Long and Short Range Correlations: A Signature of String Fusion

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The study of backward-forward and forward-forward correlations in collisions of two nuclei at high energies allow us to distinguish between the fusion of strings produced in the collision into new strings of higher color and the possibility of the fusion of produced hadrons into clusters. The results for AB collisions at the CERN Super Proton Synchrotron (SPS) and the Brookhaven Relativistic Heavy Ion Collider (RHIC) are discussed.

In the last few years many efforts have been made in the search for the quark-gluon plasma [1]. One of the main points in this search is to know how the quark-gluon plasma (QGP) can be reached in the framework of the usual models of hadronic interactions [2–4]. In these models, strings or Pomerons are exchanged between the projectile and target. The number of strings grows with the energy and with the number of nucleons of the participant nuclei. Recently, using this kind of model, two different ways to reach the QGP have been proposed. In one of them [5,6], elaborated in the framework of the VENUS model [4], the strings produced in a nucleus-nucleus collision break, forming resonances and particles, which, whenever they come closer than a given radius, fuse, forming a cluster. Afterwards, this cluster decays into resonances and particles isotropically. The critical radius is fixed by comparison to the data at $\sqrt{s_{NN}} = 19.4$ GeV. The distribution in the number of clusters as a function of the volume size is peaked at small values of the volume, as it was expected, but the probability of obtaining clusters of large volume is not negligible.

In the other proposal [7,8], the strings produced in a nucleus-nucleus collision fuse if they overlap in impact parameter space, forming a new string which has a higher color charge at its ends, corresponding to the summation of the color charges located at the ends of the original strings. Then the new strings break into hadrons according to their higher color. As a result, heavy flavor is produced more efficiently and there is a reduction of the total multiplicity [9]. New strings, like the ones proposed in Refs. [7,8], have also been found [10] by studying the diffractive process $\gamma(Q^2) + \text{quark} \to X + \text{quark}$. In a determined kinematic range, the leading diagram is a typical triple Pomeron diagram, but the Pomeron corresponding to the discontinuity through the X system is formed by two coupled ladders of gluons, instead of one ladder as with the other two Pomerons.

In the first approach, the fusion of resonances does not modify the distribution in the number of strings. There-fore there is no variation in the long range correlations. A measurement of such correlations is the backward-forward dispersion

$$D_{BF}^2 = \langle n_B n_F \rangle - \langle n_B \rangle \langle n_F \rangle, \tag{1}$$

where n_B (n_F) is the number of particles in a backward (forward) rapidity range. Indeed, in any model based on a superposition of independent exchanges (Pomerons or strings), in such a way that distinct "elementary" exchanges are statistically independent, is easy to show that the squared backward (forward) dispersion is proportional to the squared dispersion of the number of exchanges (see Ref. [11]). In order to eliminate the short range correlations we consider backward and forward intervals separated by at least 1.5 rapidity units. Cluster formation implies the fusion of particles or resonances close in rapidity (the clustering process needs some time to develop), so the long range correlations are not affected. The short range correlations are, on the contrary, increased as a result of the cluster formation. A measurement of the latter is the squared dispersion of the multiplicity distribution of particles produced in a given interval, $D^2 = \langle n^2 \rangle - \langle n \rangle^2$. D^2 is proportional to the average number of particles per cluster $\langle k \rangle$. For Bjorken's energy densities between 2 and 3 GeV/fm^3 reached in nucleus-nucleus collisions, the average cluster size is around 25 fm^3 [6], which means that $\langle k \rangle$ can be larger than two times the normal case. Although the model predicts less multiplicity than in the case of no fusion of resonances, this reduction cannot compensate a factor of 2. Therefore we expect an enhancement of the dispersion D. (The clustering can also be tested by other observables like the left-right fluctuation density $\langle [n_L(y) - n_R(y)]^2 \rangle_n - \langle n_L(y) - n_R(y) \rangle_n^2$ [12], where $n_L(y)$ and $n_R(y)$ are, respectively, the number of particles to the left or right of the rapidity y in a given event, $n = n_L(y) + n_R(y)$.)

In the model of fusion of strings, the dispersion in the number of strings is damped by the fusion of them, implying a reduction in the long range correlations. In

the limit of strong fusion, the double and single inclusive cross sections for hadron-nucleus collisions in the central rapidity region are given, respectively, by [8]

$$\frac{1}{\sigma^{hA}}\frac{d\sigma^{hA}}{dq_1\,dq_2} = I(q_1)I(q_2)$$

$$\times \left[\frac{\sigma_D}{\sigma^{hA}}\frac{(\pi R_A^2)^2 1}{(\pi R_0^2)^2}\frac{1}{A} + \frac{\pi R_A^2}{(\pi R_0^2)^2}\frac{\sigma_P^2}{\sigma^{hA}} \right] \quad (2)$$

and

$$\frac{1}{\sigma^{hA}}\frac{d\sigma^{hA}}{dq} = \frac{I(q)}{\sigma^{hA}}\sigma_P\frac{\pi R_A^2}{\pi R_0^2}. \quad (3)$$

Here the inelastic hadron-nucleus cross section $\sigma^{hA} \sim \pi R_0^2 A^{2/3}$ does not practically change compared to the no-fusion case; σ_D and σ_P are given in terms of the nucleon-nucleon double and single inclusive cross sections,

$$\frac{d\sigma}{dq} = I(q)\sigma_P, \quad \frac{d\sigma}{dq_1\,dq_2} = I(q_1)I(q_2)\sigma_D. \quad (4)$$

From Eqs. (2) and (3) it follows that the behavior of the squared dispersion and the mean multiplicity is, respectively,

$$D^2 = \frac{\sigma_D}{\pi R_0^2}A^{-1/3}\int dq_1\,dq_2\,I(q_1)I(q_2) \sim A^{-1/3} \quad (5)$$

and

$$\langle n \rangle = \frac{\sigma_P}{\pi R_0^2}\int dq\,I(q) \sim \text{const}, \quad (6)$$

to be compared with the behavior without fusion $D^2 \sim A^{1/3}$ and $\langle n \rangle \sim A^{1/3}$. However, these large differences can be lowered due to finite energy corrections and distribution in rapidity. To account for these, two Monte

Carlo codes have been builtup in the framework of the dual parton model [13] and the quark-gluon string model, which give a reasonable description of most of the existing data on nucleus-nucleus interactions. We are going to use the second one to explore the short and long range correlations. A detailed description of this Monte Carlo code can be found in Ref. [9].

Charged particle multiplicities have been studied. At the first step, the Monte Carlo string fusion code was applied to the existing experimental data on long range correlations for pp collisions at $\sqrt{s} = 45$ GeV [14], for $\bar{p}p$ collisions at $\sqrt{s} = 540$ GeV [15], and for pp, p Ar, and p Xe collisions at $p_{\text{lab}} = 200$ GeV/c per nucleon [16]. In Table I we compare the values of the parameter b (if we fit the data by the straight line $\langle n_B \rangle = a + bn_F$, b is given by $b = D_{BF}^2/D_{FF}^2$). A reasonable agreement is obtained. It is seen that the influence of string fusion is small, which was to be expected in view of a comparatively few number of strings for such energies and colliding systems. A stronger effect may be envisaged for nucleus-nucleus collisions. Unfortunately there is no available experimental nucleus-nucleus data.

In Table II, the results for D_{BF}^2, D_{FF}^2, $\langle n_F \rangle$, and b are given for SPb and PbPb collisions at $\sqrt{s_{NN}} = 19.4$ GeV and for SS and CuCu collisions at $\sqrt{s_{NN}} = 200$ GeV, without and with fusion of strings. At $\sqrt{s_{NN}} = 19.4$ GeV, the backward region (B) is defined as $y_{\text{lab}} < 2.0$ and the forward one (F) as $y_{\text{lab}} > 3.6$, while the corresponding definitions at $\sqrt{s_{NN}} = 200$ GeV are $y < -1.0$ and $y > 1.0$, respectively. The separation of more than 1.5 rapidity units eliminates the short range correlations. It is expected that at high n_F there will occur departures

TABLE I. Monte Carlo results without (NOFUS) and with (FUS) string fusion for the parameter b in different collisions and at different energies, compared with the existing experimental data (Expt) [14–16]. The number of generated events is given, together with the definitions of the backward (B) and forward (F) regions.

	Regions			
Reaction	$B \equiv$	$F \equiv$		b
pp at 45 GeV, 10 000 events	$\eta < -1$	$\eta > 1$	NOFUS	0.13
			FUS	0.11
			Expt	0.137 ± 0.023
$\bar{p}p$ at 540 GeV, 50 000 events	$\eta < -1$	$\eta > 1$	NOFUS	0.55
			FUS	0.53
	$-4 \leq \eta \leq -1$	$1 \leq \eta \leq 4$	Expt	0.41 ± 0.01
pp at 19.4 Gev, 10 000 events	$0.75 < y_{\text{lab}} < 1.75$	$3.25 < y_{\text{lab}} < 4.25$	NOFUS	0.04
			FUS	0.04
			Expt	-0.01 ± 0.01
p Ar at 19.4A GeV, 10 000 events	$0.75 < y_{\text{lab}} < 1.75$	$3.25 < y_{\text{lab}} < 4.25$	NOFUS	0.33
			FUS	0.33
			Expt	0.28 ± 0.04
p Xe at 19.4A GeV, 10 000 events	$0.75 < y_{\text{lab}} < 1.75$	$3.25 < y_{\text{lab}} < 4.25$	NOFUS	0.37
			FUS	0.35
			Expt	0.41 ± 0.04

TABLE II. Backward-forward (D_{BF}^2) and forward-forward (D_{FF}^2) squared dispersions, mean forward multiplicities ($\langle n_F \rangle$), and the slope parameter b for SPb and PbPb collisions at $\sqrt{s_{NN}}$ = 19.4 GeV and for SS and CuCu collisions at $\sqrt{s_{NN}}$ = 200 GeV, without (NOFUS) and with (FUS) string fusion taken into account. The definitions of the backward and forward regions can be found in the text.

			D_{BF}^2	D_{FF}^2	$\langle n_F \rangle$	b
$\sqrt{s_{NN}}$ = 19.4 GeV	SPb	NOFUS	1367	1373	44	1.00
		FUS	1321	1305	42	1.01
	PbPb	NOFUS	16 117	26 848	151	0.60
		FUS	15 494	25 098	145	0.62
$\sqrt{s_{NN}}$ = 200 GeV	SS	NOFUS	5595	5718	78	0.98
		FUS	4727	4858	73	0.97
	CuCu	NOFUS	26 975	27 261	156	0.99
		FUS	22 010	22 219	144	0.99

from the straight line, leading to smaller values of the slope b. This effect should be stronger in the case of fusion of strings; however, to be detected experimentally, high statistics are necessary for very central events. The results are obtained for 6000 (minimum bias) generated events in PbPb collisions at $\sqrt{s_{NN}}$ = 19.4 GeV and 10 000 in SS and CuCu at $\sqrt{s_{NN}}$ = 200 GeV and SPb at $\sqrt{s_{NN}}$ = 19.4 GeV, in all cases without and with fusion of strings. At $\sqrt{s_{NN}}$ = 19.4 GeV and for SPb, the fusion of strings produces only a very small reduction of D_{BF}^2 and D_{FF}^2. Also for the envisaged PbPb collisions at this energy, the effects are less than 5%. At energies of the Brookhaven Relativistic Heavy Ion Collider (RHIC), the reduction of D_{BF}^2 and D_{FF}^2 becomes quite clear. In the case of SS collisions for both squared dispersions it is around 15%, and for CuCu it is around 20%. This reduction is obtained without considering centrality triggers. If cuts in the forward multiplicity are applied, considering only high (forward) multiplicity events, the long range correlations are suppressed in both cases, with and without fusion of strings. However, if the experiment has high statistics, the effects of string fusion is amplified,

giving rise to a large difference in D_{BF}^2. This is clearly seen in Table III, where our results for D_{BF}^2, D_{FF}^2, $\langle n_F \rangle$, and b at RHIC energy with and without fusion of strings are shown for forward multiplicities larger than 210 and 260 for SS collisions and larger than 360 and 600 for CuCu collisions. It is observed that the fusion of strings also produces a reduction of the short range correlations, as measured by D_{FF}^2, but not as strong as the suppression of the long range correlations. In this table the results for SPb and PbPb collisions at $\sqrt{s_{NN}}$ = 19.4 GeV are also given for forward charged multiplicities larger than 80 and 550, respectively. It is seen that the fusion only gives sizable effects for PbPb collisions at this energy.

Tables II and III show a clear decrease of the slope b with the growth of n_F. This effect is very strong in the case of fusion of strings and could be detected experimentally.

Our results do not depend on the details of the Monte Carlo program used and qualitatively will not be modified in the framework of any model of strong interaction of strings, based on a superposition of independent interactions [9,13,17].

TABLE III. The same quantities as in Table II when only events with forward multiplicities higher than the ones quoted in the table are considered.

				D_{BF}^2	D_{FF}^2	$\langle n_F \rangle$	b
$\sqrt{s_{NN}}$ = 19.4 GeV	SPb	$n_F \geq 80$	NOFUS	161	146	100	1.11
			FUS	153	138	99	1.11
	PbPb	$n_F \geq 550$	NOFUS	421	930	594	0.45
			FUS	222	646	587	0.34
$\sqrt{s_{NN}}$ = 200 GeV	SS	$n_F \geq 210$	NOFUS	634	789	248	0.80
			FUS	446	606	241	0.74
		$n_F \geq 260$	NOFUS	253	341	282	0.74
			FUS	105	255	279	0.41
	CuCu	$n_F \geq 360$	NOFUS	6481	6477	480	0.93
			FUS	3844	4196	458	0.92
		$n_F \geq 600$	NOFUS	617	723	636	0.85
			FUS	103	266	620	0.39

Summarizing, the study of the long and short range correlations measured by D_{BF}^2 and D_{FF}^2 as a function of the centrality of the collision at RHIC energy can reveal evidence of such nonperturbative effects of quantum chromodynamics as the fusion of strings or large cluster formation, and also allow us to distinguish between them. This would be crucial to determine the intermediate stage of QGP formation.

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