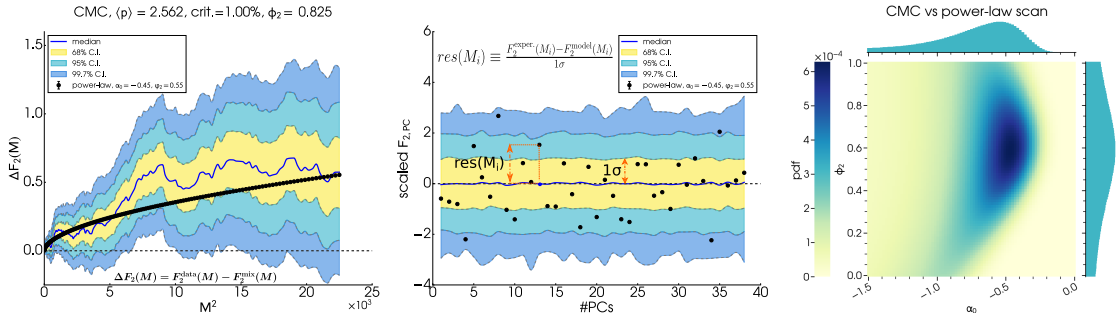

Figure 4: *(left)* Correlated proton $\Delta F_2(M)$ for $\sim$ 8K bootstrap samples [19] of a synthetic CMC data set (colored bands) corresponding to $\sim$ 400K Ar+Sc-like collisions with 1% critical protons. Black points represent a power-law model fit, with parameters (α_0, ϕ_2); *(middle)* $\Delta F_2(M)$ for the same CMC data set, transformed to the PC coordinates; *(right)* Normalized likelihood distribution for a grid of parametrized power-law models against the same CMC data set. Figures adapted from Ref. [20].

Figure 3 *(left)* shows the behaviour of proton multiplicity moments $\Delta F_2(M)$ for a number of NA61/SHINE Ar+Sc collision datasets in the energy range 13 − 150A GeV/c. The number of transverse momentum space subdivisions (bins) ranges in $1^2 \leq M^2 \leq 150^2$, in a window $-1.5 \leq p_{x,y} \leq 1.5$ GeV/c at mid-rapidity. No intermittency signal indicative of the CP is observed.

NA61/SHINE also looked into negatively charged hadrons (h^-) intermittency in Xe+La collisions at 150A GeV/c, as a check of the recently published STAR Collaboration intermittency results for all charged hadrons in Au+Au collisions [18]. Figure 3 *(middle)* shows NA61/SHINE h^- results for $r = 2 - 4$ SFMs. When a cumulative transform is applied to the momenta in order to remove baseline/spurious effects, no intermittency effect remains [16]. This suggests a baseline effect as the origin of the observed STAR result.

Figure 3 *(right)* summarizes NA61/SHINE system size & energy proton intermittency scan, showing the estimated freeze-out conditions for the analyzed systems; so far, no significant intermittency signal is observed.

The above presented NA61/SHINE intermittency results utilize independent bins in order to avoid M-bin correlations, which invalidate fitting and comparison with models. This method has the drawback of reducing event statistics per bin, thus significantly inflating uncertainties. An alternative approach has been developed to handle bin correlations [20], based on the statistical tool of Principal Component Analysis (PCA). Figure 4 illustrates how PCA works: a set of original moments generated via the Critical Monte Carlo (CMC) simulation [5, 20] *(left)* are transformed into statistically independent linear combinations of the original M-bins, called the principal components (PCs) *(middle)*. A power-law candidate model (black points), $\Delta F_2^{\text{model}}(M) \equiv 10^{\alpha_0} \left(\frac{M^2}{10^4}\right)^{\phi_2}$ is transformed in the same way, and its residuals are compared to the data bootstrap variance in the PCs. The result is a likelihood value for the model, which can be collected into a likelihood distribution of model parameters *(right)*. This allows the reliable extraction of ϕ_2 and other parameter confidence intervals from correlated data, making use of the full event statistics. We expect this method to permit more reliable studies of intermittency phenomena, in NA61/SHINE as well as other HEP experiments.

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5. Summary

In this work, we have provided a bird's-eye view of the NA61/SHINE critical point search program, including net charge fluctuations, femtoscopy analysis, and intermittency analyses on both protons and negatively charged hadrons, for a variety of system sizes and SPS collision energies. Findings from NA61/SHINE give no indication of the critical point so far; however, they point at the crucial importance of a proper understanding of non-critical (baseline) effects in the CP search.

We report a new development in intermittency analysis, which effectively solves the long-standing bin-by-bin correlation problem [20]; this allows the use of full statistics with correlated bins and reliable model scans to locate the best-fitting models to the data. Event statistics plays a crucial role, as intermittency analysis is particularly data-hungry. Nevertheless, it is within the capabilities of the upgraded NA61/SHINE detector to provide sufficient data for such analyses.

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