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NEW DEVELOPMENTS IN CORRELATION STUDIES*

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ABSTRACT

By using the recently developed technique of correlation integrals we measured correlation functions over a wide range of invariant mass 50 GeV $\geq M \geq$ 0.2809 GeV in $\bar{p}p$ reactions at collider energy. A comparison with Monte Carlo models shows that our understanding of the dynamics of multiparticle production is still insufficient. We discuss a possible improvement by including low p_T clustering effects in addition to those of Lund-strings alone.

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ABSTRACT

By using the recently developed technique of correlation integrals we measured correlation functions over a wide range of invariant mass 50 GeV $\geq M \geq$ 0.2809 GeV in $\bar{p}p$ reactions at collider energy. A comparison with Monte Carlo models shows that our understanding of the dynamics of multiparticle production is still insufficient. We discuss a possible improvement by including low p_T clustering effects in addition to those of Lund-strings alone.

INTRODUCTION

In principle, the correlation functions both of lower and higher orders provide valuable information on the multiparticle system. Because of their high dimensionality in high energy reactions, they are difficult to measure. However, since Bialas and Peschanski in 1986 have proposed to study the dependence of the factorial moments (FM) on the magnitude of phase space bins,[1] correlation studies have developed rapidly[2] and new tools, the correlation integrals,[3–5] are available now.

The crucial steps leading to the correlation integrals have been:

1. to choose differences of phase space variables between particles (e.g. $\delta y = y_1 - y_2$) and to integrate over all distinct locations in phase space; therefore, new variables like the four momentum transfer $Q_{12}^2 = -(p_1 - p_2)$ and the invariant mass $M = \sqrt{Q_{12}^2 + 4m^2}$ can be analysed,
2. to find the proper normalization* by justifying and quantifying mathematically the event mixing technique,[4]
3. to extend the event mixing technique to the numerator for estimating the cumulant correlation functions.

*Q^2 has been used frequently in the past, e.g. when measuring Bose-Einstein correlations, however, the normalization included always some arbitrariness and has been an unsolved problem. An early work of E. Berger et al.[6] should be mentioned here as an exception.

Now we are in the position to apply these tools to the data, to see whether they can help to get more sensitive information on the dynamical origin of multiparticle correlations. This is the aim of the present contribution[†].

DATA, DEFINITIONS AND GENERAL FEATURES

The data sample consists of 160.000 non-single diffractive $\bar{p}p$ reactions at $\sqrt{s} =$ 630 GeV, measured in the UA1 detector[‡]. In one distinct case, e^+e^- reactions at $\sqrt{s} = 90$ GeV from the DELPHI experiment[§] are presented for comparison. We will investigate in the following the differential density correlation function $r_2(M)$ and the moments $F_i(M)$ (i = 2-5) depending on the invariant mass M over a wide range $50 \geq M \geq 0.2809$.

$$\begin{aligned}
r_2(M) &= \frac{\rho_2(M)}{\rho_1 \otimes \rho_1(M)} \qquad (1)\\
\rho_2(M) &= \int_\Omega d^3p_1 \cdot d^3p_2 \cdot \rho_2\left(\vec{p}_1, \vec{p}_2\right) \delta\left(M - m\left(\vec{p}_1, \vec{p}_2\right)\right)\\
\rho_1 \otimes \rho_1(M) &= \int_\Omega d^3p_1 \cdot d^3p_2 \cdot \rho_1\left(\vec{p}_1\right) \cdot \rho_1\left(\vec{p}_2\right) \delta\left(M - m\left(\vec{p}_1, \vec{p}_2\right)\right)\\
\rho_2\left(\vec{p}_1, \vec{p}_2\right) &= \frac{1}{\sigma_I} \cdot \frac{d^6\sigma_{\text{incl}}}{d\,\vec{p}_1 \cdot d\,\vec{p}_2}\\
\rho_1\left(\vec{p}\right) &= \frac{1}{\sigma_I} \frac{d^3\sigma_{\text{incl}}}{d\,\vec{p}}\\
m\left(\vec{p}_1, \vec{p}_2\right) &= \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}
\end{aligned}$$

with $\vec{p}$ being the 3-momenta and E the corresponding energies with pion mass, σ_{incl} and σ_I the inclusive and event cross sections. The integration region Ω in our case is the pseudorapidity interval $-3 \leq \eta \leq 3$ and $p_T > 0.15$ GeV/c[¶].

The numerator and the denominator of eqn.(1) are shown in fig.1a. The ratio is shown in fig.1b. Whereas both quantities in fig.1a show large variations (four orders of magnitude!) over the whole mass range which are due to phase space and the shape of single particle spectrum $\rho_1(\vec{p})$, in the ratio of fig.1b this has cancelled out and the structure of correlations shows up. Beside the differential representation in eqn.(1) we will use also the integral respresentation, the moments

$$F_2(M) = \frac{\int_o^M \rho_2(M')dM'}{\int_0^M \rho_1 \otimes \rho_1(M')dM'} \qquad (2)$$

The normalization condition

$$\begin{aligned}
\int_0^{M_{\max}} \rho_2(M)dM &= \langle n(n-1) \rangle \quad \text{in} \quad \Omega \qquad (3)\\
\int_0^{M_{\max}} \rho_1 \otimes \rho_1(M)dM &= \langle n \rangle^2 \quad \text{in} \quad \Omega
\end{aligned}$$

[†]Other recent applications of correlation integrals are summarized in[2]

[‡]for details of data selection see[7]

[§]for details of data selection see[8]

[¶]In case of exception, this will be indicated in the text or figure caption.

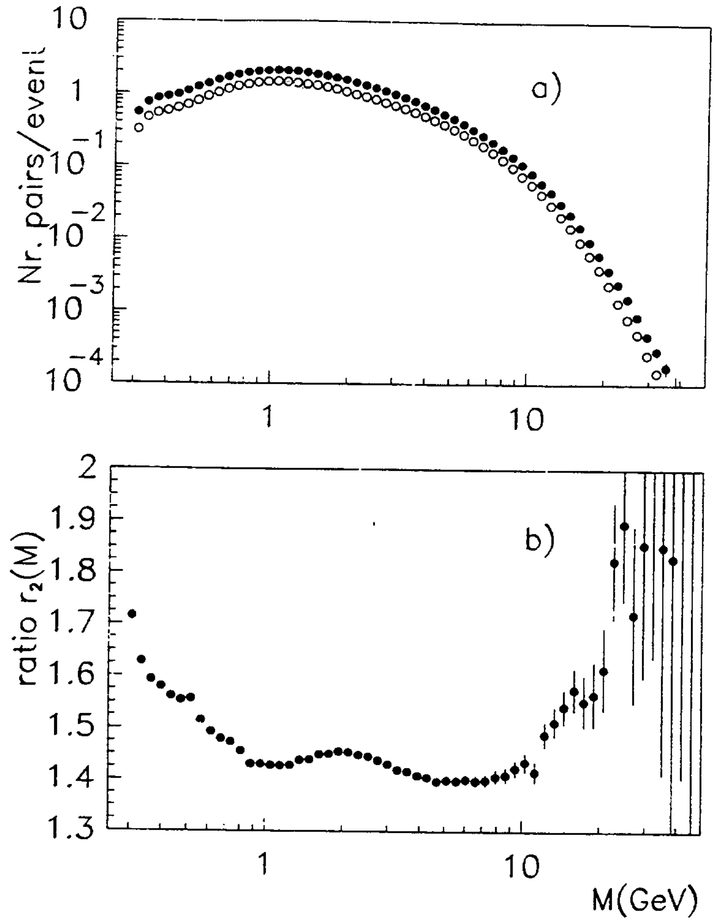

Fig.1: a) The numerator (number of pairs measured, black circles) and denominator (number of uncorrelated pairs, open circles) of eqn.(1). Only the azimuthal angle region of good acceptance is shown here, to avoid problems, which will not occure in the ratio later.
b) The corresponding ratio, eqn. (1).

establishes the connection with the scaled second order factorial moment of the multiplicity distribution in Ω :

$$F_2(M_{\max}) = \frac{< n(n-1) >}{< n >^2} \quad \text{in} \quad \Omega$$

$M_{\max}$ is the highest kinematically possible mass and n is the event multiplicity in Ω.
Higher order moments are defined similarly:

$$\begin{aligned} F_i(M) &= \frac{\int_0^M dM' \int d^3p_1 \ldots d^3p_i \cdot \rho_i(\vec{p}_1 \ldots \vec{p}_i)\delta(M' - m_i(\vec{p}_1 \ldots \vec{p}_i))}{\int_0^M dM' \int d^3p_1 \ldots d^3p_i \rho_1(\vec{p}_1) \ldots \rho_1(\vec{p}_i) \cdot \delta(M' - m_i(\vec{p}_1 \ldots \vec{p}_i))} \qquad (4) \\ F_i(M_{\max}) &= \frac{< n(n-1)\ldots(n-i+1) >}{< n >^i} \quad \text{in} \quad \Omega \end{aligned}$$

to define m_i, we used the Grassberger counting convention.[9]

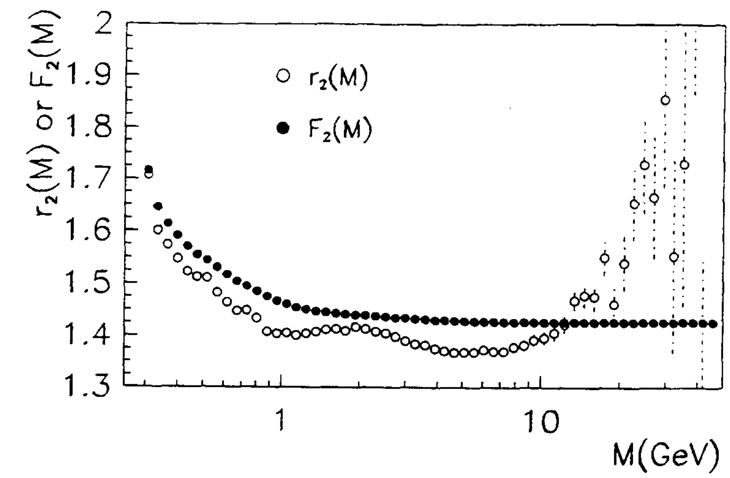

Fig.2: Differential representation (open circles, eqn. (1)) and integral representation (black circles, eqn. (2)) of the second order correlation integrals.

In figs.1-3 we can read off the whole story of long- and short-range correlations and their respective contributions to the multiplicity distribution in Ω.

1. The short-range correlations[10] show up as rise of $r_2(M)$ with decreasing M in the region $M < 1$GeV (fig.1b). We evaluated from fig.1a that the number of pairs responsible for this rise above the pedestrial value of $r_2 \approx 1.4$ contribute less then 2% to the value of $F_2(M_{\max})$ which is reached already for $M = 50$ GeV in fig.2. Similar considerations hold for the higher moments shown in fig.3.

2. In fig2 $F_2(M)$ decreases for small $M \lesssim 1$ GeV but levels off at larger M because of the presence of long-range correlations. This is seen also in $r_2(M)$, which remains > 1 in the whole range of M ($k_2 = r_2 - 1 > 0$, positive genuine correlations).

3. The values $F_i(M_{\max})$, already reached at $M \approx 50$ GeV in fig.3, represent the multiplicity distribution in Ω. The large values at higher orders i indicate a broad Negative Binomial[||] distribution. From the observations of item 1 we argue that multiplicity distributions in large phase space bins (like Ω) are almost due to long-range correlations only.

In contrast, the F_i of e^+e^- reactions at LEP energy (open circles in fig.3) do show small values at large M which is the signature of an (approximate) Poissonic[**] multiplicity distribution in Ω. Again, the large short-range correlations do contribute only with a small amount to the overall multiplicity distribution and in this case, the long-range correlations are almost absent.

Do we understand these features ? Since in e^+e^- reactions they can be reproduced even quantitatively by Monte Carlo models with QCD cascading, we will consider in the following only $\bar{p}p$ reactions.

[||]The factorial moments of the Neg. Bin. distribution have been evaluated already early by A. Giovannini.[11] They provide an equivalent and alternative parametrization of the multiplicity distribution (equivalence theorem[12]).

[**]In case of full phase space, not shown here, the F_i values of e^+e^- are even smaller and indeed near unity.

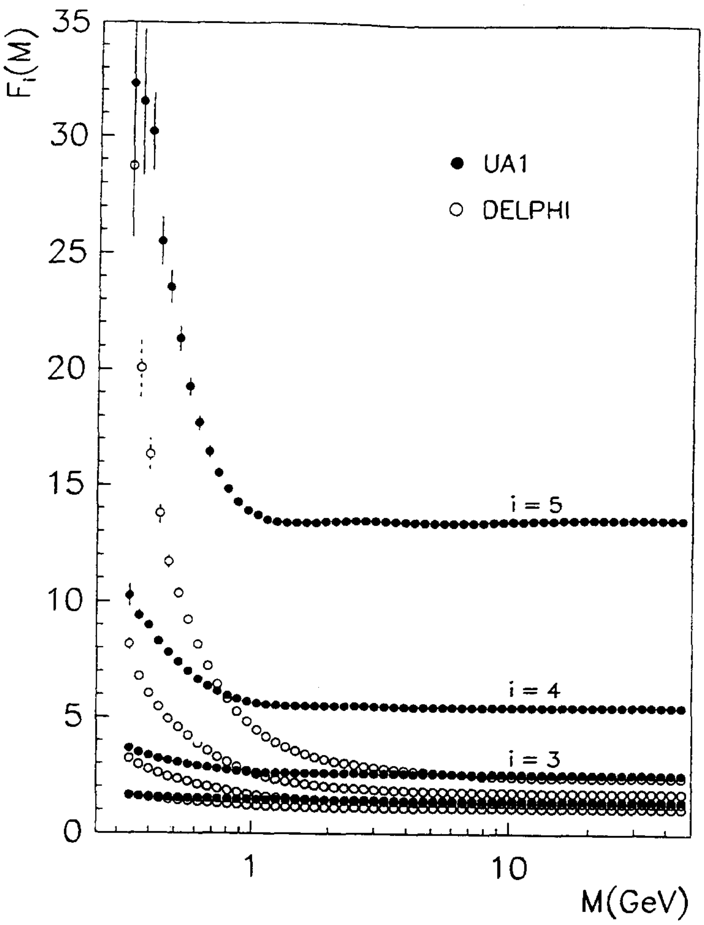

Fig.3: A comparison of correlation integrals $F_i(M)(i = 2-5)$ of $\bar{p}p$ reactions (black circles) with e^+e^- reactions (open circles).

HOW WELL DO WE UNDERSTAND THE DYNAMICAL ORIGIN OF CORRELATIONS IN *hh* REACTIONS ?

A very detailed physical picture is contained in the Lund Monte Carlo program PYTHIA.[13] A high energy collision is viewed as a collision of two parton beams. Each reaction is initialised by a hard-to-semihard parton-parton scattering with a cross section falling rapidly towards higher partonic transverse momentum p_T according to QCD. The description of inclusive event properties restricts the cut-off parameter $p_{T_{\min}}$ to 1.5-2 GeV/c. The broad multiplicity distribution is obtained by varying the number of initial parton scatterings per event from one event to another (varying centrality of the reactions together with Poissonian fluctuations). Both, the mean multiplicity and the shape of the multiplicity distribution depend on $p_{T_{\min}}$. Initial and final state radiation is created. Each parton configuration hadronises via Lund-strings spanned between the hard-scattered partons and beam remanents. PYTHIA thus contains jet and resonance production. Bose-Einstein correlations have been added as "final state interactions". Fig.4 shows a comparison of $r_2(M)$ with PYTHIA 5.6 with two selections of $p_{T_{\min}}$. We observe 1) an overestimation of correlations with large mass which can be attributed to pairs of high p_T particles, 2) no reproduction of the structure at 2 GeV[††], and 3) an underestimation of correlations at small mass. A similar result: overestimation of correlations at high p_T and high multiplicity, and underestimation at low p_T/low multiplicity by PYTHIA has been observed also in the multiplicity and p_T dependence of short-range correlations.[14]

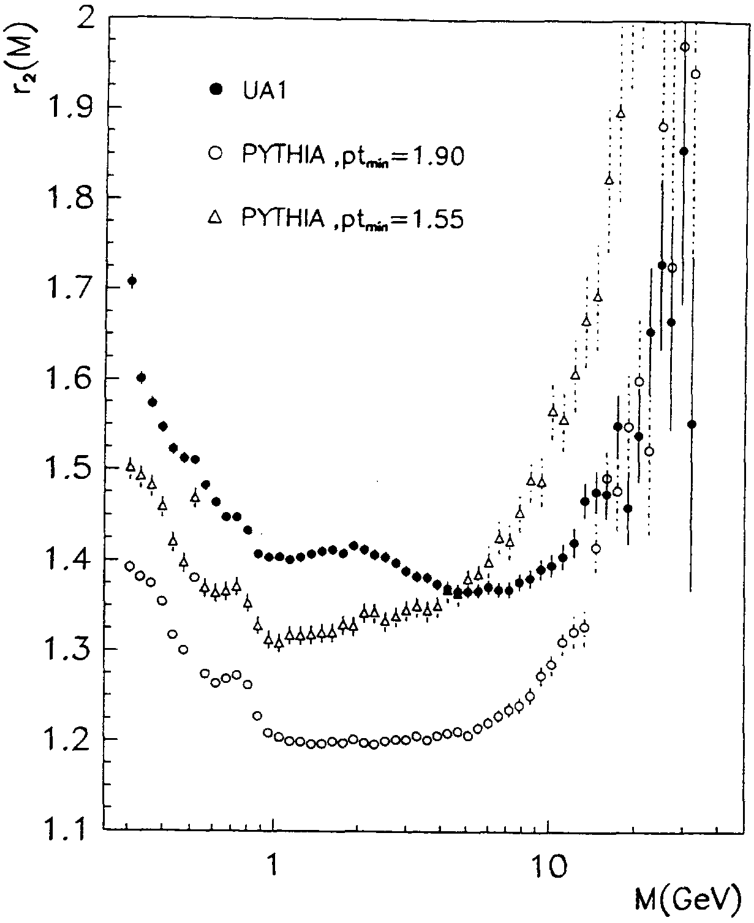

Fig.4: Comparison of $r_2(M)$ in $\bar{p}p$ reactions with PYTHIA 5.6.

How can we obtain a better agreement? Are there additional cluster effects ? Convincing evidence for the existence of fireballs has been reviewed by R. Hagedorn at this conference.[15] Does the Lund-string alone really provide an alternative description, or do we have to merge the two pictures: hard scattering processes with subsequent parton showering and string fragmentation on one side and the production of low p_T clusters or fireballs on the other side ?

A first impression, what clustering effects may achieve, can be gained with the UA5 cluster model[‡‡] GENCL.[16] It turns out, that it underestimates high p_T effects as expected and it does not repoduce the bump at 2 GeV either, but it produces strong correlations at low mass $2 \geq M \geq 0.5$ (not shown here). Since cluster effects

[††]This structure is likely to be connected with the unknown transition region hard to soft. We verified that it is due to transverse momentum compensation between hadron pairs of relatively low $p_T \approx 0.5$ GeV/c.

[‡‡]GENCL does by far not contain a detailed physical picture like PYTHIA. Most observations, like the overall multiplicity distribution are put in "by hand" only. However, clustering effects are created carefully and tuned to observed rapidity correlations. A derivation of multiplicity distributions in the framework of the Statistical Bootstrap Model has been given in ref.[17]

should show up more clearly at low p_T, we compared in figs.5a,b a subsample of low p_T particles ($0.15 \leq p_T \leq 0.3$ GeV/c) with PYTHIA and GENCL. We selected like-sign pairs to demonstrate that there is a rise of $r_2(M)$ of data (black circles) already at large M. This rise is not reproduced by PYTHIA (fig.5a). By default only pseudoskalas and vector multiplets are included. The additional inclusion of scalars, pseudoskalars and tensors does not change the flat distribution for $M > 0.8$ GeV in fig.5a. Changing $p_{T_{\min}}$ has similar effets as in fig.4, but does not improve the shape. The rise at large M observed in the data can neither be attributed to Bose-Einstein correlations according to our present understanding (compare in fig.5a triangles with open circles). If it will turn out in the future that PYTHIA with changed string structure and that also the Dual Parton Model[18] with many short chains cannot provide a satisfactory description of the data in fig.5, we should regard this as a strong indication for the occurence of additional cluster effects (see fig.5b).

To summarize, we found sensitive tools with the correlation integrals of invariant mass to study the dynamical origin of particle production. To improve our hithero unsatisfactory understanding of hh reactions, it could be necessary, instead of regarding string and cluster descriptions as alternatives, to merge the two pictures: hard scattering processes with subsequent string fragmentation on one side and the production and decay of clusters/fireballs on the other.

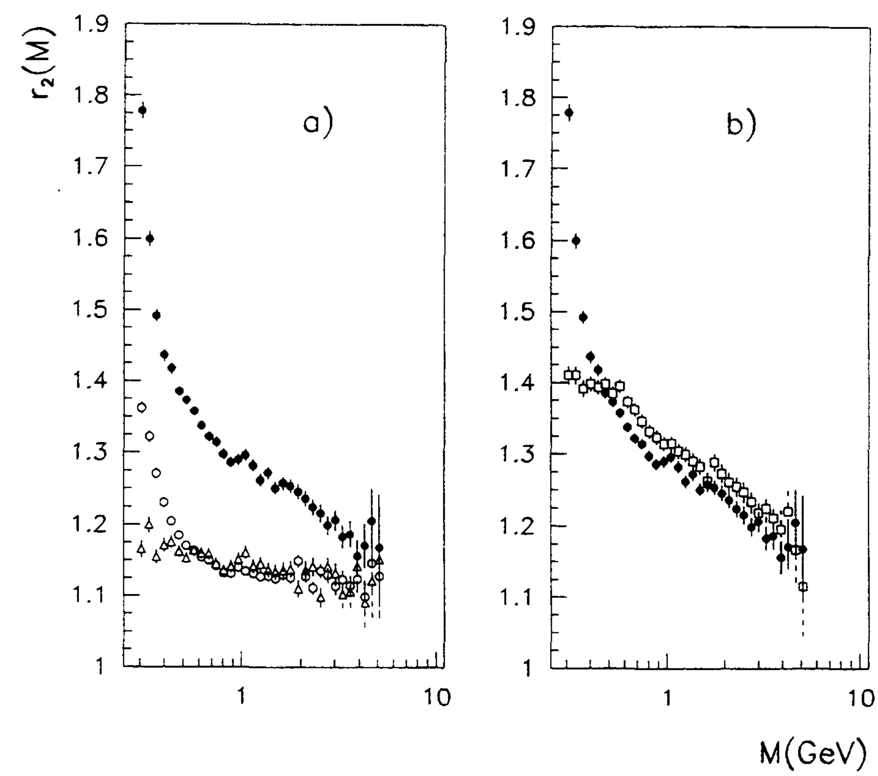

Fig.5: Comparison of $r_2(M)$ of like sign pairs (data: full circles) with Monte Carlo models;
a) Comparison with PYTHIA5 ($p_{T_{\min}} = 1.9$ GeV/c) including and excluding Bose-Einstein correlations (open circles and triangles respectively).
b) Comparison with the cluster model GENCL (squares) which does not contain Bose-Einstein correlations. The rise in GENCL is entirely due to refelctions from the decay of clusters.

Acknowledgements

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