Study of multiparticle spikes
in central $4.5A$ GeV/$c$ C-Cu collisions

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Abstract

An analysis of local fluctuations, or spikes, is performed for charged particles produced in central C-Cu collisions at 4.5 GeV/$c$/nucleon. The distributions of spike-centers and the maximum density distributions are investigated for different narrow pseudorapidity windows to search for multiparticle dynamical correlations. Two peaks over statistical background are observed in the spike-center distributions with the structure similar to that expected from the coherent gluon radiation model and recently found in hadronic interactions. The dynamical contribution to maximum density fluctuations are obtained to be hidden by statistical correlations, though behavior of the distributions shows qualitative agreement with that from the one-dimensional intermittency model. The observed features of the two different approaches, coherent vs. stochastic, to the formation of the local dynamical fluctuations are discussed.

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1 Introduction

Reflecting an intermittent structure of distributions of particles produced in high-energy collisions, local fluctuations play an important rôle in hadronization process. Intermittency/fractality studies [1] show these fluctuations to be significant in investigations of multihadronic production as well as to be a possible signal of quark-gluon plasma formation. Although a vast activity in study self-similarity have disentangled contributions of different known mechanisms to production of dynamical fluctuations/correlations, an origin of the latter remains still unclear. This arises need for applying more direct (and additional) methods of studying properties of dense groups of particles.

The data used here has been considered in our recent studies of self-similar nature of multihadronic production [2, 3]. Strong multifractality has been found, pointing out a possible non-thermal phase transition and two different regimes in particle production during the cascade. This conclusion confirms results of our earlier studies [4, 5] made with less statistics and has been recently supported by similar observations reported for ultra-relativistic nuclear collisions [3]. Further analysis [3] have shown more structure in dynamical fluctuations indicating chaotic nature of multiparticle production with a specific scaling-law referred to as erraticity [7].

Although the self-similar underlying dynamics has been obtained in searches in fractality terms, no dynamical effects was revealed in the investigations of maximum density distributions [8]. However, the analogous study performed for hadron-emulsion data in the energy range of 200-400 GeV [4] has indicated the existence of dynamical multiparticle correlations and clustering seen for high-density spikes.

In this letter we investigate local pseudorapidity fluctuations, or spikes, analyzing two types of distributions, assigned to coherent vs. chaotic approaches in particle-emission process. Respectively, the distributions of centers of spikes and maximum density distributions are considered, based on the methods, used earlier and shown to be distinguished by the reliability and the high certainty in searching for multiparticle dynamical correlations [10, 13]. Study of fluctuations in limited regions of collision phase-space allows reducing of contribution from conservation constraints and elicits underlying dynamics of particle-production process.

2 Data sample and analysis procedure

2.1 Data sample

The results presented are based on experimental data came from interactions of the JINR Synchrophasotron (Dubna) 4.5 A GeV/c $^{12}$C beam with a copper target inside the 2m Streamer Chamber SKM-200 [14]. A central collision
trigger was used: absence of charged particles with momenta \( p > 3 \text{ GeV}/c \) in a forward cone of \( 2.4^\circ \) was required. A more detailed description of the set-up design and data reduction procedure are given elsewhere \([14,15]\). Systematic errors related to the trigger effects, low-energy pion and proton detection, the admixture of electrons etc. does not exceed 3\% \([14,15]\).

The scanning and the handling of the film data were carried out on special scanning tables of the Lebedev Physical Institute (Moscow) \([17]\). The average measurement error in the momentum \( \langle \varepsilon_p/p \rangle \) was about 12\%, and that in the polar angle measurements was \( \langle \varepsilon_\vartheta \rangle \simeq 2^\circ \). In total, 663 events with charged particles in the pseudorapidity range of \( \Delta \eta = 0.2 - 2.8 \) (in the laboratory frame) were processed. The angular measurement accuracy does not exceed 0.1 in the \( \eta \)-units. In addition, particles with \( p_T > 1 \text{ GeV}/c \) are excluded from the investigation as far as no negative charged particles were observed with such a transverse momentum. Under the assumption of an equal number of positive and negative pions, this cut was applied to eliminate the contribution of protons. After the kinematic cuts, the mean multiplicity is \( 23.8 \pm 0.4 \).

### 2.2 Analysis procedure

The multiparticle fluctuations are studied in the pseudorapidity phase-space regions. The following procedure is used to search for dynamics of the fluctuations. For each event the ordered pseudorapidities, \( \eta = -\ln \tan \frac{1}{2} \vartheta \) (\( \vartheta \) is the polar angle of the particle), are scanned with a fixed pseudorapidity window (bin) across the full \( \eta \)-range of the event, and the spike with \( \delta n \) number of tracks, hit in the window \( \delta \eta \), is determined. Then the centers of spikes, \( \eta_0 = (1/\delta n) \sum_{j=1}^{\delta n} \eta_j \), are calculated for all events and the distribution in \( \eta_0 \) is investigated to reveal dynamical correlations. The distribution with respect to the maximum density fluctuations, defined as \( \rho_{\text{max}} = \delta n_{\text{max}}/\delta \eta \), where \( \delta n_{\text{max}} \) is the maximum number of particles per spike in each event for the chosen \( \delta \eta \), is analyzed as well in order to obtain dynamical character of the fluctuations observed.

The conclusions about dynamical content of the fluctuations could be affected by the dependence of such an analysis on the form of pseudorapidity distribution and the fact that the method of maximum fluctuations deals with the mostly populated regions of the distribution. To avoid these and to compare the results from different experiments, the “cumulative” variable,

\[
\tilde{\eta} (\eta) = \int_{\eta_{\text{min}}}^{\eta} \rho(\eta') d\eta' / \int_{\eta_{\text{min}}}^{\eta_{\text{max}}} \rho(\eta') d\eta',
\]

with the uniform spectrum \( \rho(\tilde{\eta}) \) within the interval \([0,1]\) was proposed to be used \([18]\). The transformed variable \( \tilde{\eta} \) are usually considered in studying intermittency \([1]\), also utilized in our recent reports \([2,3,5]\). Note, pseudorapidity
is argued to be the most suitable variable to analyze correlations providing intermittent structure of high-energy events [13].

3 Results and discussion

3.1 Spike-center distributions

The pseudorapidity spike-center distributions for the different size $\delta \tilde{\eta}$-bins and for spikes of the different density are presented in Fig. 1. The widths of the bins are chosen to be compatible with those used earlier [8, 20]. Multi-peak structure of the distributions can be seen for $\delta \tilde{\eta} = 0.04 (\delta\eta \approx 0.1)$ (Fig. 1a) and 0.08 ($\approx 0.2$) (Fig. 1b). However, one can observe two peaks placed in the region about the same $\eta_0$-positions with a tendency of the distributions to have a double-peak shape as the size of the bin increases. The two peaks become much more pronounced when the events are scanned by the large $\delta \tilde{\eta}$, e.g. of the width of 0.2 as shown in Fig. 1d. Fitting these two bumps with Gaussians, the peaks averaged over the different spikes, are found to be placed at 0.17 and 0.57. Recounted to the $\eta$-variable, the positions of the peaks are of the values of $0.60 \pm 0.05$(stat) $\pm 0.12$(syst) and $1.30 \pm 0.03$(stat) $\pm 0.10$(syst) with the distance,

$$d_0 = 0.68 \pm 0.06$(stat) $\pm 0.16$(syst) \hspace{1cm} (2)$$

between them.

Recently, the study of the spike-centers has been carried out for hadronic interactions at 205-306 GeV/c [21]. The double-peak shape of the $\eta_0$-distribution for pp-collisions vs. a single-peak structure in $\pi$/Kp-interactions have been observed in agreement with the coherent gluon-jet emission model [10]. The peaks has been found to be separated by the distance of $0.57 \pm 0.03$(stat)$\pm 0.12$(syst), also consistent with the model prediction. The double-peak form obtained here for the central nuclear interactions are similar to that for pp-type reaction, indicating superposition of nucleon-nucleon interactions in nucleus-nucleus one. Moreover, the value of the distance found exceeds that in hadronic collisions being in agreement with theoretical expectations [22].

To observe dynamical correlation effect in these distributions, the analogous distributions have been obtained from the simulated pseudorapidity one-particle spectrum $\rho(\tilde{\eta})$, in which, evidently, any information of two or more multiparticle correlations is lost. The simulation procedure was as follows. In accordance with the multiplicity distribution of the experimental sample we have randomly generated corresponding number of tracks. Then the pseudorapidities has been distributed according to the real $\rho(\tilde{\eta})$-spectrum in a quantity of the generated multiplicity. The total number of the events simulated was
66300, so that it exceeded the experimental statistics by a factor of 100. It is clear that the statistical properties of this set are completely analogous to those of the ensemble resulted from arbitrary mixing of tracks from different events, subject to the condition of retention of the \( \rho(\tilde{\eta}) \)-distribution, and the obtained sample represents the result of independent particle emission hypothesis.

The \( \tilde{\eta}_0 \)-distributions of the simulated events are shown in Fig. 1 by open circles. Remarkable difference one can observe between the experimental distributions (solid circles) and those obtained in assumption of completely uncorrelated particle production. No whatsoever peaks are seen in the latter case, following the background level and manifesting the double-peak structure to be the dominant one.

From the comparison of the experimental and simulated distributions in the spike-centers proceeded for various \( \delta \tilde{\eta} \)-windows and different many-particle spikes, one can apparently conclude about dynamical character of the production of high-density fluctuations. The dynamics of the intermittent structure of the data studied could be assigned to the model of coherent gluon radiation [10] as to one of a real candidate of the mechanism of formation of the fluctuations.

To assess the reliability of the above conclusions and the stability of the results we vary the investigation with changing the \( \Delta \eta \)-range under consideration as well as the polar angle, \( \vartheta \), within the experimental error \( \langle \varepsilon_\vartheta \rangle \). The observed character of the distributions remained unchanged.

### 3.2 Maximum density fluctuations

The further analysis deals with the normalized distributions, \( (1/N) dN/d\rho_{\text{max}} \), of \( N \) events as shown in Fig. 2 for four different scanning windows.

The exponential decrease at \( \rho_{\text{max}} > \langle \rho_{\text{max}} \rangle \) of these distributions, averaged over all multiplicities \( n \), is analogous to that observed in our previous studies [8, 20] and in other investigations performed for different reactions [4, 22]. Such a behavior differs from the poissonian one, expected for processes with weak correlations of produced hadrons or for models of multiperipheral or Regge types taking into account a limited number of reggeons. The exponential behavior of the \( \rho_{\text{max}} \)-spectra is argued to be a consequence of primordial multiparticle correlations which are irreducible to two-particle correlations [13]. The given inequality between the dispersion and the mean values \( \langle \rho_{\text{max}} \rangle \) confirms the non-poissonian character of the distributions, pointing out significant contribution of multi-particle correlations to the local fluctuations observed.

Although the transition to the “cumulative” variable did not influence much the above conclusion compared to the earlier results [8, 20], it seems to be essential in studying the distributions at high \( \rho_{\text{max}} \)-values. Indeed, if the bell-like shape for small bins (Fig. 2a) is similar to that observed in the previous
reports, an increase of the \( \delta \bar{\eta} \)-width (Fig. 2b, c) makes large \( \rho_{\text{max}} \)-tails to appear in the \( \rho_{\text{max}} \)-spectra.

A change of the shape of the maximum density distribution from the exponential to more flat one with increase of the \( \rho_{\text{max}} \) seems to be in agreement with that expected from the one-dimensional intermittency model \([1]\). The key feature of the model is an existence of two regimes in particle production process, described as turbulent and laminar components, leading to two maxima in the \( \rho_{\text{max}} \)-distributions.

It is worthwhile that the model makes predictions for the \( \rho_{\text{max}} \)-distributions considered at given multiplicity \( n \). Note, the fixed-\( n \) distributions are energy and reaction-type independent that allows increasing statistics by compiling results from different experiments. A study of the fixed-\( n \) distributions has been carried out for hadronic interactions and the large-\( \rho_{\text{max}} \) tails have been observed for \( \delta \eta = 0.1 \) \([2]\).

In Fig. 2 we present the \( \rho_{\text{max}} \)-distributions for two different narrow \( n \)-intervals (solid squares and triangles). An effect of deviation of the \( \rho_{\text{max}} \)-distribution from the exponential behavior at large maximal densities are well seen and became more prominent compared to the case of mixed-\( n \) distributions. Already at \( \delta \eta \approx 0.1 \) (Fig. 2a) the shape of the distributions develops tails at \( \rho_{\text{max}} > \langle \rho_{\text{max}} \rangle \), apparent also for larger \( \delta \bar{\eta} \)-bins, \( \delta \bar{\eta} = 0.12 \) and \( 0.2 \), but only for high-multiplicity events, \( 24 < n < 30 \) (triangles in Fig. 2b, c).

For the widest \( \delta \bar{\eta} \) shown, \( \delta \bar{\eta} = 0.4 \) (Fig. 2d), one can not see the difference in the behavior of the distributions for fixed \( n \)-regions. However, the distribution for all multiplicities shows slight flattening at large \( \rho_{\text{max}} \), but, in our opinion, this is rather due to the averaging over all \( n \)'s available.

Similar to the mixed-\( n \) spectra the fixed-\( n \) interval distributions show their non-poissonian character resulting to an inequality between the dispersion and the \( \langle \rho_{\text{max}} \rangle \) and indicating contribution of multiparticle correlations.

To reveal dynamical correlation effect, the obtained distributions are compared to those based on the above described sample of the simulated events, in which no whatsoever dynamical correlations exist. The resulted distributions for the four bins studied are shown in Fig. 2 for total multiplicity as well as for the two fixed-\( n \) intervals. The values of \( \chi^2/\text{DOF} \) give a quite good fit between the data and the generated spectra independent of the width of the bins or the multiplicity. From this comparison one can not conclude about (intermittency) dynamics behind observed multiparticle fluctuations. It seems that the dynamical correlations in the distributions of maximum densities are too suppressed by statistical “noise” to be detected.

However, it is worth to notice that the \( \rho_{\text{max}} \)-distributions at \( \delta \bar{\eta} = 0.12 \) and \( 0.2 \) and \( 24 < n < 30 \) (fig. 2b, c), obtained from the uncorrelated emission hypothesis deviate from the data-based spectra at high-\( \rho_{\text{max}} \) values: if the flattening is well-seen for the measured distributions, there is no change in the
behavior of these distributions from the simulated sample.

The non-poissonian behavior found to be stronger for smaller bin-sizes and the deviations between the data and the simulated distributions observed for higher maximum densities, both seem to be a reason of non-statistical fluctuations found by us via the method of normalized scaled factorial moments \[2–5\] and leading to extreme fluctuations recently proposed to be searched for \[25\].

All these indicates a need of more detailed analysis to be done with higher multiplicity reactions. Note, that such an analysis could be compared with that performed here due to the “cumulative” variable used and fixed-\(n\) intervals considered.

A study of influence of the error \(\langle \varepsilon_\theta \rangle\) in the measurement of the polar angle \(\theta\) of the produced charge particles demonstrated stability of the obtained distributions and, therefore, the reliability of the conclusions above.

### 4 Conclusions

In summary, a study of spike production in central C-Cu collisions at 4.5 GeV/\(c\) per nucleon is presented. To avoid the dependence of the results on the form of the pseudorapidity distribution the transformation to the uniform spectrum variable is utilized. The spike-center distributions and those in maximum density fluctuations are investigated for various narrow pseudorapidity windows to obtain dynamical collective effects.

The double-peak shape of the spike-center distributions is found, similar to that recently obtained in high-energy pp-interactions. The distance between the positions of the peaks seems to be in agreement with the expectation of the coherent gluon jet-emission model. Comparison with the results of completely uncorrelated particle-production model confirms dynamical origin of the effects observed.

The maximum density distributions are investigated for mixed-\(n\) values as well as for fixed-\(n\) intervals. Non-poissonian character of the distributions is found indicating contribution of multiparticle correlations to the spikes. A flattening of the shape of the distributions at large maximum densities is obtained for high multiplicities in qualitative agreement with one-dimensional intermittency model. The dynamics are found to be hidden by strong statistical correlations, though visible deviations in the behavior of the simulated distributions compared to the measured ones are indicated.

To conclude, a direct study of two different approaches – coherent vs. stochastic – to the formation of the local dynamical fluctuations in multiparticle production in central nuclear collisions at intermediate energy is performed. The coherent nature of dense group production is found to be clearly manifested with a structure similar to that recently found in hadronic interactions. Though no dynamics is obtained by means of the stochastic (intermittent) ap-
proach, the features of the maximum density distributions indicate a possible origin of self-similarity of the local fluctuations.

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References

[1] E.A. De Wolf, I.M. Dremin, W. Kittel, Phys. Reports 270 (1996) 1; P. Bożek, M. Płoszańczak, R. Botet, Phys. Reports 252 (1995) 101.

[2] E.K. Sarkisyan et al., 7th Int. Workshop on Multiparticle Production, “Correlations and Fluctuations” (Nijmegen, 1996), eds. R.C. Hwa et al. (World Scientific, 1997), p. 271.

[3] L.K. Gelovani et al., 8th Int. Symposium on “Advances in Nuclear Physics and Related Areas” (Thessaloniki, 1997), to be published.

[4] E.K. Sarkisyan et al., Phys. Lett. B 318 (1993) 568.

[5] E.K. Sarkisyan et al., Phys. Lett. B 347 (1995) 439.

[6] D. Ghosh et al., Z. Phys. C 71 (1996) 243; ibid. 73 (1997) 269.

[7] Z. Cao and R.C. Hwa, Phys. Rev. E 56 (1997) 326.

[8] E.K. Sarkisyan, I.V. Paziashvili, G.G. Taran, Sov. J. Nucl. Phys. 53 (1991) 824.

[9] D. Ghosh, S. Sen, J. Roy, Phys. Rev. D 47 (1993) 1235.

[10] I.M. Dremin, JETP Lett. 30 (1979) 140; Sov. J. Part. Nucl. 18 (1987) 31.

[11] J. Dias de Deus, Phys. Lett. B 194 (1987) 297.

[12] T. Kanki et al., Prog. Theor. Phys. Suppl. 97A (1988) 1.

[13] I.M. Dremin, Sov. Phys. Usp. 33 (1990) 647.

[14] A. Abdurakhimov et al., Instrum. Exp. Tech. 21 (1979) 1210.

[15] M. Anikina et al., Phys. Rev. C 33 (1986) 895.

[16] SKM-200 Collab., M. Anikina et al., JINR report E1-84-785 (1984).

[17] G.G. Taran et al., FIAN (Moscow) preprint No.20 (1987).

[18] A. Białas and M. Gazdzicki, Phys. Lett. B 252 (1990) 483; W. Ochs, Z. Phys. C 50 (1991) 339.

[19] I.V. Andreev et al., Int. J. Mod. Phys. A 10 (1995) 3951.

[20] E.K. Sarkisyan and G.G. Taran, Phys. Lett. B 279 (1992) 177; Sov. J. Nucl. Phys. 55 (1992) 417.

[21] N.M. Agababyan et al., EHS/NA22 Collab., Phys. Lett. B 389 (1996) 397.
[22] I.M. Dremin, private communication.

[23] G. Singh, K. Sengupta, P.L. Jain, Phys. Rev. Lett. 61 (1988) 1073; P.L. 
    Jain and G. Singh, Phys. Rev. C 54 (1996) 1892;
    A. Abduzhamilov et al., FIAN (Moscow) preprint No.160 (1989).

[24] I.V. Ajinenko et al., EHS/NA22 Collab., Phys. Lett. B 222 (1989) 306.

[25] F. Takagi and D. Kiang, Phys. Rev. D 56 (1997) 5862.
Figure captions

Fig. 1. Experimental (●) and simulated (○) spike-center distributions for different $\delta \tilde{\eta}$-bins and various $\delta n$-number of particles per bin:
(a) $\delta \tilde{\eta} = 0.04$, $\delta n = 4$, (b) $\delta \tilde{\eta} = 0.08$, $\delta n = 5$,
(c) $\delta \tilde{\eta} = 0.12$, $\delta n = 7$, (d) $\delta \tilde{\eta} = 0.2$, $\delta n = 9$.

Fig. 2. Normalized experimental (solid symbols) and simulated (open symbols) distributions in maximum density $\rho_{\text{max}}$ for different $\delta \tilde{\eta}$-windows and three multiplicity patterns:
(a) $\delta \tilde{\eta} = 0.04$, $\chi^2/\text{DOF} \simeq 1.3$ (all $n$, $\langle \rho_{\text{max}} \rangle \simeq 39.4$, RMS $\simeq 11.2$),
$\chi^2/\text{DOF} \simeq 0.5$ (14 < $n$ < 20, $\langle \rho_{\text{max}} \rangle \simeq 38.6$, RMS $\simeq 8.1$),
$\chi^2/\text{DOF} \simeq 0.7$ (24 < $n$ < 30, $\langle \rho_{\text{max}} \rangle \simeq 49.2$, RMS $\simeq 9.0$),
(b) $\delta \tilde{\eta} = 0.12$, $\chi^2/\text{DOF} \simeq 1.2$ (all $n$, $\langle \rho_{\text{max}} \rangle \simeq 22.0$, RMS $\simeq 6.6$),
$\chi^2/\text{DOF} \simeq 1.3$ (14 < $n$ < 20, $\langle \rho_{\text{max}} \rangle \simeq 12.8$, RMS $\simeq 3.6$),
$\chi^2/\text{DOF} \simeq 2.0$ (24 < $n$ < 30, $\langle \rho_{\text{max}} \rangle \simeq 25.2$, RMS $\simeq 4.4$),
(c) $\delta \tilde{\eta} = 0.2$, $\chi^2/\text{DOF} \simeq 1.1$ (all $n$, $\langle \rho_{\text{max}} \rangle \simeq 17.4$, RMS $\simeq 5.2$),
$\chi^2/\text{DOF} \simeq 1.0$ (14 < $n$ < 20, $\langle \rho_{\text{max}} \rangle \simeq 14.0$, RMS $\simeq 2.6$),
$\chi^2/\text{DOF} \simeq 1.7$ (24 < $n$ < 30, $\langle \rho_{\text{max}} \rangle \simeq 20.2$, RMS $\simeq 2.8$),
(d) $\delta \tilde{\eta} = 0.4$, $\chi^2/\text{DOF} \simeq 0.9$ (all $n$, $\langle \rho_{\text{max}} \rangle \simeq 13.2$, RMS $\simeq 4.2$),
$\chi^2/\text{DOF} \simeq 0.7$ (14 < $n$ < 20, $\langle \rho_{\text{max}} \rangle \simeq 10.3$, RMS $\simeq 1.6$),
$\chi^2/\text{DOF} \simeq 0.9$ (24 < $n$ < 30, $\langle \rho_{\text{max}} \rangle \simeq 18.2$, RMS $\simeq 1.8$),
Figure 1
Figure 2