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MULTIPARTICLE PRODUCTION: SESSION SUMMARY*

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1. LONG-RANGE AND SHORT-RANGE CORRELATIONS

Studying multiparticle dynamics amounts basically to investigation of multiparticle correlations. It took some time before this rather obvious statement found its way into high-energy physics. If I remember correctly, the turning point was the paper by Mueller,¹ who adapted the techniques known from statistical physics and showed explicitly how to relate multiplicity distributions and correlation parameters.

Historically we distinguish long-range and short-range correlations in momentum space. Long-range correlations describe total multiplicity and measure simply the deviation of the data from the Poisson distribution. They are easiest to determine (counting of tracks is sufficient) and, therefore, were studied first. At not too low energies (to avoid constraints from conservation laws) the observed distribution is broader than Poisson. This is interpreted as evidence for a multicomponent nature of high energy collisions. The great success of the negative binomial distribution in description of the data² is the best example of this situation. Indeed, the negative binomial spectrum can be written as a (continuous) superposition of Poisson distributions:

$$P(n; \bar{n}, k) = \frac{k^k}{\Gamma(k)} \int z^{k-1} e^{-kz} e^{-\bar{n}z} \frac{(\bar{n}z)^n}{n!} dz \quad (1)$$

showing explicitly its multicomponent character.

More information is obtained if one measures the momentum dependence of the correlation functions. Numerous studies in the seventies showed that the data can be described in terms of clusters, i.e. isotropically decaying objects, rather densely packed in the phase space available for soft particles (it is not clear if the clusters can be reduced to the known resonances but this cannot be excluded). Surprisingly enough, the data in different rapidity intervals can also be described by the negative binomial distribution.² This is probably explained by the fact that, as emphasized by Giovannini and Van Hove, the negative binomial distribution can also be written in the form which corresponds to independent emission of clusters³. The negative binomial description of the data was discussed extensively during our session — mainly by Tannenbaum⁴ who confirmed its excellent agreement with the data in varying intervals

of rapidity, and established a simple linear relation between the parameter k of the distribution and the size of the interval in question.

Since few years the main focus of research is on correlations of very short range, much shorter than those related to isotropic cluster decay. This kinematic region — very difficult experimentally — became accessible by increasing statistics and quality of the data, and by the development of new, sensitive tools. It started with factorial moments⁵ which played an important role at the beginning. Two new applications of factorial moments were described at this meeting. Derado⁶ showed that the technique of factorial moments can be very helpful in tracing the phenomenon of "Baked Alaska"^{7,8} even if such events are very rare. Meunier⁹ presented generalization of factorial moments to non-integer and to negative ranks. He showed that they can be exceedingly useful in discriminating between different models.

2. SCALING OF CORRELATION FUNCTIONS

The early observation that the data¹⁰ indicate the presence of very short range correlations led to the suggestion that — perhaps — there exist correlations at all scales.⁵ A natural consequence was the idea of scaling, i.e. power law dependence of the factorial moments on the size of the phase-space bin (called "intermittency" in ref. 5). Experimental investigations of factorial moments allowed to confirm existence of intermittency in e^+e^- , $p\bar{p}$, πp and heavy ion collisions¹¹.

Fig.1. Second cumulant of the charged particles distribution produced in $p\bar{p}$ collisions at 640 GeV/c plotted versus $l = \delta\phi\delta y\delta(\log p_\perp)$. UA1 coll. ref. 13.

Significant progress was possible when a novel technique, called "correlation integrals" was proposed and developed by the Tucson-Vienna collaboration¹². This turned out to be a great improvement which allowed to measure correlation functions with an unprecedented precision. A typical result is shown in Fig. 1, where the second cumulant of the charged particle distribution in 600 GeV $p\bar{p}$ collisions¹³ is plotted versus the size of the three-dimensional bin in momentum space. One sees that the

data follow rather accurately a straight line which, in this log-log plot, represents the power law:

$$C(\delta) \sim \delta^{-f}, \quad (2)$$

i.e. scaling in the 3-dimensional momentum space.

I feel that it is difficult to ignore the data of this quality and therefore it is important to search seriously for a possible physical origin of this phenomenon. Attempts in this direction are described in the next section.

3. MODELS OF SCALING BEHAVIOUR

It should perhaps be emphasized that observation of scaling does not — and by far — point out uniquely what kind of physics is responsible for it. Therefore, several possibilities were considered.

(a) Cascade Models

Self similar cascade produces scaling behaviour of the factorial moments and therefore served as a guiding example from the very beginning. In particular, the original suggestion⁵ of the scaling phenomenon was modelled as a cascade of a “strongly interacting liquid” in analogy to the turbulent flow in hydrodynamics. This analogy emphasizes the relation of the observed phenomenon to the “chaotic behaviour” of the system in question. In view of the recent work by Müller and collaborators¹⁴ who find a clear signal of chaotic behaviour of the gluon fields, it is not unlikely that this may turn out to be more than just a formal analogy.

The first serious self-similar cascade calculation — in the framework of the cluster model — was performed by Ochs and Wosiek¹⁵. They confirmed the idea of approximate scaling and found a more general regularity which was valid independently of the phase-space dimension

$$C_q(\delta) \sim \{C_2(\delta)\}^{f_q} \quad (3)$$

(in low-dimensional analysis the second moment saturates at small distances, but the eq.(3) is nevertheless valid).

Recently, analytic calculations of the QCD parton cascade became available. Three groups produced results almost simultaneously¹⁶. These results and very recent progress were reported by Ochs at our session¹⁷. The major results are (a) the QCD cascade is not actually self-similar because the coupling constant varies along the cascade. Consequently, the scaling is only approximate and the moments tend to saturate at small distances in 3-dimensional phase-space; (b) new observables for testing the predicted behaviour were suggested. They are constructed of angular variables and thus are relatively easy to analyze experimentally.

(b) Phase Transitions

Second order phase transition is well known to imply scaling of the correlation functions¹⁸. This was realized immediately¹⁹ and the analysis of intermittency in the Ising model was carried out²⁰. Recently, Hwa discussed the problem in the Ginzburg-Landau model²¹. He determined the relevant intermittency exponents and found — among other results — that even for the first order transition the Ochs-Wosiek relation (3) is valid (with a rather simple formula for f_q).

It is not clear, of course, if and how the Ising model and/or Ginzburg-Landau theory can actually be applied to particle distributions and what can be the physics of the phase-transition in question.

(c) Self-Organized Criticality

Another attractive mechanism giving scaling of the correlation functions is the self-organized criticality (“theory of avalanches”) of Bak et al.²². It turns out that many non-linear systems develop automatically the scaling behaviour in a very broad range of the parameters which describe the system. Thus no fine tuning is necessary to obtain scaling (this is in contrast to the phase transition which takes place only at the critical temperature). It was realized already from some time that this provides an interesting possibility of explanation of the scaling behaviour of particle spectra. Only recently, however, Hwa and collaborators found a self-organized critical system which could be applied to multiparticle production. The results were presented during the session²³.

4. HADRONIZATION

All these explanations of scaling in multiparticle spectra have one common drawback: they are formulated in terms of partons or other non-observable degrees of freedom rather than in terms of the final measured hadrons. This brings immediately the question: why the process of hadronization does not spoil the scaling behaviour. I would like to emphasize that this question is a very serious one: we are talking here about the momentum resolution up to about 40 MeV — significantly below the pion mass — and it is really difficult to understand why the reshuffling of partons into observed hadrons does not affect even such small momentum differences. This puzzled us all for some time and was — I think — a serious obstacle to the progress.

5. HBT CORRELATIONS

About two years ago the experimental analyses²⁴ provided an unambiguous evidence that, as suggested from some time²⁵ at very small difference of momenta, correlations are dominated by HBT effect, i.e. quantum interference²⁶. This is illustrated in Fig. 2, where the data from UA1 and DELPHI collaborations²⁷ are plotted versus Q , the difference of particle four-momenta squared. One clearly sees that at small Q the correlations between like-sign particles are much stronger than those between unlike-sign ones. In the simplest interpretation this implies that (a) the production of pions in this kinematic range is, at least to a large extent, incoherent (this is the necessary condition for HBT correlations to be present); (b) the correlations observed at low Q are related to the space-time structure of the system rather than to its structure in momentum space.

I would like to emphasize the importance of the conclusion (b): it drastically changes the way of thinking about the problem, as compared to the ideas based on cascade in momentum space described in section 3. What is perhaps even more important, it allows finally to understand why hadronization is not an obstacle for having strong correlations at low Q . Indeed, since the correlations reflect only the space-time structure of the source, they are little sensitive to details of its composition

Fig.2. Two-particle correlation integrals for like-sign and unlike-sign particles produced in 640 GeV $p\bar{p}$ collisions and in Z^0 decays. DELPHI and UA1 coll. ref. 27.

and on momentum distribution of the constituents. That is to say, it does not matter if the source of pions is made of partons, of hadronic fluid, of decaying clusters, or of anything else. Also, the mechanism of formation of the final pions is (almost) irrelevant. What matters is the space-time structure of the source and incoherent character of pion emission.

Thus one annoying problem seems solved. Others remain, however.

The first one : how can one justify the scaling law (2) at small Q ? To underline the importance of this question, the data for like-sign pion correlation function²⁷ are again shown in Fig. 3 (in different scale). One sees that they do indeed closely follow the power law at small Q .

Fig. 3. Second factorial moment plotted versus $Q^2 = |(p_1 - p_2)^2|$. UA1 coll. ref. 28.

There are basically two possible answers: either (a) the observed power law is just a numerical accident which dissimulates a more complicate structure²⁹ or (b) there is a genuine scaling in the system.

In the case (a) one has to find a reason for the presence of very short range correlations. Two suggestions were made. One is based on the idea of Grassberger³⁰ which relates the HBT correlation length to the widths of resonances produced in the collision. If a substantial number of relatively narrow resonances is produced, the small correlation length in momentum space is naturally explained³¹. The second suggestion takes advantage of the fact that, as emphasized by Weiner during the session,²⁹ HBT correlations do not simply reflect the shape of the interaction volume but also correlations inside it. The resulting structure is rich enough to describe the data, as was explicitly shown by Weiner during the morning session. Other detailed features of HBT correlations, related particularly to expansion of the interacting system were discussed during the session by Sinyukov³².

In the case (b) it is necessary to accept that the region of pion emission does not have a well-defined radius but rather a long tail decreasing as a power of distance (at large distances from the center)³³. It remains an open question if a fractal structure of the source is also necessary to explain the data. This can be eventually decided when precise data on higher order correlations are available³⁴.

The second question, which I myself find rather fundamental, can be formulated as follows. The comparison of e^+e^- data and the existing QCD cascade models shows that the region of medium Q ($0.2 \text{ GeV} < Q \lesssim \text{few GeV}$) can possibly be described by the standard quark-gluon cascade followed by hadronization³⁵. On the other hand, we have just seen that the very small Q region ($Q \lesssim 0.1 \text{ GeV}$) reflects the space-time structure of the system. This — *a priori* — has nothing to do with the anomalous QCD dimensions and the value of the strong coupling constant determining the behaviour of the QCD cascade in the medium Q region. How can one thus explain that the shape of the correlation function (Figs 2, 3) does not visibly change when one passes from one region to another? The problem is most clearly seen when one compares the data for like sign and unlike-sign pions in the data of DELPHI coll. shown in Fig. 2. For unlike pairs there is a clear change of shape at $Q = 0.2 \text{ GeV}$ indicating the end of the scaling region of the quark-gluon cascade. For like-sign pairs, however, the slope continues essentially unchanged until the smallest Q measured. This indicates a surprising connection between the original quark-gluon cascade and the space-time structure of the region of pion emission at the late stage of the collision. It would be of course very interesting to understand better this relation.

6. UNIVERSALITY

Universality of the correlation functions is a controversial issue which is still far from being resolved. At the present meeting Sarcevic pointed out one marked difference between the heavy ion data and the data from simpler targets³⁶. The data show that there are practically no correlations beyond the second order in the heavy ion data, in contrast to the hadron-hadron and e^+e^- collisions. She argued that this observation has an important implication, as it allows to describe particle production in heavy ion collisions by a field theory³⁶. Numerous further consequences follow from this approach. It shall be of course very interesting to see if they are confirmed by the future data.

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