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V.Z. REYNA ORTIZ for the NA61/SHINE Collaboration
Jan Kochanowski University of Kielce
(Ul. Żeromskiego, 5, 25-369 Kielce, Poland; e-mail: val.reyna@cern.ch)

SEARCH FOR THE CRITICAL POINT VIA INTERMITTENCY ANALYSIS IN NA61/SHINE[1]

The existence and location of the QCD critical point are objects of both experimental and theoretical studies. The comprehensive data collected by NA61/SHINE during a two-dimensional scan in beam momentum and system size allows for a systematic search for the critical point – a search for a non-monotonic dependence of various correlation and fluctuation observables on collision energy and size of colliding nuclei. Intermittency analysis is a statistical tool used in heavy ion collisions that includes the study of scaled factorial moments (SFMs) of multiplicity distributions in the 2D transverse momentum space to detect power-law fluctuations and explore different aspects of the QCD phase diagram. In particular, proton intermittency has been used to locate the critical point of strongly interacting matter, and, more recently, intermittency of negatively charged hadrons have also been used to study the properties of QCD interactions.

Keywords: critical point, intermittency.

1. Introduction

This proceeding presents and discusses the experimental results obtained by the NA61/SHINE collaboration regarding proton intermittency in central $^{40}\mathrm{Ar} + {}^{45}\mathrm{Sc}$ at $13A$, $19A$, $30A$, $40A$, $75A$ and $150A$ GeV/c beam momenta ($\sqrt{s_{NN}} = 5.1$, 6.1, 7.6, 8.8, 11.9, 16.8 GeV) collisions and negatively charged hadron intermittency in central $^{131}\mathrm{Xe} + {}^{139}\mathrm{La}$ collisions at $150A$ GeV/c ($\sqrt{s_{NN}} = 16.8$ GeV). The reported results focus on the search for the critical point (CP) and the identification of misleading signals.

2. NA61/SHINE Search for the Critical Point

The multi-purpose NA61/SHINE experiment [1] conducted the measurements at the CERN Super Proton Synchrotron (SPS). Within the strong interactions program, NA61/SHINE studies the properties of the onset of deconfinement and seeks the critical point of strongly interacting matter. The primary strategy of the NA61/SHINE collaboration in this study [2] is to perform a comprehensive two-dimensional scan of the phase diagram of strongly interacting matter by varying the energy (beam momentum $13A$–$150A$ GeV/c) and the size of the colliding systems (p + p, p + Pb, Be + Be, Ar + Sc, Xe + La).

Determining the structure of the phase diagram of strongly interacting matter is a significant task in heavy ions physics. Lattice quantum chromodynamics (QCD) predicts a crossover between confined and deconfined states at low baryochemical potential and high temperature during the freeze-out stage. A phase transition occurs between nuclear liquid and gas at low temperatures and high baryochemical potential. Experimental evidence [3, 4] and theoretical predictions [5, 6] suggest a distinct transition between hadron gas and quark-gluon plasma (QGP), commonly proposed to be separated by a first-order phase-transition line that ends at the critical point. However, the exact location of this critical end-point is still unknown, and some calculations indicate there may not be a critical point, but rather a crossover [6].

If the system freezes out close to the critical point in terms of temperature and baryochemical potential, the characteristic signatures of the critical point could

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[1] This work is based on the results presented at the 2024 "New Trends in High-Energy and Low-x Physics" Conference.

be observed. This raises the possibility that fluctuations may be enhanced at specific collision energies and system sizes within the NA61/SHINE phase-diagram-scan program [7, 8].

The analysis discussed in this proceeding is motivated by two key factors. First, it aims to explore the detection of the QCD critical point not only through the study of global fluctuations in integrated quantities on an event-by-event basis [9–11], but also by examining local power-law fluctuations [12] of QCD order parameters. At finite baryochemical potentials, critical fluctuations can also manifest themselves in the net-proton density and may be observed through the intermittent behavior [13].

The second motivation concerns the results obtained by STAR collaboration and published in [14], where the STAR experiment presented their measurements of intermittency in heavy-ion collisions at RHIC. They studied scaled factorial moments of identified charged hadrons combining p^+, p^-, $K\pm$, and $\pi\pm$ and calculated up to the sixth order in central Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7–200 GeV. Reference [14] presents an increase in $\Delta F_q(M)$ in Au + Au collisions at all energies after the background subtraction [see methodology section], but there was a missing physics explanation for this phenomenon. NA61/SHINE investigates this behavior using 0–20% central Xe + La collisions at $150A$ GeV/c in laboratory frame.

3. Intermittency

The original concept [16], followed by experimental data results in the NA49 experiment [15] suggest that particle-density fluctuations should exhibit a power-law dependence on the phase-space resolution, if the system freezes out near the critical point [17]. The mentioned analysis focuses on the behavior of second-scaled factorial moments (SFMs) of second-order in the transverse-momentum space [18, 19] as a function of the number of equal-size cells used for partitioning, which serves as a measure of proton-density fluctuations. More on experimental and theoretical development of intermittency can be found in [17–22].

4. Methodology: Scaled Factorial Moments

Intermittency analysis examines how the Scaled Factorial Moments (SFMs) $F_r(M)$ of particle transverse momenta scale with the number of, subdivided (p_x, p_y) plane into equally-sized 2D bins M^2

$$F_r(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m-1)...(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^r}, \quad (1)$$

where n_m is the number of protons in the m-th bin and $\langle ... \rangle$ denotes averaging over events. In particular, for the second-order moment:

$$F_2(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m-1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^2}. \quad (2)$$

When the system freezes out at CP, the second scaled factorial moment $F_r(M)$ is expected to follow a power-law behavior $F_r(M) \sim (M^2)^{\phi_r}$. In particular, for protons and $r = 2$, $\phi_2 = 5/6$ [15].

Scaled factorial moments strongly depend on the single-particle transverse momentum distribution that may dominate the possible effect of the critical point. There are two possible ways to study them.

4.1. p_T binning

The first, standard way of performing this analysis is to subdivide the (p_x, p_y) plane into equally-sized bins and note that the background of non-critical pairs must be subtracted at the level of factorial moments to eliminate trivial and non-critical correlations [15] (with a characteristic length scale that does not scale with bin size). First, a mixed event data set is constructed by mixing particles from the recorded data such that each mixed event consists of particles from different original events. Thus, we define $\Delta F_2(M)$ in terms of moments of original and mixed events:

$$\Delta F_2(M) = F_2^{\mathrm{data}}(M) - F_2^{\mathrm{mix}}(M). \quad (3)$$

Intuitively, STAR collaboration [14] also calculates Eq. (4), this quantity is also calculated for the present work of NA61/SHINE for negatively charged hadrons

$$\Delta F_r(M) = F_r^{\mathrm{data}}(M) - F_r^{\mathrm{mix}}(M). \quad (4)$$

4.2. Cumulative p_T binning

The other possibility is to transform transverse momentum components, p_x and p_y, into their cumulative

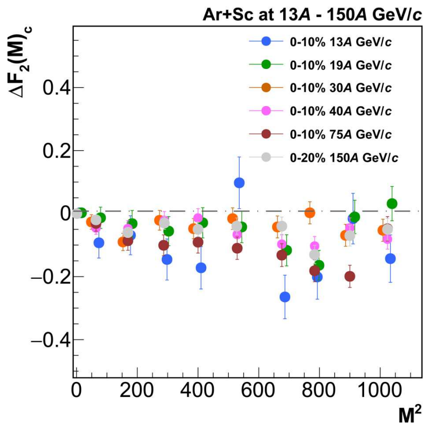

Fig. 1. Summary of published proton intermittency results from NA61/SHINE Ar + Sc energy scan. Results on the dependence of the scaled factorial moment of proton multiplicity distribution on the number of subdivisions in cumulative transverse momentum space M^2 for $1^2 \leq M^2 \leq 32^2$ are shown. Points for different energies are slightly shifted in the horizontal axis to increase readability

equivalents [23]. This transforms their distributions into uniform, preserving (approximately) the power-law relation, and the intermittency index of an ideal power-law correlation function remains invariant.

Examples of the effect of the transformation can be found in Refs. [24, 25] along with a full discussion.

For the present analysis of NA61/SHINE, we display results as:

$$\Delta F_r(M)_c = F_r(M) - F_r(1), \tag{5}$$

where $F_r(M)$ and $F_r(1)$ are obtained by employing the cumulative p_T binning. $F_r(1) = F_r(M)$ for uncorrelated particles in p_T).

5. Results

5.1. Proton Intermittency in central Ar + Sc collisions

The NA61/SHINE results on the proton intermittency in 0–10% central Ar + Sc collisions at 13*A*, 19*A*, 30*A*, 40*A*, and 75*A* GeV/*c* beam momenta ($\sqrt{s_{NN}} =$ = 5.1, 6.1, 7.6, 8.8, and 11.9 GeV) and 150*A* GeV/*c* ($\sqrt{s_{NN}}$ = 16.8 GeV) were published in [24, 25]. This analysis examined the behavior of the second-order scaled factorial moment of the proton multiplicity distribution, $F_2(M)$, with the increasing number of cells M^2 in cumulative transverse momentum.

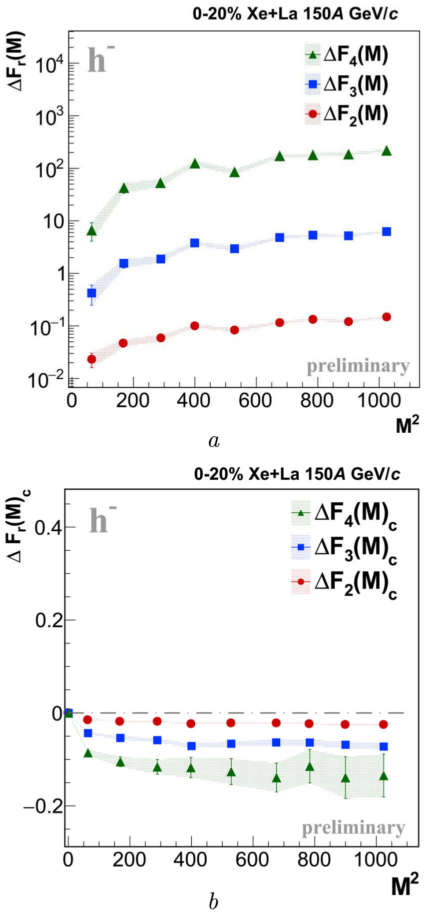

Fig. 2. Negatively charged hadrons intermittency results from NA61/SHINE Xe + La collisions at 150*A* GeV/*c* beam momentum. Results on 2nd, 3rd, and 4th scaled factorial moments of negatively charged hadrons multiplicity distribution on the number of subdivisions in p_T binning (*a*) transverse momentum space $1^2 \leq M^2 \leq 32^2$ and in cumulative p_T binning cumulative transverse momentum space (*b*) are shown. The open circles represent results on 0–20% central Xe+La collisions at 150*A* GeV/*c*

To eliminate the dependence of $F_2(M)$ on the shape of the single-particle transverse momentum distribution, its components, p_x and p_y, have been transformed into their cumulative equivalents. Moreover, the $F_2(M)$ values for different M^2 are statistically independent, as each data point was calculated using a separate sub-sample of available events. This removes possible undesirable correlation but at the cost of limiting the corresponding statistics.

The dependence of the second-order scaled factorial moment of proton multiplicity distribution at midrapidity on the number of subdivisions in cumulative transverse momentum space is shown in Fig. 1. The results show no intermittency signal due to the absence of a power-law of $\Delta F_2(M)_c$ vs M^2.

5.2. Negatively charged hadrons intermittency in central Xe + La collisions

A similar study of SFMs $\Delta F_n(M)_c$, for negatively charged hadrons produced in 0–20% central Xe + La collisions at $150A$ GeV/c was presented at this conference and at CPOD 2024 [26] with no indication of non-trivial power-law scaling.

However, the analysis was performed using p_T binning and cumulative p_T binning. In the first case, a peculiar behavior was seen. A structure of increase of $\Delta F_2(M)$ with M using Eq. (4) emerged; see Fig. 2, *a*. This structure is qualitatively similar to that in charged hadron results from STAR [14].

But this structure does not appear in cumulative p_T binning result, see Fig. 2, *b*. The key of this observation is that, by definition, the cumulative transformation preserves the scale-invariant power-law correlations and destroys other types of non-scale invariant correlations.

The fact that the procedure of cumulative transformation eliminates the characteristic structure from 2, *a* has been investigated by NA61/SHINE. It has been argued [26] that the short-range (HBT) correlations can explain this structure and, consequently, that the latter could also be the source of the cited STAR result.

These findings highlight the need for further development of experimental and theoretical methodologies to eliminate non-critical effects in the search for the critical point (CP) and strongly confirm the importance of having a solid baseline model, as emphasized in Refs [26, 27] and [28].

For now, numerous models available on the market still struggle to describe various non-critical phenomena. This could pose a significant obstacle in current and future efforts to establish the presence of the critical point.

6. Conclusions

NA61/SHINE contributes to the search with a extensive experimental program that, while yielding an overall negative result, underscores the critical importance of thoroughly understanding the non-critical 'baseline'. This refers to the non-critical effects that could otherwise be mistakenly interpreted as signs of the systemyh freezing out close to the critical point.

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В.З. Рейна Ортіс
від імені колаборації NA61/SHINE

ПОШУК КРИТИЧНОЇ ТОЧКИ
КХД В ЕКСПЕРИМЕНТІ NA61/SHINE

Існування та розташування критичної точки КХД є актуальними питаннями як експериментальних, так і теоретичних досліджень. Комплексні дані, зібрані NA61/SHINE під час двовимірного сканування по імпульсу променя та розміру системи, дозволяють здійснювати систематичний пошук критичної точки – пошук немонотонної залежності різних кореляційних і флуктуаційних спостережуваних величин від енергії зіткнення та розміру ядер, що зіштовхуються. Аналіз нерегулярностей – це статистичний метод, який використовується при вивченні процесів зіткнення важких іонів, що включає дослідження масштабованих факторних моментів (SFM) розподілу множинності в двовимірному просторі поперечного імпульсу для виявлення відхилення від степеневого закону та дослідження різних аспектів фазової діаграми КХД. Зокрема, протонна нерегулярність використовувалася для визначення критичної точки сильно взаємодіючої матерії, а нещодавно проводився аналіз нерегулярностей у випадку негативно заряджених гадронів для вивчення властивостей взаємодій у КХД.

Ключові слова: критична точка, нерегулярність.