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Correlations in pp-collisions and two-component models

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Abstract. Some general consequences of charge conservation inclusive sum rules for the correlation integrals f_k and f_{0k} are given. It is also pointed out that the energy dependence of f_k or f_{0k} is $\langle n \rangle^k$ for $k \leq 7$ for pp-collisions and that the data suggest all the f_k and f_{0k}'s are non-zero. Further, two-component models for the charge multiplicity distribution consistent with charge conservation, are considered and compared with the data for pp-collisions.

Keywords. pp-collisions; multiplicity distribution; charge conservation.

1. Introduction

An analysis of the correlations in inclusive reactions is expected to give some information regarding the underlying production mechanism. The measurement of the k-particle inclusive distribution would yield information on the k-particle correlation function or density ρ_k $(p_1, p_2, \ldots p_k)$, where $p_1, \ldots p_k$ are the momenta of the correlated particles (Predazzi and Veneziano 1971). To extract ρ_k one has to know all the inclusive distributions from the single particle to the k-particle distribution. For k more than 3 or 4 this would be a difficult task experimentally and it will be some time before such detailed data will be available. However, data exist from a few GeV to high energies for the charged particle multiplicity distributions, that is for the probability P_n for producing n charged particles. These data enable one to calculate and study the correlation integrals f_k (Mueller 1971), which are just the integral of ρ_k over all the momenta. In this paper we study the f_k's with the aim of obtaining some insight into the nature of the multiplicity distribution and the nature of the correlations among charged particles in pp-collisions.

The effect of charge conservation constraints on the correlation integrals are discussed in section 2. It is pointed out that on the basis of these constraints the data on f_{0k} (for definition *see* section 2) for pp-collisions seems to require an infinite number of correlation integrals f_k and f_{0k} for a successful model. One can achieve this by having a two component model even though in each individual component there may be little or no correlations present. These are discussed in section 3.

The expressions for the charged multiplicity, *i.e.* P_n are given for the two simplest models, consistent with charge conservation constraints. The last section gives the results of the confrontation of these models with data from 50 GeV/c to 405 GeV/c for pp-collisions together with our conclusions.

2. Some consequences of charge conservation

In defining the correlation integral f_k, for k charged particles, one does not distinguish between positively and negatively charged particles. Thus, the total charge Q_T of the correlated particles can be between 0 or 1 to k, assuming each particle carries only one unit of charge. One can separate the contribution to f_k, for a given total charge Q_T of the correlated particles, by defining f_{ab} as the correlation integral for 'a' positively and 'b' negatively charged particles. Then, for $k = a + b$, one has

$$f_k = \sum_{a=0}^{k} \frac{k\,!}{a\,!\,b\,!} f_{ab} \tag{1}$$

It is of great interest to find out the relative contributions of the various f_{ab} to f_k as this may give us a physical basis for approximation and construction of models for the charged multiplicity distribution.

In studying correlations one has to take into account the constraints due to the conservation of energy-momentum, charge, strangeness, etc. These conservation constraints have been expressed as inclusive cross-section sum rules by many authors [*See* Gupta (1972 *a*, *b* and *c*) for reference to earlier work]. For the study of correlations in general and for the f_{ab} in particular the charge conservation sum rules are of prime importance and have been exploited to some extent earlier (Gupta 1972 *b* and *c*; Brown 1972). In terms of the f_{ab} these sum rules can be written (for particles carrying one unit of charge) as

$$(a - b) f_{ab} + f_{(a+1)b} - f_{a(b+1)} = 0, \qquad a + b \geqslant 1 \tag{2 a}$$

$$Q_{\text{in}} = f_{10} - f_{01} \tag{2 b}$$

where Q_{in} is the total charge of the two incoming particles. For example, $Q_{\text{in}} = 2$ for pp-collisions and $Q_{\text{in}} = 0$ for π^-p collisions. Now f_{10} and f_{01} are the average multiplicities of only the positively and negatively charged particles respectively, so that the total average charged multiplicity

$$\langle n \rangle = f_1 = f_{10} + f_{01} \tag{3}$$

An immediate consequence of equation (2) is that

$$f_{k0} - f_{0k} = (-1)^{k-1} (k-1)\,!\, Q_{\text{in}} \tag{4}$$

$$f_{ab} = f_{ba}, \qquad a, b \geqslant 1 \tag{5}$$

The result of equation (4) implies that the difference $f_{k0} - f_{0k}$ is known and is energy independent so that the energy dependence of f_{k0} and f_{0k} is exactly the same except for a constant determined by Q_{in}. Further, $f_{k0} - f_{0k}$ is same for different incoming particles as long as Q_{in} is the same, for example for K$^+$p and pp-collisions.

Table 1. Correlation integrals for negative particles only. For reference to data from 50 to 400 GeV/*c* *see* table 2. Note the revised data for 102 GeV/*c* have been used. The data for 19 GeV/*c* have been taken from Boggild *et al* (1971).

P_{LAB} (GeV/*c*)	19	50	69	102	205	303	405
f_{01}	1·01	1·74	1·91	2·16	2·82	3·43	3·49
	± ·01	± ·05	± ·06	± ·03	± ·08	± ·08	± ·07
f_{02}	− 0·24	− 0·09	0·07	0·28	0·94	1·37	2·14
	± ·01	± ·09	± ·10	± ·07	± ·21	± ·25	± ·23
f_{03}	0·21	− 0·10	− 0·36	− 0·50	− 1·21	− 0·43	0·20
	± ·02	± ·17	± ·19	± ·16	± ·45	± ·73	± ·87
f_{04}	− 0·30	0·03	− 0·29	− 0·01	− 1·56	− 4·37	0·71
	± ·04	± ·34	± ·39	± ·36	± ·96	± 2·3	± 4·2
f_{05}	0·60	0·32	2·54	1·88	6·08	2·96	3·79
	± ·11	± 0·84	± 1·0	± 1·1	± 4·6	±11·0	± 17·0
f_{06}	− 1·42	− 1·99	− 5·28	− 7·38	3·99	− 0·54	− 82
	± ·32	± 2·4	± 3·5	± 4·6	±20·0	±62·0	±107
f_{07}	−292	(− 2·71	(− 6·13	(− 1·64	(− 1·26	(− 4·87	(− 6·40
	± 32·0	± ·42)	± ·95)	± ·16)	± ·18)	± ·67)	± ·76)
		$\times 10^4$	$\times 10^4$	$\times 10^5$	$\times 10^6$	$\times 10^6$	$\times 10^6$

Using the constraints of equation (2) one can see that for a given $k = a + b$ only one of the $(k+1) f_{ab}$'s is independent. Thus using equations (1) and (2) one can solve for all the f_{ab}'s for $k = a + b$ in terms of $f_1, f_2 \ldots f_k$. For $k = 2$ and $k = 3$ one obtains

$$2f_{11} = \tfrac{1}{2}(f_2 + f_1) \tag{6 a}$$

$$f_{20} + f_{02} = \tfrac{1}{2}(f_2 - f_1) \tag{6 b}$$

and

$$8 f_{12} = f_3 + (f_2 - f_1) \tag{7 a}$$

$$4(f_{30} + f_{03}) = f_3 - 3(f_2 - f_1) \tag{7 b}$$

Intuitively one may feel that correlations with large total charge Q_T may be unimportant compared to those with small total charge and give a physical basis for approximation, *e.g.* $f_{11} \gg f_{20} + f_{02}$, etc. For example, one may assume that $f_{k0} + f_{0k} = 0$, $k \geqslant m$ where $m = 2$, 3, etc. This would give a finite number of f_k's with $f_k = 0$, $k \geqslant (m+1)$. However, using equation (4) one sees one would have an infinite number of f_{0k}'s. For $k \geqslant m$ one has that $f_{0k} = -\tfrac{1}{2}(-1)^{k-1} \times (k-1)!\ Q_{in}$ and is energy independent. To see whether such approximations are feasible we study the f_{0k}'s. We have calculated the experimental values of f_{0k} up to $k = 7$ for pp-collisions at various energies. These are tabulated in table 1. Their values and signs do not show any simple pattern with increasing energy. We have looked at the energy dependence of these by plotting $f_{0k}/(f_{01})^k$ in figure 1. Recall that $f_{01} = \langle n_- \rangle$ where $n_- = \tfrac{1}{2}(n-2)$ is the number of negatively charged particles produced. One notices that from 50 GeV/*c* upwards $f_{0k}/(f_{01})^k$ is essen-

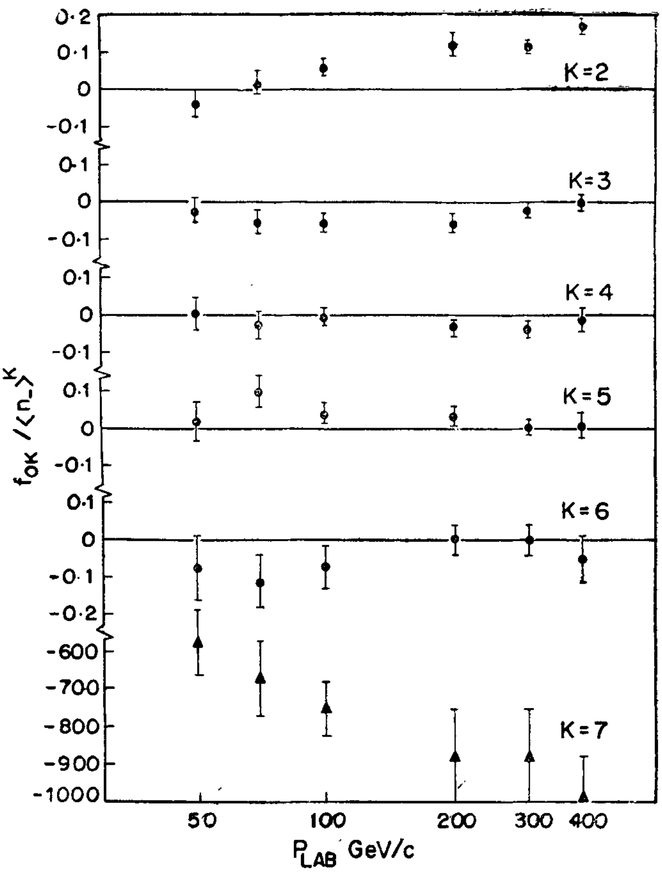

Figure 1. Energy dependence of $f_{0k}/\langle n_-\rangle^k$ for $k = 2$ to 7.

tially constant within errors for $k \geqslant 3$ while for $k = 2$ constancy is achieved only above 200 GeV/c or so. Thus asymptotically it seems f_{0k} behave as $\langle n_- \rangle^k$. This also tells us the energy dependence of f_k because one can express it in terms of f_{0k}'s. One obtains, in general,

$$f_k = (-1)^{k-1}(k-1)!\,Q_{\text{in}} + \sum_{r=0}^{r_{\max}} \frac{2^{k-2r}\,k\,!}{(k-2r)\,!\,r\,!} f_{0(k-r)} \tag{8}$$

where $r_{\max} = k/2$ for even k and is $= \frac{1}{2}(k-1)$ for odd k. From the above result for f_{0k} it follows that asymptotically the $f_k \sim f_1^k = \langle n \rangle^k$ at least for $k \leqslant 7$ for pp-collisions. We have also checked this directly from the data. It is clear [from equations like (6) and (7) for example] that if $f_k \sim f_1^k$ then as a consequence of charge conservation all f_{ab}'s for $k = a + b$ will increase as f_1^k with energy so that correlations with arbitrary amount of total charge Q_T will be important. This would imply that models based on uncorrelated production of simple resonances which subsequently decay into pions, etc., are unlikely to be successful.

We have seen that the approximation of keeping only a finite number of non-zero f_k's is unlikely to work. Further the large negative value of f_{07} in table 1 would suggest that f_{0k} for $k > 7$ are unlikely to be small. Thus it would seem that a successful model for pp-collisions would have to have possibly an infinite number of non-zero f_k's and f_{0k}'s. A simple way to achieve infinite number of non-zero correlation integrals both f_k and f_{0k}'s is to have a two or more component model, in which each individual component has a simple physical picturization. We discuss the multiplicity distribution for two such models in the next section.

3. Models of charge multiplicity distribution

In discussing the multiplicity distribution of charged particles it is convenient to consider the generating function $G(h_+, h_-)$ where the variables h_+ and h_- are the generators associated with the positively and negatively charged particles. Webber (1972) has shown that the generating function incorporating the charge conservation constraints is given by

$$G(h_+, h_-) = (1 + h_+)^{Q_{in}} \exp\left[\sum_{k=1} \frac{f_{0k}}{k!}(h_+ + h_- + h_+h_-)^k\right] \tag{9}$$

where the correlation integral for k negatively charged particles f_{0k} have been taken to be independent. This form is only convenient for incident particles with $Q_{in} \geqslant 0$ which is normally the case experimentally. The generating function for all charged particles (positive and negative) is obtained from equation (9) by putting $h_+ = h_- = h$ and is

$$G(h) = (1 + h)^{Q_{in}} \exp\left[\sum_{k=1} \frac{f_{0k}}{k!}(h^2 + 2h)^k\right] \tag{10}$$

The multiplicity distribution or the probability for producing n charged particles is then given by

$$P_n = \frac{1}{n!}\left[\frac{d^n G(h)}{dh^n}\right]_{h=-1} \tag{11}$$

In terms of the correlation integrals f_k,

$$G(h) = \exp\left(\sum_{k=1} \frac{h^k}{k!} f_k\right) \tag{12}$$

This also serves to define the f_k's. For $Q_{in} \geqslant 0$ the multiplicity distribution of negative particles only can be worked out from equation (9) by putting $h_+ = 0$ and taking derivatives of $G(0, h_-)$ with respect to h_-. Further the factor $(1 + h_+)^{Q_{in}}$ in equation (10) insures that $P_n = 0$ for $n < Q_{in}$, *e.g.* $P_0 = P_1 = 0$ for pp-collisions, as required by charge conservation.

It was suggested in section 2 that a successful model for pp-collisions would require an infinite number of non-zero f_k and f_{0k}. Two-component models provide a simple way to achieve this. The two components may correspond to two types of collisions (Nielsen and Olesen 1973, Harari and Rabinovici 1973, Van Hove 1973, Fialkowski and Mieltinen 1973) or both the components may be present in varying proportions in each event (Chaudhary *et al* 1974). We discuss here two-component models in which two different types of collisions are envisaged. The two types of collisions are usually referred to as the diffractive and central (*i.e.* non-diffractive or pionization) components. In such a model the multiplicity distribution will have two parts with relative probabilities p and q. Since charge will be conserved in either type of collision or component separately the generating function can be written as

$$G(h) = p\,(1+h)^{Q_{in}} \exp\left[\sum_k \frac{d_{0k}\,(h^2+2h)^k}{k\,!}\right] + q \exp\left[\sum_k \frac{C_{0k}\,(h^2+2h)^k}{k\,!}\right](1+h)^{Q_{in}}, \qquad p+q=1 \quad (13)$$

The d_{0k} and C_{0k} are the correlation integrals (corresponding to f_{0k}) for negative particles for the diffractive and central components respectively. Then, the total average number of charged particles

$$\langle n \rangle = f_1 = Q_{in} + 2\,(pd_{01} + qC_{01}) \quad (14)$$

where d_{01} and C_{01} are the average multiplicities of the negative particles in the diffractive and central components respectively. We now consider approximations to equation (13) for a general $Q_{in} \geqslant 0$ and later confront them with experimental data in the case of pp-collisions.

Model I. The simplest approximation is to assume that $d_{0k} = C_{0k} = 0$, $k \geqslant 2$. This leads to the charge multiplicity distribution

$$P_n = p\,\frac{e^{-d_{01}}\,(d_{01})^{n_-}}{n_-\,!} + q\,\frac{e^{-C_{01}}\,(C_{01})^{n_-}}{n_-\,!} \quad (15)$$

where $n_- = \frac{1}{2}(n - Q_{in})$ is the number of negatively charged particles. This distribution depends on three parameters p, d_{01} and C_{01} which are to be determined at a given energy and has been considered with fair success, by Lach and Malamud (1973) and Rama Rao (1973), for pp-collisions. In this model each component is simple in that there are no correlations among the negative particles, though all the correlation integrals for all charged particles d_k and C_k in each component are non-zero. In fact $d_1 = Q_{in} + 2d_{01}$, $d_2 = -Q_{in} + 2d_{01}$ and $d_k = (-1)^{k-1}\, k-1\,!\; Q_{in}$, $k \geqslant 3$ with exactly the same relations for the C_k's. Further the total correlation integrals for negative particles f_{0k} are proportional to $(d_{01} - C_{01})^k$ and consequently $f_k \propto (d_{01} - C_{01})^k$, *i.e.* $\langle n \rangle^k$ if the leading energy dependence of d_{01} and C_{01} is different.

Model II. The next simplest model consistent with charge conservation is characterized by $d_{0k} = C_{0k} = 0$, $k \geqslant 3$ and gives

$$P_n = p \exp\left(-d_{01} + \tfrac{1}{2} d_{02}\right) \sum_r \frac{(d_{01} - d_{02})^{n_- - 2r}}{n_- - 2r\,!\; r\,!}\left(\frac{d_{02}}{2}\right)^r + (p \to q,\; d_{0k} \to C_{0k}) \quad (16)$$

where sum over r goes from $r = 0, 1, 2, \ldots \frac{1}{2}n_-$ for even n_-, while it goes from $r = 0, 1, 2, \ldots \frac{1}{2}(n_- - 1)$ if n_- is odd. This distribution depends on five parameters p, d_{01}, d_{02}, C_{01} and C_{02}. However we feel this model may be more realistic in the sense that it permits two negative particle correlations in each component.

The correlation integrals f_{0k} or f_k depend on d_{01}, C_{01}, etc., through $A_1 \equiv d_{01} - C_{01}$ and $A_2 \equiv d_{02} - C_{02}$. In fact one has

$$\begin{aligned} f_{01} &= pd_{01} + qC_{01}, \\ f_{02} &= pd_{02} + qC_{02} + pqA_1^2, \\ f_{03} &= pq\,(q-p)\,A_1^3 + 3pqA_1A_2, \\ f_{04} &= pq\,(1-6pq)\,A_1^4 + 6pq\,(q-p)\,A_1^2A_2 + 3pqA_2^2, \text{ etc.} \end{aligned} \tag{17}$$

The expressions for f_{0k} for model I can be obtained by putting $C_{02} = d_{02} = 0$, *i.e.* $A_2 = 0$ in the above. However, one notices that for $C_{02} = d_{02} \neq 0$ so that $A_2 = 0$ both the models will give the same correlation integrals f_{0k} for $k \geqslant 3$ though the P_n's given by them will differ. So it is of interest to investigate model II with four parameters, *viz.*, p, d_{01}, C_{01} and $d_{02} = C_{02}$ and compare it with the results of model I. Another point of interest of model II is the energy dependence of f_{0k} as compared to model I. If C_{02} and d_{02} are small compared to C_{01} and d_{01} then the leading behaviour of $f_{0k} \sim A_1^k$, *i.e.* $\langle n_- \rangle^k$ but if C_{02} or d_{02} asymptotically behaves as $\langle n_- \rangle^2$ then all the terms in f_{0k} go as $\langle n_- \rangle^k$ and cancellations may make them small.

We confront the distribution of model II with pp-collision data from 50-400 GeV/c for the cases

(*a*) four parameters with $C_{02} = 0$ but $d_{02} \neq 0$. The motivation for this choice is that in the central or pionization component the particles are expected to be produced statistically and so a Poisson would hopefully give a reasonable description of it.

(*b*) four parameters with $A_2 = 0$ but $d_{02} = C_{02} \neq 0$.

(*c*) five parameters with d_{02}, C_{02} and A_2 non-zero. We will refer to the three cases as models II *a*, II *b* and II *c* below.

4. Results and conclusions

In confronting a model with data it is best to fit directly the multiplicity distribution since a good fit to the P_n's will guarantee that the moments and the correlation integrals will also agree with the data. We fit the expression for P_n for models I, II *a*, II *b* and II *c* with 3, 4, 4 and 5 free parameters respectively at each energy to obtain the best χ^2-fit to data. For the case of model II one has to keep in mind the constraints $d_{01} \geqslant d_{02} \geqslant 0$ and $C_{01} \geqslant C_{02} \geqslant 0$ which are necessary to obtain positive probabilities for each component separately (Gupta and Singh 1973). We discuss the results for the various models individually below.

Model I. The three parameter fit given by this model is displayed in table 2. From 50 to 303 GeV/c we naturally reproduce the results of Lach and Malamud

Table 2. The three parameter fit of model I.

P_{LAB} (GeV/c)	p	d_{01}	C_{01}	χ^2/data points	Reference
50	0	0	$1\cdot67\pm0\cdot04$	9/8	Ammosov *et al* (1972)
69	$0\cdot1\pm0\cdot06$	$0\cdot81\pm0\cdot34$	$2\cdot08\pm0\cdot05$	10/9	Ammosov *et al* (1972)
102	$0\cdot15\pm0\cdot05$	$0\cdot82\pm0\cdot25$	$2\cdot39\pm0\cdot06$	5/10	Bromberg *et al* (1973)
205	$0\cdot29\pm0\cdot06$	$1\cdot36\pm0\cdot3$	$3\cdot46\pm0\cdot12$	8/11	Charlton *et al* (1972)
303	$0\cdot38\pm0\cdot08$	$1\cdot85\pm0\cdot27$	$4\cdot30\pm0\cdot21$	12/13	Dao *et al.* (1972)
405	$0\cdot33\pm0\cdot06$	$1\cdot59\pm0\cdot3$	$4\cdot32\pm0\cdot2$	27/16	Bromberg *et al* (1973)

(1973) and Rama Rao (1973). However, we have used the revised data for 102 GeV/c and in addition fitted the data for 405 GeV/c which were not available to these authors. Points to be noticed are (i) that for 50 GeV/c only one component, *viz.*, the central is required, (ii) that though the probability p for the diffractive components increases up to 303 GeV/c, it seems to decrease at 405 GeV/c. Of course the fit at 405 GeV/c is not as good as that for the lower energies mainly because in the fit P_{16} alone gives a contribution of 10 to the total chi-square.

Model II *a*. This gives a four parameter fit with the extra parameter d_{02} with $C_{02}\equiv 0$. We find that from 50 to 303 GeV/c the best χ^2-fit requires that $d_{02}=0$, which is model I. However for 405 GeV/c a non-zero d_{02} improves the fit requiring $p=0\cdot66\pm0\cdot15$, $d_{01}=2\cdot64\pm0\cdot34$, $C_{01}=4\cdot97\pm0\cdot21$ and $d_{02}=1\cdot00\pm0\cdot07$; with $\chi^2=21$.

Model II *b*. This is also a four parameter fit with the extra parameter $d_{02}=C_{02}\neq 0$ compared to model I. As noted earlier this model and model I have the same f_{01} and f_{0k}, $k\geqslant 3$ for given d_{01}, C_{01} and p and differ only in the value of f_{02} since $d_{02}=C_{02}\neq 0$. We find that from 50 to 303 GeV/c the best χ^2-fit requires that $d_{02}=C_{02}=0$ as in model I. However, for 405 GeV/c a non-zero value $d_{02}=C_{02}=0\cdot74\pm0\cdot50$ improves the fit giving $\chi^2=19$ with $p=0\cdot37\pm0\cdot02$, $d_{01}=2\cdot0\pm0\cdot13$ and $C_{01}=4\cdot25\pm0\cdot20$.

Model II *c*. In this model we have five parameters p, d_{01}, C_{01}, d_{02} and C_{02}. Again predictably enough the best χ^2-fit is improved by the presence of non-zero $d_{02}=0\cdot68\pm0\cdot5$ and $C_{02}=0\cdot73\pm0\cdot8$ only for 405 GeV/c, giving a $\chi^2=19$ with $p=0\cdot38\pm0\cdot10$, $d_{01}=1\cdot98\pm0\cdot38$ and $C_{01}=4\cdot30\pm0\cdot20$.

To summarize, our results show that

(*a*) Model I is adequate up to 303 GeV/c. Introduction of one or two more parameters, as above, does not improve the fit. Thus no two negative particle correlations in either component are required.

(*b*) For 405 GeV/c and presumably at higher energies the presence of two negative particle correlations, *i.e.*, non-zero d_{02} and C_{02} seem to be required. However, our results do not enable us to choose between either of the three cases of model II.

It is possible that to obtain better results than for model I with a two-component model of the type considered here one may have to make one or both the components different from a Poisson distribution in n_-. Further, it should be noted that this type of two-component model, that is requiring two types of collisions, fails to fit the data at lower energies (*e.g.* 19 GeV/*c*). It is possible that such two-component models may turn out to have limitations at higher energies and one may instead have to resort to two-component models of the type in which both the components are present in varying proportions. A model of this type was shown recently by Chaudhary *et al* (1974) to be capable of fitting the data over the entire energy range from 5 to 300 GeV/*c*.

As pointed out earlier, our concern with two-component models was because each individual component could be easily visualised physically (*e.g.* model I) and yet lead to an infinite number of non-zero f_{0k} and f_k's with an asymptotic energy dependence given by $\langle n \rangle^k$. As pointed in section 2 this seems to be true for the charged multiplicity distribution in pp-collisions. We feel that this information about the correlation integrals is a basic feature of the data and should be kept in mind, while constructing a model for pp-collisions.

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