INTERMITTENCY AND THE HANBURY-BROWN–TWISS EFFECT

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Dedicated to Wiesław Czyż in honour of his 65th birthday

Relation of the intermittency phenomenon observed in spectra of particles produced in high-energy collisions to the intensity correlations between identical particles is discussed. It is argued that the compatibility of the two effects requires scale-invariant (power law) fluctuations of the size of the interaction region.

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1. Introduction

Intermittency in high-energy collisions was defined [1] as a specific property of the spectra of the produced particles. The spectrum is called intermittent if the scaled factorial moments

$$F_q \equiv \frac{\langle n(n-1)\ldots(n-q+1)\rangle}{\langle n\rangle^q} \tag{1}$$

obey the power law

$$F_q(\delta) = \left(\frac{\Delta}{\delta}\right)^{f_q} F_q(\Delta) \tag{2}$$

for $\delta \to 0$. Here δ and Δ are phase-space volumes in which F_q is calculated, and n is the number of particles in the given volume. $\langle\ldots\rangle$ denotes averaging and q is an integer, $q \geq 2$. The positive constants f_q are called intermittency exponents.

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The factorial moment

$$F_q(\delta) = \langle n(n-1)\ldots(n-q+1)\rangle_\delta \tag{3}$$

measures the average number of the q-plets of particles found in the region of size δ. Therefore (see *e.g.* [2]) it is related to the q-particle density $\rho(p_1,\ldots,p_q)$:

$$F_q(\delta) = \int\limits_\delta \rho(p_1,\ldots,p_q)dp_1\ldots dp_q\,. \tag{4}$$

Consequently, the condition (2) implies that the q-particle density must show a power-law singularity in the limit where the difference between two (or more) momenta tends to zero, *e.g.*

$$\rho_2(p_1,p_2) \to A|p_1-p_2|^{-f_q}\,, \tag{5}$$

where A is a constant. This implies, in turn, that also the multiparticle correlation functions are singular in this limit, *e.g.*

$$C_2(p_1,p_2) \equiv \rho_2(p_1,p_2) - \rho_1(p_1)\rho_2(p_2) \to A|p_1-p_2|^{-f_q}\,. \tag{6}$$

These properties imply that the "intermittent" multi-particle system is scale-invariant in the limit $|p_1-p_2| \to 0$, *i.e.* at large distances:

$$|x_1-x_2| \to \infty\,. \tag{7}$$

At this point it should perhaps be emphasized that the "singularities" (6) and (7) are not to be understood in the strict mathematical sense: in physical phenomena one always expects eventually a cut-off. The problem therefore can be formulated as a quest for the region in which the power laws (6) and (7) are valid, *i.e.* in which the system is scale-invariant.

Recently, a rather good evidence was obtained for the power law (2) in the three-dimensional spectra of several high-energy processes [3–5]. There are also indications that the effect may be universal, *i.e.* that the intermittency exponents f_q are independent of the process considered [6].

On the other hand there exist also numerous measurements giving a convincing evidence for short range correlations between momenta of identical pions [7]. These data can be interpreted as measurements of the size of the interaction volume [8]. Therefore the question arises about the compatibility of the two phenomena.

The suggestion that the HBT effect may be responsible for the observed intermittency phenomena was formulated already some time ago [9, 10]. Since the standard theory of the HBT effect [11] does not give any singularity of the correlation function, the conclusion of Refs [9] and [10] was that the observed power law (2) is only a numerical accident, and no scale invariance is actually present in the data.

In this paper, following the idea first formulated in Ref. [12], we investigate the relation between the HBT effect and intermittency phenomenon. We show that they are perfectly compatible. The most important consequence of this point of view is the existence of scale invariant fluctuations of the interaction volume (as measured by HBT effect).

2. HBT effect

If the HBT effect is indeed responsible for intermittency, one expects that the intermittency parameters for identical and non-identical particles must be different. In particular, the ratio of 2 between the intermittency exponents for identical and for all particles was predicted [10]. This was investigated in several papers with respect to rapidity distribution but the results were not conclusive (see *e.g.* [13, 14]).

Recently, the multiparticle correlations for like-charge particles were studied by the UA1-MB and NA22 collaborations [15, 16] in three dimensional spectra. When plotted versus the squared difference of momenta Q^2, defined as [17]

$$Q_{ij}^2 = -\left(p_i - p_j\right)^2 , \qquad Q^2 = \sum_{ij} Q_{ij}^2 , \tag{8}$$

the spectra show an impressive agreement with the power law behaviour (2). At the same time the spectra show a clear difference between like-charge and all charged particles: the ratio of slopes is close to the factor two, as predicted for HBT effect.

These data show on one hand that the HBT effect is an important factor determining the short-range correlations in momentum space. On the other hand, however, they indicate that the existing interpretation of HBT correlations may be missing an important point, namely much larger than expected fluctuations of the size of the source. Indeed, it was realized some time ago [12] that, if the HBT effect is responsible for the observed intermittency phenomenon, it implies power law fluctuations of the size of the interaction region.

3. Intermittency from the HBT effect

The range of HBT correlations measures the size of the volume from which the particles are emitted. The detailed shape of the correlation function, however, depends on the shape of the source. Let us consider the simplest example of a static gaussian source

$$\rho(r) = R^{-3}\pi^{3/2} \exp\left(\frac{-r^2}{R^2}\right), \tag{9}$$

for which the correlation function between the identical particles is (see *e.g.* [11])

$$C(p_1,p_2) = \exp\left(-\frac{(\Delta p)^2 R^2}{2}\right) \tag{10}$$

with $\Delta p = |p_1 - p_2|$. Clearly, this correlation function has nothing to do with the power law. Consider, however, the situation when the radius R of the source is not fixed, but fluctuates itself following the probability distribution:

$$F(R)dR = \gamma L^{-\gamma} R^{\gamma-1} \Theta(R-L)dR, \tag{11}$$

where γ is a constant, $1 \geq \gamma \geq 0$. The Heaviside function Θ represents a necessary cutoff of the power law distribution (11) (otherwise the distribution cannot be normalized). Using (11), we obtain for the normalized correlation function

$$C(p_1,p_2) = \gamma L^{-\gamma} \int_0^L dR\, R^{\gamma-1} \exp\left(-\frac{R^2(\Delta p)^2}{2}\right)$$
$$= \gamma(L\Delta p)^{-\gamma} \int_0^{L\Delta p} dz\, z^{\gamma-1} \exp\left(-\frac{z^2}{2}\right). \tag{12}$$

The result depends only on dimensionless product ΔpL, since no other scale was present in the problem. In Fig. 1 $C(p_1,p_2)$ is plotted *vs* (ΔpL) for $\gamma = 1/2$. One sees that in the region $\Delta p \geq L^{-1}$ the correlation function (12) exhibits the power law behaviour. For $\Delta p \leq L^{-1}$, however, the cutt-off starts to operate and the singularity is washed out: $C(p_1 = p_2) = 1$, as necessary to obey the normalization condition.

This derivation of the power-law singularity (12) is, of course, a purely formal exercise (it is clearly not restricted to objects of gaussian shape and can be generalized to other distributions exhibiting a power law dependence in configuration space). The real question is how such strong fluctuations of the size of the system (as described by (11)) can occur. There are two possibilities.

(a) The shape of interaction region being regular (*e.g.* gaussian, as in (9)), its size fluctuates from event to event according to (11).

(b) The interaction region is itself a self-similar fractal, extending over a very large volume.

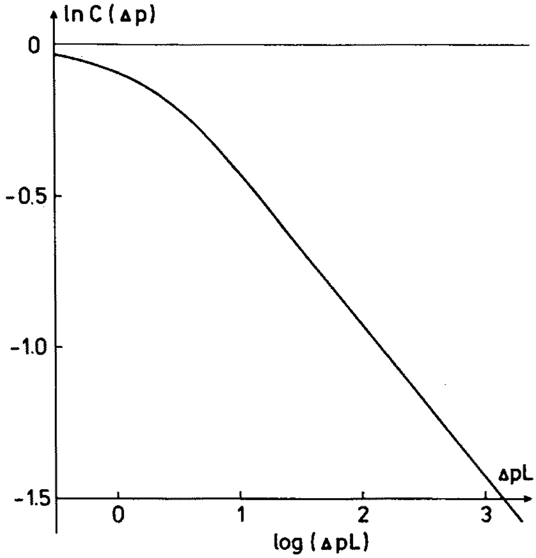

Fig. 1. The correlation function between two identical particles. One sees the power-law behaviour for $\Delta p \geq L^{-1}$.

Although the second possibility seems very radical when compared to the standard analyses of the HBT correlations [7–11], it appears rather natural if one takes into account that the interaction volume is very likely a complicated structure made of coloured "strings" stretched in all directions by the colored partons trying to escape the interaction region. Hadrons can be created at any point of this structure and therefore large fluctuations in the space-time distance between them are actually expected. Why are these fluctuations governed by a power law is of course another question. Some speculations on this problem can be found in Ref. [18].

Let me close this paper with the following remark.

The idea that intermittency is related to the HBT effect removes one serious difficulty which plagues the interpretations of intermittency in terms of parton distributions. The problem is that, even if one explains the existence of very short-range correlations in the parton system (*e.g.* by a branching process) this is clearly not enough to explain the data: the experiment observes hadrons, not partons. Consequently, one must take into account the process of hadronization. And it is rather hard to imagine why the "reshuffling" of momenta of partons when they change into hadronic resonances which in turn decay into observed pions and kaons does not destroy the singular nature of the correlations. Clearly, a mysterious "conspiracy" is necessary. One invokes usually at this point the principle of "parton-hadron duality" but this is just giving a name to the phenomenon which is in fact not understood. However, if intermittency is caused by the HBT phenomenon, there is no problem: the HBT effect works already on hadron level (*i.e.* after hadronization and after the decay of resonances). In my opinion this argument gives a substantial support to the idea.

In conclusion, we have found that the recent data on intermittency and on the HBT effect suggest the existence of large, self-similar fluctuations of the size of interaction volume in high-energy reactions.

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