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Long and short range correlations and the search of the Quark Gluon Plasma

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Abstract

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 colour, 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.

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In the last years many efforts have been done in the search of 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, 3, 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 models, 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 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 colour charge at its ends, corresponding to the summation of the colour charges located at the ends of the original strings. Then the new strings break into hadrons according to their higher colour. As a result, heavy flavour 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]) studying the diffractive process $\gamma(Q^2)+$ quark $\rightarrow X+$ 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 the other two Pomerons.

In the first approach the fusion of resonances does not modify the distribution in the number of strings. Therefore there is no variation in the long range correlations (see Ref. [11]). A measurement of such correlations is the backward–forward dispersion

$$D^2_{BF} = < n_B\ n_F > - < n_B > < n_F > \quad , \tag{1}$$

where n_B (n_F) is the number of particles in a backward (forward) rapidity range. In order to eliminate the short range correlations we consider backward and forward intervals separated by at least 1.5 rapidity units. 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, $D^2 =< n^2 > - < n >^2$. D^2 is proportional to the average number of particles per cluster $< k >$. 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 $< k >$ 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 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 $< [n_L(y) - n_R(y)]^2 >_n - < n_L(y) - n_R(y) >_n^2$ ([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, 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])

$$\frac{1}{\sigma^{hA}} \frac{d\sigma^{hA}}{dq_1 dq_2} = I(q_1)I(q_2) \left[\frac{\sigma_D}{\sigma^{hA}} \frac{(\pi R_A^2)^2}{(\pi R_0^2)^2} \frac{1}{A} + \frac{\pi R_A^2}{(\pi R_0^2)^2} \frac{\sigma_P^2}{\sigma^{hA}} \right] \tag{2}$$

and

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

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,

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

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

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

and

$$< n >= \frac{\sigma_P}{\pi R_0^2} \int dq I(q) \sim const. \quad , \tag{6}$$

to be compared with the behaviour without fusion $D^2 \sim A^{1/3}$ and $< n > \sim A^{1/3}$. 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 built up, 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, pAr and pXe collisions at $p_{lab} = 200\ GeV/c$ per nucleon ([16]). In Table 1 we compare the values of the parameter b (if we fit the data by the straight line $< n_B >= a + b\ n_F$, b is given by $b = D^2_{BF}/D^2_{FF}$). 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 not any available experimental nucleus–nucleus data.

In Table 2 the results for D^2_{BF}, D^2_{FF}, $< n_F >$ 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 $y_{lab} < 2.0$ and the forward one (F) as $y_{lab} > 3.6$, 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 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 is 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 10000 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^2_{BF} and D^2_{FF}. Also for the envisaged $PbPb$ collisions at this energy, the effects are less than 5%. At $RHIC$ energy the reduction of D^2_{BF} and D^2_{FF} 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 supressed in both cases, with and without fusion of strings. However, if the experiment has high statistics, the effect of string fusion is amplified, giving rise to a large difference in D^2_{BF}. This is clearly seen in Table 3, where our results for D^2_{BF}, D^2_{FF}, $< n_F >$ 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^2_{FF}, but not so strong as the suppresion 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 sizeable effects for $PbPb$ collisions at this energy.

Tables 2 and 3 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.

Summarizing, the study of the long and short range correlations measured by D^2_{BF} and D^2_{FF} as a function of the centrality of the collision at $RHIC$ energy can reveal evidence of such non–perturbative 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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Table Captions

Table 1. 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 ($Exp.$) ([14, 15, 16]). The number of generated events is given, together with the definitions of the backward (B) and forward (F) regions.

Table 2. Backward–forward (D^2_{BF}) and forward–forward (D^2_{FF}) squared dispersions, mean forward multiplicities ($< n_F >$) 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.

Table 3. The same quantities as in Table 2 when only events with forward multiplicities higher than the ones quoted in the table are considered.

Table 1

Reaction	Regions		b	
	$B \equiv$	$F \equiv$		
pp at 45 GeV, 10000 events	$\eta < -1$	$\eta > 1$	$NOFUS$	0.13
			FUS	0.11
			$Exp.$	0.137 ± 0.023
$\overline{p}p$ at 540 GeV, 50000 events	$\eta < -1$	$\eta > 1$	$NOFUS$	0.55
			FUS	0.53
	$-4 \leq \eta \leq -1$	$1 \leq \eta \leq 4$	$Exp.$	0.41 ± 0.01
pp at 19.4 GeV, 10000 events	$0.75 < y_{lab} < 1.75$	$3.25 < y_{lab} < 4.25$	$NOFUS$	0.04
			FUS	0.04
			$Exp.$	-0.01 ± 0.01
pAr at 19.4 $AGeV$, 10000 events	$0.75 < y_{lab} < 1.75$	$3.25 < y_{lab} < 4.25$	$NOFUS$	0.33
			FUS	0.33
			$Exp.$	0.28 ± 0.04
pXe at 19.4 $AGeV$, 10000 events	$0.75 < y_{lab} < 1.75$	$3.25 < y_{lab} < 4.25$	$NOFUS$	0.37
			FUS	0.35
			$Exp.$	0.41 ± 0.04

Table 2

			D^2_{BF}	D^2_{FF}	$< n_F >$	b
$\sqrt{s_{NN}} = 19.4\ GeV$	SPb	$NOFUS$	1367	1373	44	1.00
		FUS	1321	1305	42	1.01
	$PbPb$	$NOFUS$	16117	26848	151	0.60
		FUS	15494	25098	145	0.62
$\sqrt{s_{NN}} = 200\ GeV$	SS	$NOFUS$	5595	5718	78	0.98
		FUS	4727	4858	73	0.97
	$CuCu$	$NOFUS$	26975	27261	156	0.99
		FUS	22010	22219	144	0.99

Table 3

				D^2_{BF}	D^2_{FF}	$< n_F >$	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