Search for critical behavior of strongly interacting matter in the NA61/SHINE experiment

Daria Prokhorova for the NA61/SHINE Collaboration
Saint Petersburg State University, Saint Petersburg, Russia
E-mail: daria.prokhorova@cern.ch

Abstract. NA61/SHINE is a fixed-target experiment at CERN SPS which studies strongly interacting matter. The search for experimental signatures of the critical point is performed via a comprehensive two-dimensional scan of the phase diagram of strongly interacting matter by changing beam momenta (13A - 150A GeV/c) and the size of colliding systems (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb). Recent NA61/SHINE results on the search for critical behavior search in two-particle correlations, multiplicity and transverse momentum fluctuations, femtoscopy studies and intermittency analysis were presented.

1. Introduction

The aim of the strong interactions program of NA61/SHINE [1] is to study the properties of the onset of deconfinement and search for the critical point of strongly interacting matter. This study is of particular interest now due to the extensive experimental [2], [3] and theoretical work [4], [5], [6] investigating the structure of the phase diagram of QCD [7]. The most common scenario [8] suggests the hadron gas and quark-gluon plasma regions to be separated by a first order phase transition line at high baryo-chemical potentials and moderate temperatures. A crossover between both phases is assumed for high temperatures and low baryo-chemical potentials. The first order phase transition line then ends in a critical point. But the exact location of the critical end-point in the phase diagram is unknown. Moreover, some lattice QCD calculations suggest that there might be no critical point at all and only a crossover separates the two phases.

Since the direct control of the freeze-out temperature and baryo-chemical potential is impossible, one can only change the initial conditions. Therefore, the main strategy of the NA61/SHINE Collaboration in this study [9] is to perform the comprehensive two-dimensional scan of the phase diagram of strongly interacting matter by changing the energy and size of colliding systems. The characteristic signatures of the critical point could be observed, if the freeze-out point is located close to the expected critical one. Moreover, infinite correlation length in the scaled-invariant system in the vicinity of the expected QCD critical point [10], [11] is assumed to cause divergences of measurable event quantities distributions, e.g. charged particle multiplicity. In other words, expected non-monotonic behavior originated from the second-order phase transition could be detected in the experiment.

Thus, if the critical point exists and can be reached within the NA61/SHINE phase diagram scan program, then at some values of colliding energy and system size an enhancement of fluctuation signals should be observed [12].
2. Multiplicity and transverse momentum fluctuation measures

The signature of the critical point is expected to be a divergence [13] of central second moments of distribution of an extensive event quantity, i.e. charged particle multiplicity or total transverse momentum, which is measurable experimentally. However, the challenge is to detect this properly since the critical signal could be shadowed by the trivial volume fluctuations or simply unfavourable detector effects. This led to the idea to use intensive and strongly intensive quantities as probes for the critical behaviour [14], [15].

In order to make meaningful comparisons of the results obtained for different colliding systems, one should choose so-called intensive variables which are independent of the system size. Multiplicity fluctuations, for instance, can then be characterized by the scaled variance of the distribution of multiplicity \( N \), an intensive quantity: \( \omega[N] = \frac{(N^2) - \langle N \rangle^2}{\langle N \rangle} \) [15]. The normalization results in \( \omega[N] = 0 \) in the absence of fluctuations of \( N \) and \( \omega[N] = 1 \) in the case of a Poisson distribution of \( N \) [16]. Note that \( \omega[N] \) is still sensitive to fluctuations of the volume.

In particular, due to the imperfect centrality determination in A+A collisions, one should expect event-by-event volume fluctuations. Consequently, to eliminate the influence of usually poorly known distributions of the system volume, it was suggested to use strongly intensive quantities which are independent both of the volume and fluctuations of the volume within the statistical model of the ideal Boltzmann gas in the grand canonical ensemble formulation [15], [16]. Therefore, by studying strongly intensive quantities one may expect much higher sensitivity in the search for the critical point.

Two families of strongly intensive variables \( \Delta[P_T, N] \) and \( \Sigma[P_T, N] \) were suggested [16] which are functions of two extensive event quantities: multiplicity of charged hadrons \( N \) and scalar sum of their transverse momenta \( P_T \):

\[
\Delta[P_T, N] = \frac{1}{C_\Delta} \left[ \langle P_T \rangle \omega[N] - \langle N \rangle \omega[P_T] \right], \quad C_\Delta = \langle N \rangle \omega(p_T)
\]

\[
\Sigma[P_T, N] = \frac{1}{C_\Sigma} \left[ \langle P_T \rangle \omega[N] + \langle N \rangle \omega[P_T] - 2 \cdot (\langle P_T \cdot N \rangle - \langle N \rangle \langle P_T \rangle) \right], \quad C_\Sigma = \langle N \rangle \omega(p_T)
\]

The normalization of these variables can be chosen such that [16]: \( \Sigma[P_T, N] = \Delta[P_T, N] = 0 \) in the absence of \( P_T \) and \( N \) fluctuations; \( \Sigma[P_T, N] = \Delta[P_T, N] = 1 \) in the independent particle production model or Ideal Boltzmann gas within both Grand Canonical Ensemble and Canonical Ensemble formulation.

Scaled variance and strongly intensive quantities might be sensitive to critical fluctuations as it was shown, for example, in the model of the classical Van der Waals gas within the Grand Canonical Ensemble formulation [13], [17].

NA61/SHINE measured the quantities \( \omega[N], \Sigma[P_T, N] \) and \( \Delta[P_T, N] \) for charged hadrons with \( p_T < 1.5 \) GeV/c produced in the experimental acceptance [18]. The fluctuation analysis was performed for three different systems: inelastic \( p+p \) interactions at 20, 30, 40, 80 and 158 GeV/c beam momenta [19], [20], as well as for Be+Be and Ar+Sc most central collisions at 19, 30, 40, 75 and 150A GeV/c [21], [22]. Centrality in A+A collisions was measured as a percentile of the distribution of forward energy deposited by spectators in the forward hadron calorimeter PSD both in the data and in simulations (for the latter centrality was determined as a percentile of the distribution of energy of all final state particles in the PSD kinematic acceptance [23]).

The preliminary results are presented for all studied systems and energies in figure 1, but the observed structures gave no indication of a critical behavior [21]. However, as shown in [24], the ratio of \( p \) and \( \bar{p} \) produced in inelastic \( p+p \) collisions at SPS energies changes significantly with the rapidity. Consequently, the baryo-chemical potential strongly depends on the pseudorapidity [25] and the choice of a pseudorapidity phase-space could probe different parts of the critical region on the phase diagram. Therefore, the analysis was extended. A study of the dependence
Figure 1. Experimental results [21] for $\Sigma[P_T, N]$ and $\Delta[P_T, N]$ calculated for all charged hadrons with $p_T < 1.5 \text{ GeV}/c$ produced in inelastic p+p (black squares) interactions, 5% of the most central Be+Be (red triangles) and Ar+Sc (blue circles) collisions. Axes are c.m.s. collision energy $\sqrt{s_{NN}}$ and mean number of wounded nucleons $\langle W \rangle$ [42].

Figure 2. $\Sigma[P_T, N]$ as a function of pseudorapidity interval width for all charged hadrons with $p_T < 1.5 \text{ GeV}/c$ produced in inelastic p+p (left, window width normalized on maximal value) interactions at 158 GeV/c [19], [20] and 8% of the most central Be+Be (right, window width in absolute units) collisions at 150A GeV/c [22]. Experimental results (dots) are compared with EPOS1.99 predictions (lines).

of strongly intensive quantities $\Sigma[P_T, N]$ (see conference slides) and $\Delta[P_T, N]$ (figure 2) on the width and position of pseudorapidity intervals width and location was done for p+p [19], [20] and 8% most central Be+Be collisions [22].

Results for p+p and Be+Be data were compared with simulations using the EPOS1.99 [26] event generator within the NA61/SHINE experimental acceptance [18]. The behaviour of strongly intensive quantities with the width of the window agrees for inelastic p+p interactions and the 8% most central Be+Be collisions. However, a significant discrepancy between data and EPOS1.99 calculations was observed (figure 2) for $\Delta[P_T, N]$ at all collision energies both [20] for p+p [19] and Be+Be [22] collisions. The disagreement increases with the pseudorapidity interval width.

3. Femtoscopy study

Another search for the critical point was performed by NA61/SHINE with a study of the space-time structure of the hadron emission source via the measurement of Bose-Einstein momentum correlations. Since at the critical point fluctuations appear at all scales and the spatial correlation function becomes a power-law $r^{-(d-2+\eta)}$, one can predict a critical exponent $\eta$ at the critical point of QCD, using knowledge about the universality class, which is the 3D-Ising model for QCD [27], [28]. 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 transform of $S(r)$. The data analysis was done by using a Levy distributed source function. Since it leads to the same power-law tails, the Levy exponent $\alpha$ was assumed to be identical to the spatial correlation exponent $\eta$. In the vicinity of the critical point, very low $\alpha$ values (around 0.5) may be expected and this can be measured by investigating the Bose-Einstein correlation function $C(q) = 1 + \lambda e^{-(qR)\alpha}$.

Performance results (figure 3) were shown for the Be+Be data at 150$A$ GeV/$c$ for a selection of events with centrality higher than 20%, where the latter was defined using the PSD. Due to non-uniform efficiency in this range, this event selection may be prone to trigger bias. The correlation function $C(q)$ of the invariant 4-momentum difference $q$ of charged particle pairs was calculated by dividing the distribution of real pairs by that obtained from event mixing. The resulting correlation function was fitted with the above equation, taking into account also a Coulomb correction. From the fit function three important parameters were determined: $R$, $\lambda$ and $\alpha$. The parameter $R$ is the Levy scale, which determines the length of homogeneity, $\lambda$ is a correlation strength parameter and $\alpha$ is the Levy exponent, which may show a signal for anomalous diffusion and could be compared with the value derived from 3d-Ising model. The performance results were compared to the world data and they demonstrate the possibility to measure Bose-Einstein correlations in NA61/SHINE even in this low multiplicity collision system.

4. Intermittency analysis

The QCD critical point, if existing, might be detected not only via study of event-by-event (global) fluctuations of integrated quantities, but also by an observation of multiplicity fluctuations with a power law dependence on the phase space resolution. The study might be done for the order parameters of QCD, which are the chiral condensate and the net-baryon density. Critical fluctuations show up in fluctuations of the net-baryon density and can be observed by intermittent behavior of the net-proton or proton density. Through a Fourier transform, long-range correlations of the order parameter in transverse configuration space correspond to power-law correlations in transverse momentum space in the limit of small momentum transfer. The latter can be detected within the framework of an intermittency analysis of proton density fluctuations in transverse momentum space by use of scaled factorial moments.

The analysis was performed in transverse momentum space, which was partitioned into $M^2$ cells. If the system exhibits critical fluctuations, second scaled factorial moments $F_2(M)$ as a function of the cell size (or the number of cells) are expected to scale with $M$, for large values of $M$, as a power-law, with $\phi_2$ being the intermittency index: $F(M) \sim M^{2\phi_2}$. This behavior can possibly be observed if the system freeze-out occurs exactly at the critical point.
Figure 4. (top row) $F_2(M)$ of original (filled circles) and mixed events (filled triangles) for NA61 Ar+Sc collisions at 5-10% (left) and 10-15% (right) centrality at 150A GeV/$c$ ($\sqrt{s_{NN}} = 16.8$ GeV). (bottom row) $\Delta F_2^{(e)}(M)$ for the corresponding systems. The solid curves are drawn to guide the eye and correspond to power-law scaling functions, $\Delta F_2^{(e)}(M; C, \phi_2) = e^{C(M^2)}\phi_2$ with parameters: (left) $\phi_2 = 0.36, C = -4.84$; (right) $\phi_2 = 0.49, C = -5.4$.

of non-critical proton pairs has to be subtracted at the level of factorial moments in order to eliminate trivial (baseline) and non-critical correlations (with a characteristic length scale, that do not scale with bin size). The analysis for Ar+Sc collisions at 150A GeV/$c$ was done for different centralities and purity of proton selection.

Preliminary NA61/SHINE results (figure 4) exhibit power-law scaling of the second scaled factorial moments $\Delta F_2(M)$ (with the subtraction of a non-critical background) of proton density as a function of transverse momentum bin size for Ar+Sc collisions at 150A GeV/$c$. Critical intermittency index $\phi_2$ values are still to be evaluated properly, taking into account the magnitude of second scaled factorial moments uncertainties, and the fact that $F_2(M)$ values for distinct $M$ are correlated; the quality of $\Delta F_2(M)$ power-law scaling remains to be established, and an estimation of $\phi_2$ confidence intervals is still pending. However, qualitatively one may observe that intermittent behaviour in Ar+Sc shows centrality dependence possibly due to the change of baryo-chemical potential and the small extent of the critical region in the phase diagram [39]. The observed effect is also sensitive to the proton purity selection and increases with the increase of the purity threshold. Up to now, no observed power-law behavior was detected for "C"+C, Pb+Pb (NA49) and Be+Be (NA61/SHINE) systems. However, a first indication of a non-trivial intermittency effect in NA61/SHINE Ar+Sc collisions at 150A GeV/$c$ is consistent with the one observed for "Si"+Si (NA49) collisions at 158A GeV/$c$, but with
large statistical uncertainties. For "Si"+Si the estimated value of the intermittency index \(0.96^{+0.38}_{-0.25}\) overlaps with the critical QCD prediction. We note that EPOS1.99 does not reproduce the observed phenomenon. NA61/SHINE is continuing the analysis of other systems (Xe+La, Pb+Pb) and SPS energies (Ar+Sc) in order to obtain a reliable interpretation of the observed intermittency signal.

5. Two-particle correlations

Recent results on two-particle correlations in azimuthal angle and pseudorapidity were shown for Be+Be collisions at SPS beam momenta. The experimental correlation structures for Be+Be collisions were compared with EPOS1.99 model calculations and with already published p+p data [40], [41]. The results show that correlations in Be+Be are generally much weaker than in p+p due to a higher combinatorical background that dilutes the signal of correlations. There is a prominent enhancement at \((\delta\eta, \delta\phi) = (0, \pi)\), which is mostly visible in unlike-sign pairs and weaker in like-sign pairs, produced by resonance decays and momentum conservation. Another observed structure is a small maximum at \((0, 0)\) appearing in all charge combinations. In unlike-sign pairs of particles it is probably a result of Coulomb attraction, while in like-sign pairs it may come from the interplay of Bose-Einstein enhancement and Fermi-Dirac repulsion effects. The EPOS1.99 model predictions are in general similar to the real data of NA61/SHINE. The only exception is the lack of enhancement near \((0, 0)\), which is due to the fact that no short-range correlations (quantum statistics, Coulomb interactions) are generated by the model. Qualitatively, the measured structures in both systems are similar with exception of \((0, 0)\) maximum which is more prominent in Be+Be.

6. Conclusions

Results on system size versus collision energy dependence of \(N\) and \([P_T, N]\) fluctuations for charged particles produced in strong processes within the NA61/SHINE acceptance show no indication of the critical point so far. The analysis of the pseudorapidity dependence of fluctuation measures revealed a significant discrepancy between EPOS1.99 and both p+p and Be+Be data for the \(\Delta[P_T, N]\) measure. Two-particle correlation studies in Be+Be revealed two main structures: an away-side enhancement due to momentum conservation and resonance decays and a near-side peak due to Coulomb attraction in pairs of unlike-charge particles and quantum statistics enhancement for pairs of like charge. First measurements of the Bose-Einstein correlation function were performed for Be+Be collisions at 150\(A GeV/c\) and analysed using the Levy parameterisation of the source function.

Up to now the most intriguing result is the first possible indication of the intermittency effect in middle-central NA61/SHINE Ar+Sc collisions at 150\(A GeV/c\).

Acknowledgments

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