News from the NA61/SHINE experiment

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Abstract. NA61/SHINE is a fixed target experiment operating at the CERN SPS. Its main goals are to search for the critical point of strongly interacting matter and to study the onset of deconfinement. For these goals a scan of the two dimensional phase diagram (T-μ_B) is being performed at the SPS by measurements of hadron production in proton-proton, proton-nucleus and nucleus-nucleus interactions as a function of collision energy.

In this paper the status of the NA61/SHINE strong interaction physics programme is presented including recent results on proton intermittency, strongly intensive fluctuation observables of multiplicity and transverse momentum fluctuations. These measurements are expected to be sensitive to the correlation length in the produced matter and, therefore, have the ability to reveal the existence of the critical point via possible non-monotonic behavior. The NA61/SHINE results are compared to the model predictions.

1 Introduction

The NA61/SHINE experiment [1] is a multi-purpose fixed target experiment at the Super Proton Synchrotron (SPS) of the European Organization for Nuclear Research (CERN). The strong interactions programme of NA61/SHINE is devoted to the studies of the phase structure of Quantum Chromodynamics and, in particular, search for the critical point (CP) [2] of strongly interacting matter. NA61/SHINE is probing different regions of the phase diagram by performing measurements of hadron production in collisions of protons and various nuclei (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) in a range of beam momenta (13A - 150/158*A* GeV/*c*). It is expected that there will be a non-monotonic dependence of fluctuations of a number of observables on energy and system size in this scan due to the phase transition of strongly interacting matter and the possible existence of the CP [3]. Some hints of such behaviour have already been observed by the NA49 experiment [4].

2 $P_T - N$ fluctuation measures

Study of event-by-event fluctuations is one of the main tools to search for the posible existence of the critical point. The strength of fluctuations of a given observable can be quantified by the moments of its distribution. The commonly studied quantity is the scaled variance that is constructed for a given observable, X, from the first and second moments of the multiplicity distribution as $\omega[X] = \frac{\langle X^2\rangle - \langle X\rangle^2}{\langle X\rangle}$, where $\langle\cdots\rangle$ stands for the averaging over all events.

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The scaled variance is an intensive quantity which does not depend on the volume of the system for an ideal Boltzmann gas in the grand canonical ensemble (GCE) or on the number of sources within models of independent sources such as the wounded nucleon model (WNM) [5]. Unfortunately, its sensitivity to the critical point signals [6] can be shadowed by contributions from volume fluctuations which cannot be avoided in experiments.

In order to minimize the influence of volume fluctuations strongly intensive observables are used in the search for the critical point [7, 8]:

$$\Delta[P_T,N] = \frac{1}{\langle N\rangle\omega[p_T]}\Big[\langle N\rangle\omega[P_T] - \langle P_T\rangle\omega[N]\Big] \tag{1}$$

$$\Sigma[P_T,N] = \frac{1}{\langle N\rangle\omega[p_T]}\Big[\langle N\rangle\omega[P_T] + \langle P_T\rangle\omega[N] - 2(\langle P_T N\rangle - \langle P_T\rangle\langle N\rangle)\Big]. \tag{2}$$

where $P_T = \sum_{i=1}^{N} p_{T_i}$ and $\omega[p_T]$ is the scaled variance of the inclusive p_T spectrum.

The advantage of the strongly intensive quantities is that in the models of independent sources [5] and in the models of independent particle production the contribution from volume fluctuations is eliminated, allowing to probe the genuine CP signals. Moreover, in the models of independent particle production $\Delta[P_T,N] = \Sigma[P_T,N] = 1$.

In recent measurements by the NA61/SHINE collaboration of the strongly intensive quantities $\Delta[P_T,N]$ and $\Sigma[P_T,N]$ in p+p, Be+Be and Ar+Sc collisions no anomaly attributable to the CP was observed [9]. The analysis was extended to studies of the pseudorapidity dependence of strongly intensive observables in order to probe different values of baryochemical potential [10].

In this paper new results on fluctuations for primary charged hadrons produced in strong and electromagnetic processes were obtained for Be+Be collisions at 150*A* GeV/c selected for the smallest 8% of forward energies. Fluctuations were studied in 9 pseudorapidity intervals defined in the laboratory reference frame. The forward edge of the intervals was fixed at 5.2 units of pseudorapidity, with the backward edge changing from 3 up to 4.6 units. The choice of lower bounds was motivated by the small azimuthal angle acceptance at smaller pseudorapidities. The upper bound was introduced in order to suppress possible quasi-diffractive or electromagnetic effects which become important at larger pseudorapidities. The selection of the most central events by the forward energy in A+A collisions was done using information from the NA61/SHINE forward calorimeter, the PSD. Transverse momenta of all charged hadrons were restricted to $0 < p_T < 1.5$ GeV/*c*. Moreover, the NA61/SHINE acceptance map [11] was applied. The results for Be+Be and Ar+Sc collisions were not corrected for detector inefficiencies and trigger biases as simulations have shown that their effect estimated using the GEANT3 package does not exceed 5%. To the contrary the trigger bias modifies results significantly for p+p interactions and, therefore, requires corrections described precisely in Ref. [12]. The statistical uncertainties were determined using the subsample method. Analysis of the systematic uncertainties is not finished but they are estimated to be smaller than 5%.

Figure 1 shows preliminary results for the dependence of $\Delta[P_T,N]$ and $\Sigma[P_T,N]$ on the width of the pseudorapidity interval and comparisons to the EPOS1.99 model [13] predictions. Both quantities change monotonously for the data in contrast to the EPOS1.99 results for $\Delta[P_T,N]$ which show a minimum for intermediate width and lie significantly above the measurements. The measurements of $\Sigma[P_T,N]$ are well reproduced by EPOS1.99. Another observation is that for smaller windows these quantities approach unity (independent particle production limit) as the number of particles in the interval gets small. Moreover, the inequalities $\Delta[P_T,N] < 1$ and $\Sigma[P_T,N] \geq 1$, previously observed for all studied systems at all collision energies [9], also hold when modifying the width of the pseudorapidity window of the measurement. Similar pseudorapidity dependences are observed in inelastic p+p interactions [14]. In general, no traces of the possible critical point of strongly interacting matter are visible.

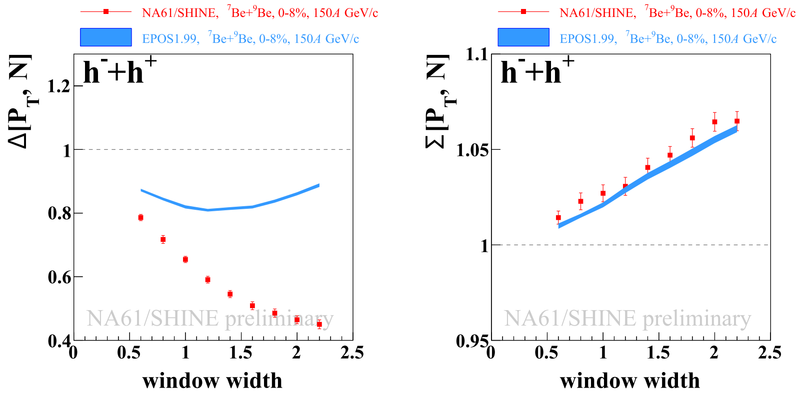

Figure 1. Dependence of $\Delta[P_T, N]$ (left) and $\Sigma[P_T, N]$ (right) on the width of the pseudorapidity window. Red squares are preliminary NA61/SHINE measurements for 0-8% Be+Be collisions at 150*A* GeV/c. Blue band represents the EPOS1.99 model predictions.

3 $N - N$, $P_T - N$ and $P_T - P_T$ fluctuations in two rapidity intervals

By analogy with the $P_T - N$ case described in the previous section one can introduce a number of other strongly intensive observables. Joint fluctuations of two quantities in two separated pseudorapidity intervals are of special interest because they are closely connected with studies of forward-backward correlations that have a long history of measurements [15, 16]. Forward-backward correlations are usually quantified by the correlation coefficient which is not strongly intensive and is sensitive to the employed centrality selection procedures in nucleus-nucleus collisions [17]. Use of strongly intensive quantities can suppress these trivial fluctuations and allows to study the intrinsic properties of particle emitting sources. Therefore, for studies of joint fluctuations of multiplicities (N_F, N_B) and the sum of transverse momenta (P_{TF}, P_{TB}) in two windows of rapidity the following quantities are defined [18]:

$$\Sigma[n_F, n_B] = \frac{1}{\langle n_B\rangle + \langle n_F\rangle} \cdot \Big[\langle n_B\rangle\omega[n_F] + \langle n_F\rangle\omega[n_B] - 2(\langle n_F n_B\rangle - \langle n_F\rangle\langle n_B\rangle)\Big] \tag{3}$$

$$\Sigma[n_F, P_{TB}] = \frac{1}{(\langle n_B\rangle + \langle n_F\rangle)\cdot \overline{p_T}_B + \langle n_F\rangle\omega[p_T]_B} \cdot$$
$$\Big[\langle P_{TB}\rangle\omega[n_F] + \langle n_F\rangle\omega[P_{TB}] - 2(\langle n_F P_{TB}\rangle - \langle n_F\rangle\langle P_{TB}\rangle)\Big] \tag{4}$$

$$\Sigma[P_{TF}, P_{TB}] = \frac{1}{\langle P_{TB}\rangle\left(\overline{p_T}_F + \omega[p_T]_F\right) + \langle P_{TF}\rangle\left(\overline{p_T}_B + \omega[p_T]_B\right)} \cdot$$
$$\Big[\langle P_{TB}\rangle\omega[P_{TF}] + \langle P_{TF}\rangle\omega[P_{TB}] - 2(\langle P_{TF}P_{TB}\rangle - \langle P_{TF}\rangle\langle P_{TB}\rangle)\Big] \tag{5}$$

Here, averaging over all tracks in the forward (backward) window is denoted as:

$$\overline{p_T}_{F,B} = \frac{1}{N_{tr}} \sum_{tr_{F,B}} p_T \ . \tag{6}$$

Moreover, the scaled variance of inclusive p_T spectra $\omega[p_T]_{F,B}$ is introduced for both forward and backward windows.

Typically, forward-backward correlations are studied not for the sum of transverse momenta but for the event mean transverse momentum [19], but in order to construct a strongly intensive quantity from two observables A and B both of these quantities have to be extensive [7].

The analysis was performed for 7 pairs of pseudorapidity intervals, with the forward window fixed at (4.7,5.2) and the backward window moving from (3,3.5) to (4.2,4.7). Figure 2 shows preliminary results for the dependence of quantities (3)-(5) on the separation between the two windows. It is peculiar that all three quantities show qualitatively the same behaviour which is quite well reproduced by the EPOS1.99 model. Moreover, analogous behaviour was predicted by the quark-gluon string model [20] for p+p interactions at LHC energies. The PHOBOS collaboration studied joint fluctuations of multiplicities in two windows quantified by the variance of $C = \frac{N_F - N_B}{\sqrt{N_F + N_B}}$ [21] which has similar properties like $\Sigma[n_F, n_B]$, although it is not strongly intensive. The variance of C showed a similar trend with separation between rapidity windows in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

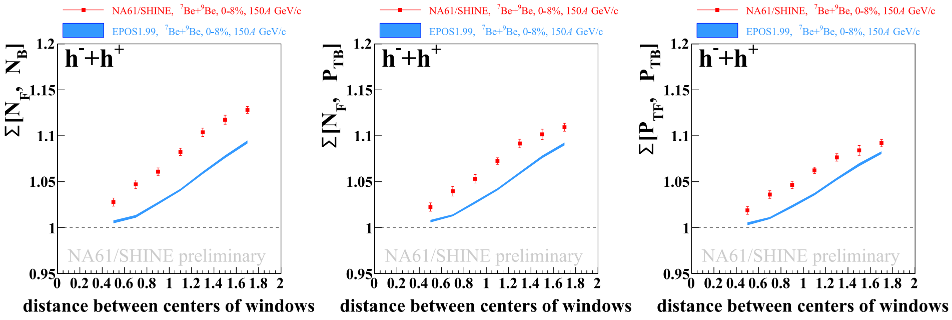

Figure 2. Dependence of $\Sigma[n_F, n_B]$ (left), $\Sigma[n_F, P_{TB}]$ (middle) and $\Sigma[P_{TF}, P_{TB}]$ (right) on the separation between the two pseudorapidity windows. Red squares are preliminary NA61/SHINE measurements for 0-8% Be+Be collisions at 150A GeV/c. Blue band represents the EPOS1.99 model predictions.

4 Proton density fluctuations: intermittency

In the grand canonical ensemble the correlation length diverges at the critical point and the system becomes scale invariant [22]. In a pure critical system, intermittency in transverse momentum space can be revealed by the scaling of the Second Scaled Factorial Moments of protons as a function of bin size [23]. For that purpose, a region of transverse momentum space is partitioned into $M \times M$ equal-size bins and these moments are defined as:

$$F_2(M) = \frac{\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i - 1) \rangle}{\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \rangle^2} \tag{7}$$

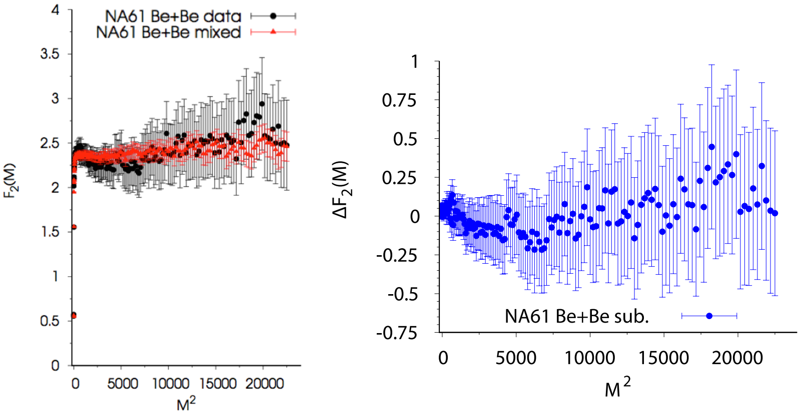

Figure 3. NA61/SHINE preliminary results for Be+Be at 150*A*GeV/*c*: (Left) The second factorial moments of protons $F_2(M)$ for real data (black) and mixed events (red). (Right) $\Delta F_2(M)$

where n_i is the number of particles in the i-th bin. If the system exhibits critical fluctuations, $F_2(M)$ is expected to scale with M, for large values of M, as a power-law $F_2(M) \sim M^{2\phi_2}$, where ϕ_2 is the intermittency index.

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. Therefore one studies $\Delta F_2(M) = F_2(M) - F_2^{mix}(M)$.

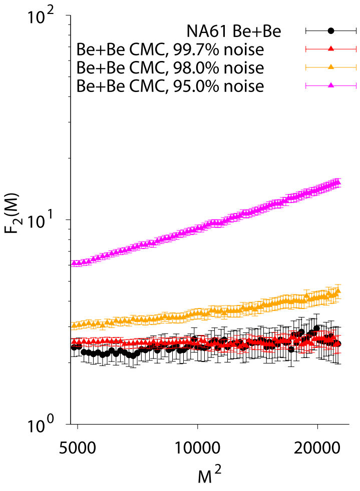

Figure 4. The second factorial moments of protons $F_2(M)$ from Be+Be interactions at 150*A*GeV/*c* in NA61/SHINE (black) and from the CMC for different noise levels (magenta, orange, red).

Intermittency analysis was performed for NA61/SHINE data on Be+Be collisions (0-10%) at 150A GeV/c beam momentum. In Figure 3, preliminary results on intermittency analysis results are shown. $F_2(M)$ for data and mixed events overlap; thus, $\Delta F_2(M)$ fluctuates around zero, and no intermittency effect is observed. Figure 4 shows the predictions of the Critical Monte Carlo model (CMC) [24] for several levels of noise. We see that $F_2(M)$ of noisy CMC approximates Be+Be data for a 99.7% noise level. Based on this result, we estimate an upper limit of the order of 0.3% for the fraction of critical protons in Be+Be data. For more details see Ref. [25].

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