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MULTIPARTICLE PROCESSES AT HIGH ENERGIES[1]

VLADISLAV ŠIMÁK*, Praha

Selected features of multiparticle reactions are presented. The first part describes some results of multiplicity distributions and the possibility of scaling in the distributions.

The second part presents a few basic observations as regards one-particle distributions and some recent results of exclusive reactions. The last part is a survey on models of and theoretical approaches to multibody reactions.

I. INTRODUCTION

Since the days of early cosmic ray physics many things have been discovered in particle physics and many new apparatuses have been constructed. However, what we see now in the field of strong interactions is the renaissance of very old studies of cosmic ray jets [1—3] as: multiplicity dependences, rapidity distributions, azimuthal correlations, isobar productions versus the pionisation.

Indeed, the cosmic rays and nuclear emulsion time is over but the physics remains unsolved and continues with new experiments and theories. Fig. 1 and Fig. 2 show some old results published more than ten years ago, suggesting the division of isobars (or NOVA's, or diffraction dissociation) or pionisation into two fire-balls with different primary energies, even the transversal momenta correlations. However, most of the observed effects were not very significant.

An enormous number of experimental data from high energy accelerators and bubble chamber pictures show a depending understanding of the production processes.

The following remarks are not meant to be another summary of multiparticle reactions and do not try to cover the problem systematically and completely. They are a selection of information from other summaties and some additional articles and comments.

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* Fyzikální ústav ČSAV, 180 00 PRAHA 8, Na Slovance 2.

II. MULTIPLICITY AND BASIC CHARACTERISTICS OF MANY-BODY REACTIONS

In high energy collisions of nucleons the most produced particles are pions, 90 % at accelerator energy (≈ 20 GeV) and 80 % at ISR (≈ 2000 GeV) [4]. The ratios of the different particles depend on the longitudinal momenta in the CM system. At the ISR energies the rate for pions is $R(\pi^+/\pi^-) \approx 1$ for

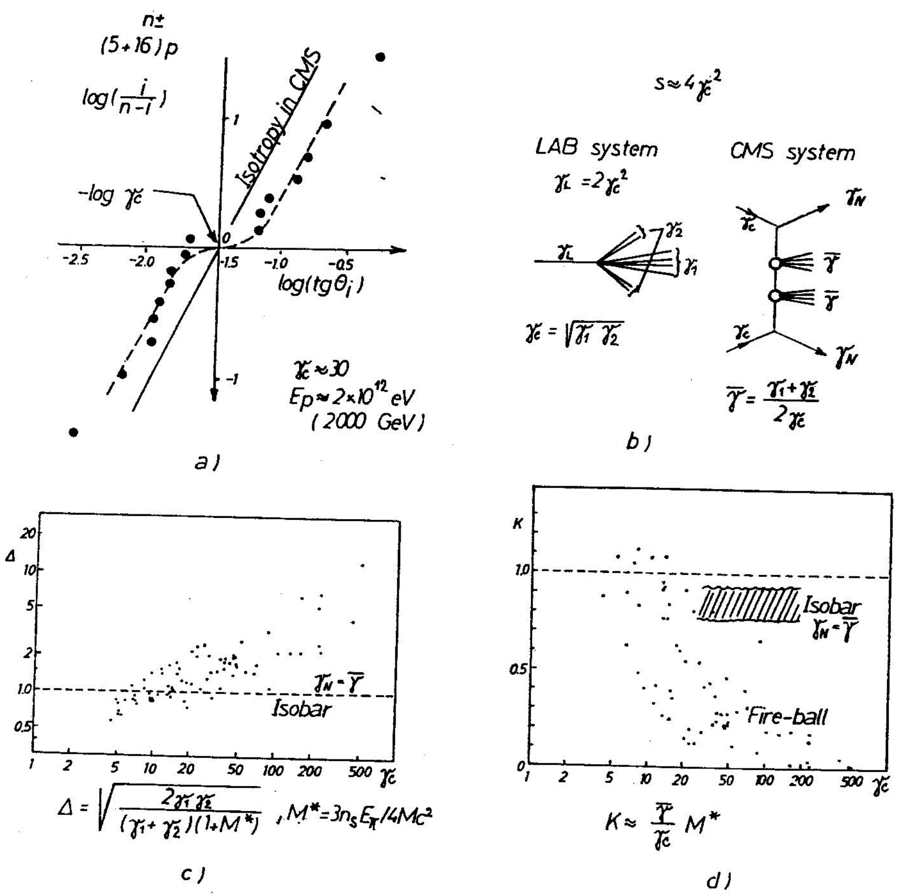

Fig. 1. **a.** An example of the angular distribution in a cosmic ray jet (Duller-Walker-plot) suggesting a two-centre mechanism. **b.** The kinematics of two isobar or fire-balls. **c.** The measure of the isobar production versus fire-balls as a function of primary energy [3] d. The coefficient of inelasticity (ratio energy going into secondaries to the total energy calculated for a two-centre model [3].

a region of small longitudinal momenta $x \approx 0$. For the other particles the ratios are: $R = (\bar{p}/\pi^-) = 0.04$ and $R(K^-/\pi^-) = 0.08$ for $0 \leqslant x \leqslant 0.4$ and $0.3 \leqslant pP \leqslant 0.5$ GeV/c [5]. The distribution of secondary particles at ISR may be summarized as follows (approximately only):

$$n \approx 18 \approx 12^{\pm} + 6^{\circ} \approx 4.8\,\pi^+ + 4.3\,\pi^- + 4.6\,\pi^{\circ} + 0.7\,K^+ + \\ + 0.4\,K^- + 1.5\,p + 0.3\,\bar{p} + \ldots \quad (1)$$

The energy dependence of the number of produced charged particles is presented in Fig. 3 and fitted (two parameter fits) with two types of functions [6].

$$\langle n_{ch} \rangle = 0.48 + 1.27 \ln p, \quad (2a)$$

$$\langle n_{ch} \rangle = 1.7 + 1.45\left(1 - \frac{0.93}{p^{1/4}}\right) \ln p. \quad (2b)$$

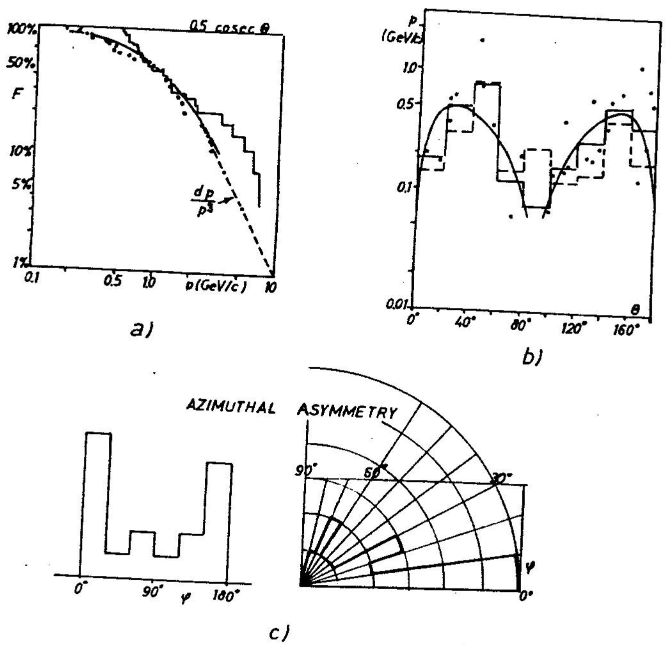

Fig. 2. a. The momentum spectrum of secondaries (the dots correspond to measurement, the histogram represents a spectrum calculated from the assumption $p_\perp = \text{const}$) [1]. b. The dependence of $p_\perp$ on the angle in CMS measured (points) and calculated from a two-centre mechanism [1]. c. The distribution of the azimuthal angle in one jet. The $\varphi = 0$ was selected in a transversal plane as an axis of maximal asymetry [2].

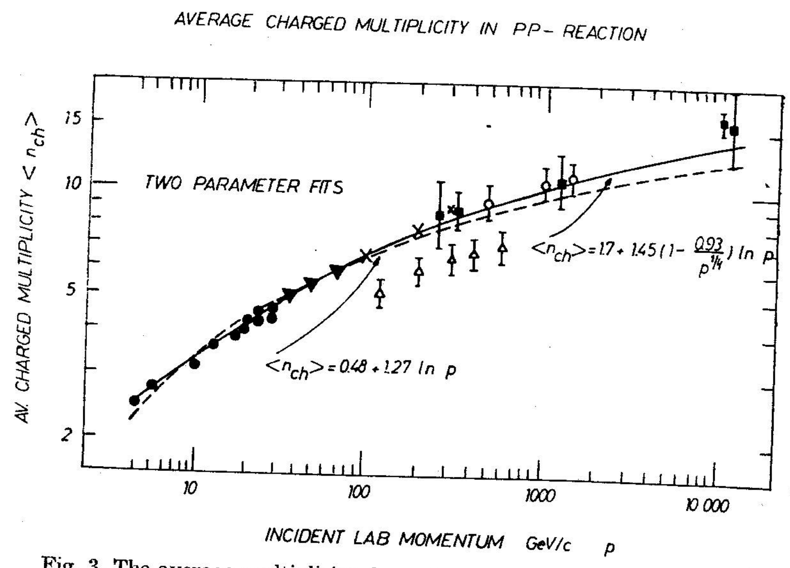

Fig. 3. The average multiplicity dependence on the primaty energy [13].

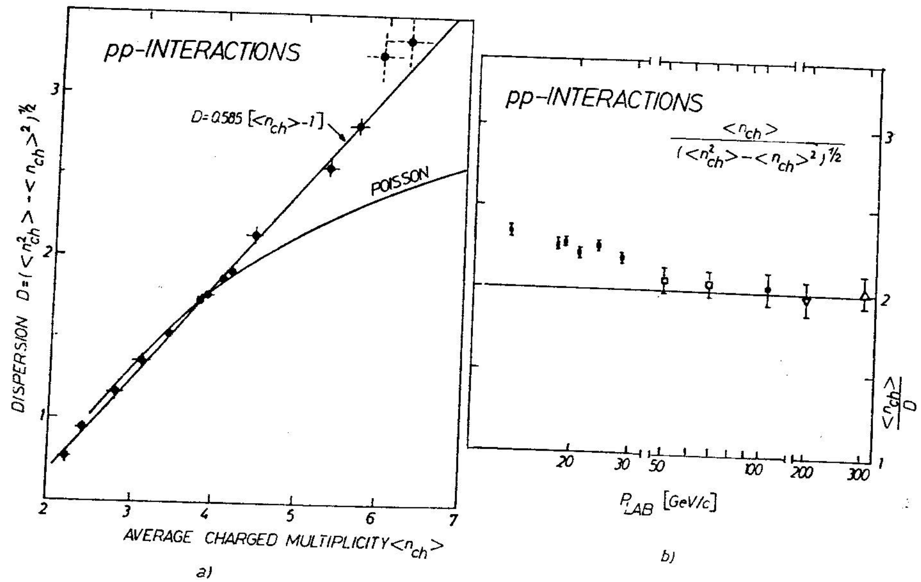

Fig. 4. a. The linear dependence of the dispersion of multiplicity [7] on $\langle n \rangle$. b. The asymptotical behaviour of $\langle n \rangle / D$ [4].

The second takes into account an influence of a slow increase of the cross section at the cental region in CMS ($x \approx 0$) and seems to follow the experimental points better than the first. Most of the models and theories predict a general logarithmic increase with primary energy.

Another information which can be concluded from the multiplicity distribution at a given energy is the dispersion $D^2 = (\langle n^2 \rangle - \langle n \rangle^2)^{1/2}$ for which the empirical linear dependence on $\langle n \rangle$ has been found [7]

$$D = 0.585\,(\langle n \rangle - 1). \tag{3}$$

The experimental points are given in Fig. 4a and show a clear disagreement with the simple Poisson law predicted by simple models. It seems also that the experimental law (3) at high energies can be approximated by the asymtotic behaviour of $\langle n \rangle / D$ which has the limit 2 for high energies [2]

$$\frac{\langle n \rangle}{D} \sim 2 \tag{4}$$

as shown in Fig. 4b. Such behaviour can be understood as an interference of two mechanisms of particle productions; each having approximately a constant cross section and a reasonably small dispersion, but one of them should have considerably larger multiplicities than the other [8].

The fact that with an increasing energy the distribution of multiplicity becomes broader than Poisson (Fig. 5) may be seen from the correlation parameter f_2

$$f_2 = D^2 - \langle n \rangle = \langle n^2 \rangle - \langle n \rangle^2 - \langle n \rangle. \tag{5}$$

The f_2 dependence on primary energies $f_2 = 0$ for Poisson calculated for negative particles is given in Fig. 5a and indicates the change of sign in the region around 50 GeV. This again means an interference of two mechanism, one which may be a simple diffraction dissociation predicting f_2 negative and the second a type of a multiperipheral or fragmentation model. The Eg. (4) dependence corresponds to [4]

$$f_2 \approx \langle n \rangle^2 \approx \ln^2 p. \tag{6}$$

A multiplicity distributin compared with Poisson for two extreme energies is given in Fig. 7.

There has been suggested by the genergalized Muller optical theorem a possibility of scaling in semi-inclusive reactions $A + B \to 1 + \ldots \quad \ldots n +$ + anything [9]

$$\langle n \rangle \frac{\sigma_n}{\sigma_{in}} \xrightarrow[s \to \infty]{} \Psi\left(\frac{n}{\langle n \rangle}\right), \tag{7}$$

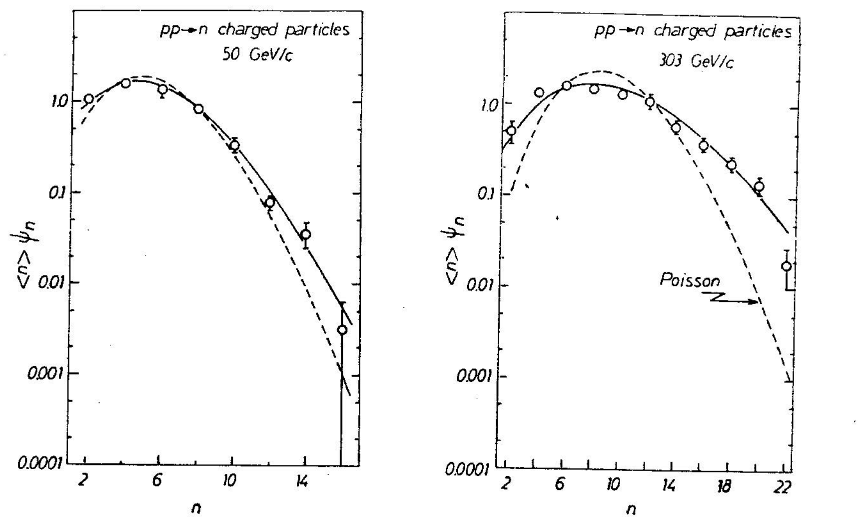

Fig. 5. The multiplicity distribution of charged particles in proton-proton interactions at 50 and 300 GeV [28].

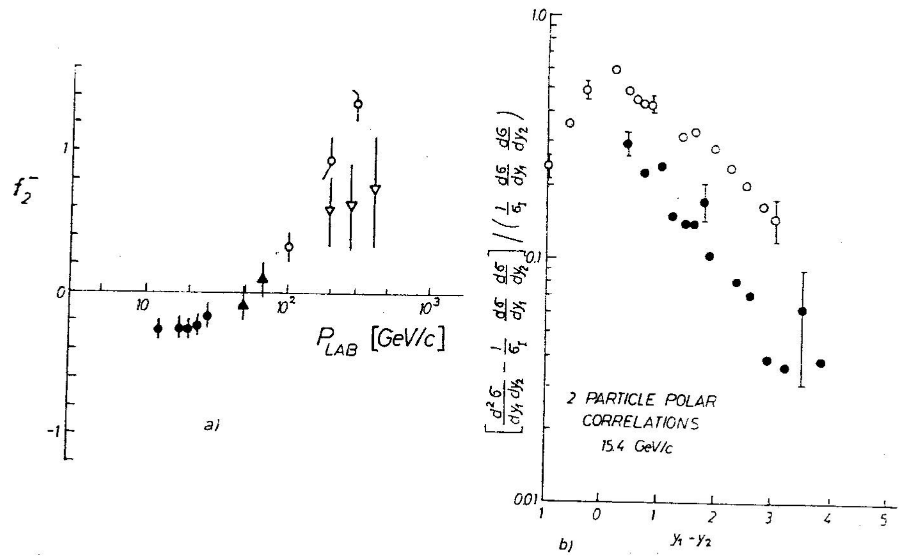

Fig. 6. **a.** The correlation f_2 for negative particles produced in proton-proton collisions [4]. **b.** The distribution of the difference of rapidities for two particles at ISR energies.

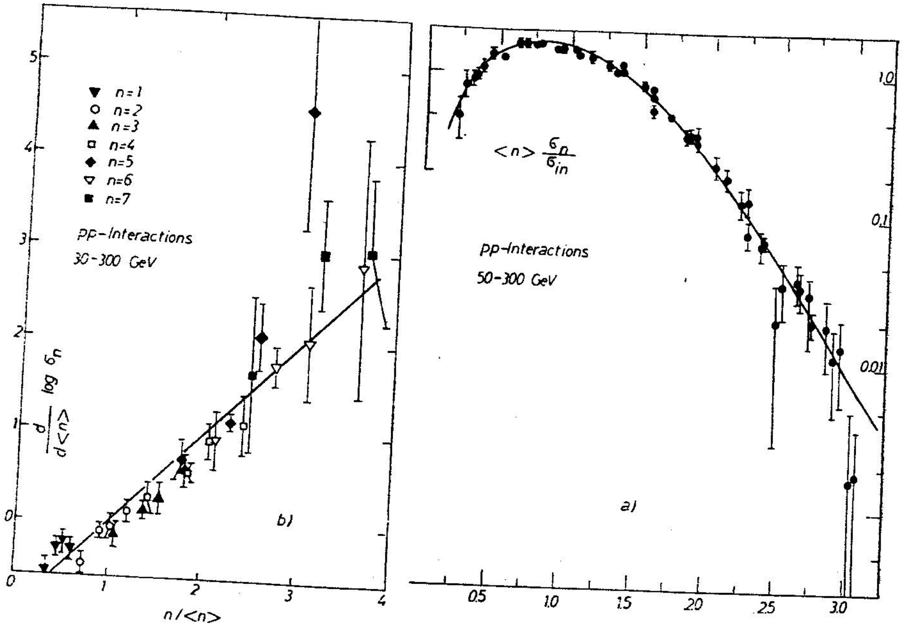

Fig. 7. **a.** The scaling function $\Psi(n/\langle n\rangle)$ [10]. **b.** A possible scaling of d $\ln \sigma_n/\mathrm{d}\langle n\rangle$ [11]

where $\Psi(n/\langle n\rangle)$ is a universal function independent from energy. This scaling seems to be very well fulfilled by experiment [10] (Fig. 6a). However, another type of scaling in semiinclusive reactions, which does not agree with the previous one, was suggested recently [11]

$$\frac{\mathrm{d}\ln \sigma_n(\langle n\rangle)}{\mathrm{d}\langle n\rangle} \approx p\left(\frac{n}{\langle n\rangle}\right) \tag{8}$$

and fits the experimental data reasonably well, too (Fig. 6b). The problem of scaling in semiinclusive reactions is not yet completely understood and will need new experiments as well as new ideas.

III. INCLUSIVE REACTIONS AND SINGLE PARTICLE DISTRIBUTIONS

As basic characteristics of secondary particles are considered the distributions of longitudinal momenta in the CM-system (p^*_{II}) and transversal momenta ($p_\perp$). The longitudinal momentum distribution is usually presented

as normalized to the incident momentum in the CM-system ($x = p^*_{II}/p_c$). In Fig. 8 are presented distributions of $d\sigma/\mathrm{d}p_\perp^2$ at $x \approx 0$ and $\mathrm{d}\sigma/\mathrm{d}x$, for pp collisions at energies 20—2000 GeV. A similar distribution at 20 GeV to 2000 GeV of both variables strongly supports the scaling hypothesis in strong interactions. The other scaling variables can be seen from the equivalents

$$E^* \frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}p_\perp^2} = \frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_\perp^2} = \frac{\mathrm{d}^2\sigma}{\mathrm{d}t\mathrm{d}(M^2/s)}, \tag{9}$$

where y is the rapidity, t is the four-momentum transfer between the primary particle and the secondary one and M is the missing mass of the selected particle. Thus the distribution of M^2/s scales also as it is seen in Fig. 9a. The distribution of rapidity developed at ISR energies a plateau (Fig. 9b) the edges of which increase logarithmically with the primary energy. The level of the plateau increases slowly with the primary energy and has an asymptotic value at the infinite energy, as it has been recently shown by compilation of $E^*\mathrm{d}\sigma/\mathrm{d}p^*_{II}$ at $x \approx 0$ [12]. This supports strongly the Feynmann

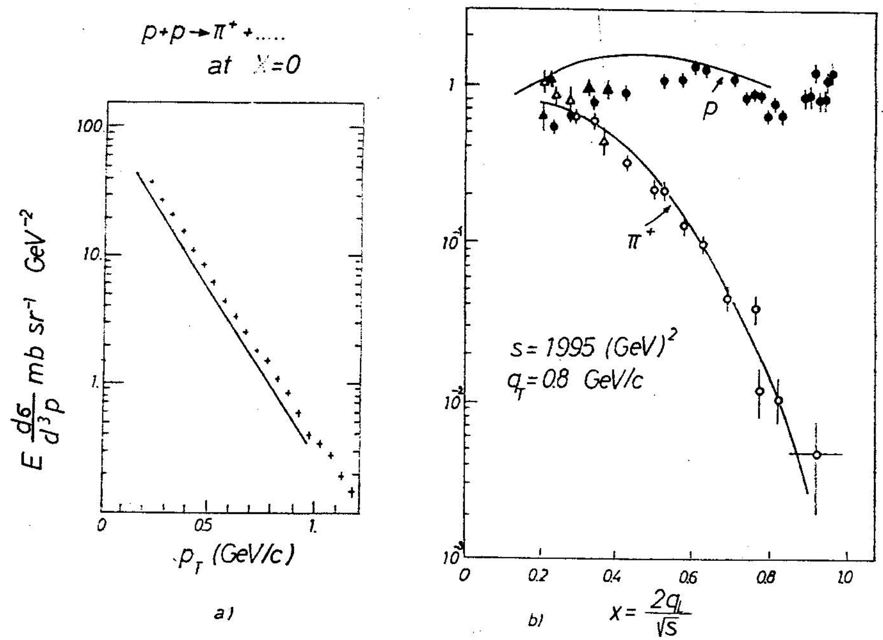

Fig. 8. **a.** The distribution of $p_\perp$ at ISR energies (points) and at classical accelerator energies (line) for $x = 0$ region [4]. **b.** d $\sigma/\mathrm{d}x$ from ISR (points) as compared with 20 GeV interactions (lines) [4].

scaling. The central value of the rapidity distribution is an essential parameter for the multiplicity function (2). Incorporated dependence of Fig. 10a into the multiplicity gave Eq. (2b), which agress reasonably well with the experiment. Inclusive reactions with exotic quantum numbers among three involved particles (e.g. $K^+p \to \pi^- + \ldots$) scale earlier than reactions with no exotic combinations (Fig. 10b). The produced K-mesons and antiprotons approach the plateau very slowly and scale only for very high momenta. (Fig. 11) (contrary to the pions).

In semi-inclusive reactions we deal with more than one particle. We can study, therefore, the momenta distribution of two particles and their mutual correlations. If we neglect the resonance production as a typical correlation

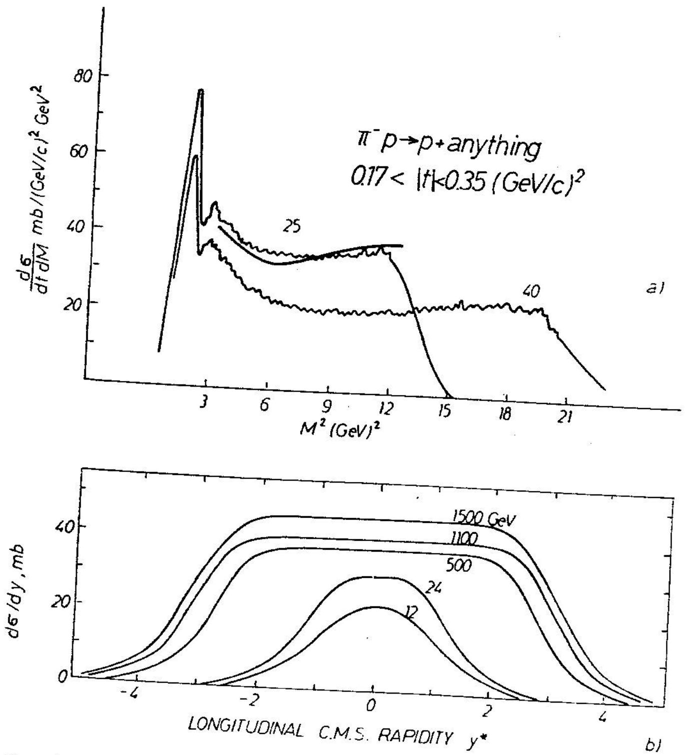

Fig. 9. **a.** Scaling in the M^2/s variable. The line is scaled 40 GeV distribution to 22 GeV [4]. **b.** The increase in rapidity and the development of the plateau at high energy interactions [26].

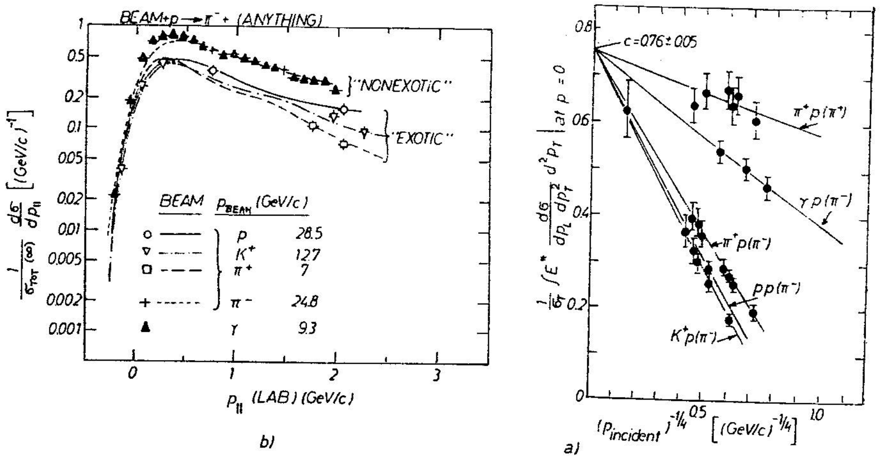

Fig. 10. **a.** A comparison of the lognitudinal momenta distribution for inclusive reactions according to the quantum numbers of the involved particles [27]. **b.** A compilation of $E^* \, d\sigma/dp_\perp^2 \, dx$ at $x = 0$ for inclusive distributins [12].

effect at intermediate energies we can see the dynamical effects of two particle distributions. In this connection the correlation function

$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{1}{\sigma_{in}} \frac{d^6\sigma}{dy_1 dy_2 d\boldsymbol{p}_{\perp 1} d\boldsymbol{p}_{\perp 2}} - \frac{1}{\sigma_{in}^2} \frac{d^3\sigma}{dy_1 d\boldsymbol{p}_{\perp 1}} \frac{d^3\sigma}{dy_2 d\boldsymbol{p}_{\perp 2}} \quad (10)$$

could be investigated. The value of $C(p_1, p_2) = 0$ corresponds to not correlated particles. The existence of some correlation at ISR energies (short range correlations) is seen from the distribution of the rapidity difference of secondary particles (Fig. 6b). On the other hand there is no correlation between the number of particles produced backward and forward in the CM system (Fig. 12a). The scatter diagram of longitudinal momenta of two particles at ISR studied by a 2-arm spectrometer is a clear evidence for the elastic scattering and the inelastic interactions. The quasi-elastic interactions (probably diffracion dissociations of one of the two interacting particles are clearly distinguished from the other inelastic channels (Fig. 12b). Generally one can see that the correlation among the secondary particles may give some new view on the production mechanism.

IV. EXCLUSIVE REACTIONS

In the past decade extensive studies of the exclusive reaction (a reaction with a given number of particles in the final state(have led to the discovery

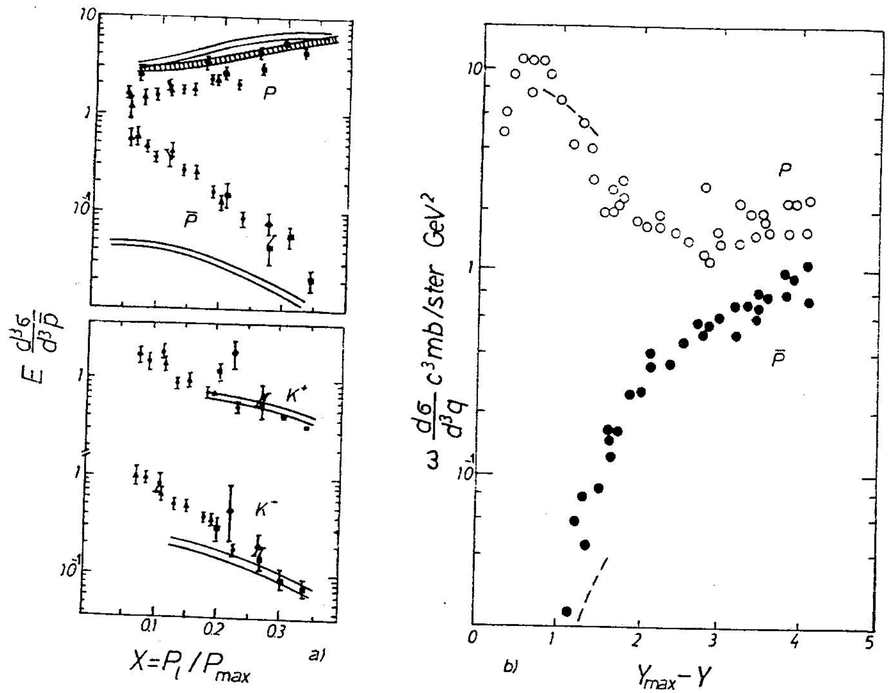

Fig. 11. **a.** The distribution of x at the ISR energies of the produced K-mesons and antiprotons as compared with the classical accelerator energies (lines) [4]. **b.** Late scaling of the produced antiprotons at ISR [4].

of a large number of resonances. The special study of quasi-two-particle reactions gave a support to the Regge exchange idea which qualitatively explains the peripherabity of secondary particles and the exchange of quantum numbers in reactions. Finally, the idea of duality connects the different reactions with the explicit crossing correlations and distinguishes between the interactions involving exchanges of pomerons and interactions explained by the Regge trajectory exchange.

Recently the new effect in a quasi-two-body reaction has been seen in the distribution of the momentum transfer. The reactions of particles and antiparticles with the same target show the cross-over which can be interpreted as the interference between the Regge trajectories with an even and an odd parity [13] (Fig. 13a). An evidence for the independence of the cross section from primaty energy for reactions with a pomeron exchange (e.g. $K + p \to Qp$) is a typical feature which differs from the Regge exchange reactions (Fig. 13b).

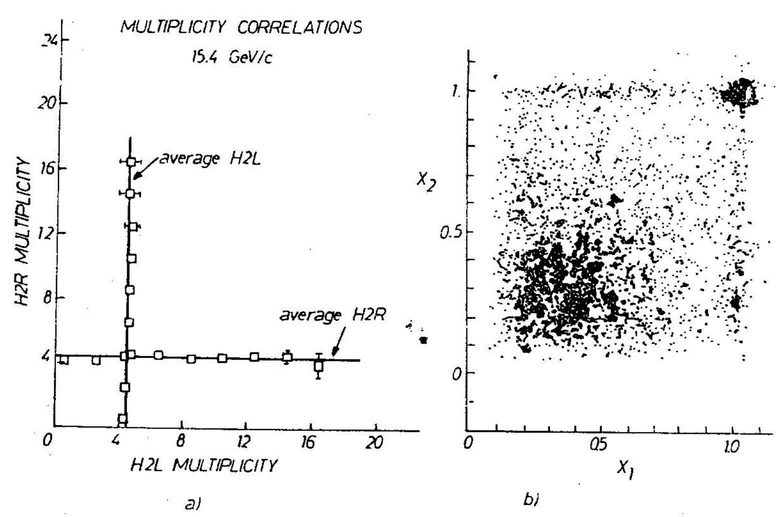

Fig. 12. **a.** Nocorrelation between the average multiplicity of forward and backward going particles at ISR [4]. **b.** The correlation of logitudinal momenta of forward and backward particles. The top right points correspond to the elastic scattering and $x_2(max)$ or $x_1(max)$ to the diffraction dissociation regions.

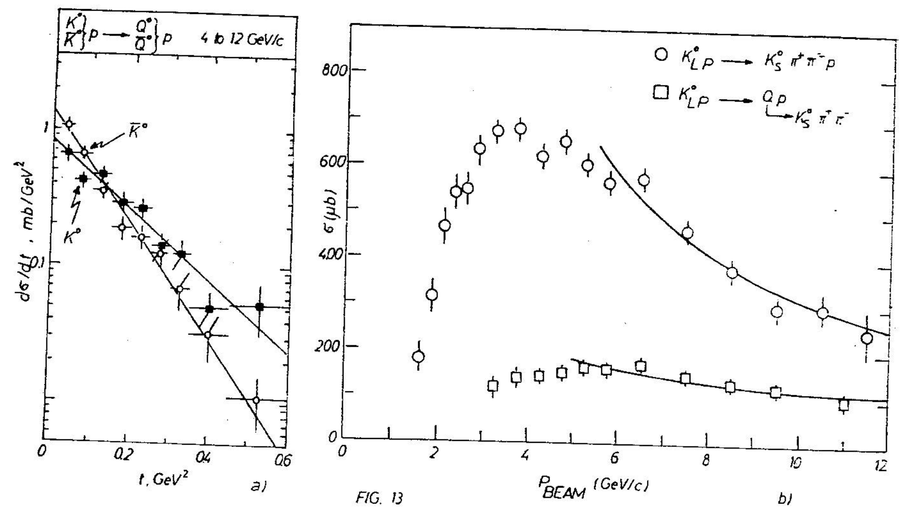

Fig. 13. **a.** The cross-over effect in K^0p quasi-two-body reactions at 4 – 12 GeV [13] **b.** Cross section for the process $K^0_Lp \to K^0\pi^+\pi^-p$ and the sub-process $K^0_Lp \to Q^0p$ as functions of energy [13].

Neglecting the spin, two-body reactions are completely described by two kinematic variables (as s, t). In the three-body final state we need five kinematical variables which can hardly be studied simultaneously by an ordinary display in one or two dimensional histograms. Resonance production in a three-body reaction is usually studied by the Dalitz plots and the dynamics are studied by the L.P.S. analysis. Recently a connection between the two methods has been suggested by the so called prisma plot technique [14].

For the three-body final state a complete set of kinematic variables has been selected (the Dalitz plot coordinates and the Van Hove angle forming the prisma). Thus a remarkable effect has been achieved by a combination of dynamic and resonance productions (Fig. 14b). The method has been generalized to four particles in the final state with a three dimensional Dalitz plot and a two-dimensional Van Hove plot (forming the five-dimensional prisma plus another two kinematically independent variables). The analysis in a seven-dimensional space of complete kinematic variables has been performed in a computer and compared with Monte Carlo events. The selection of different final states (quasi-three-body reactions formed by four-body reactions) has been done by interpolation between Monte Carlo events of

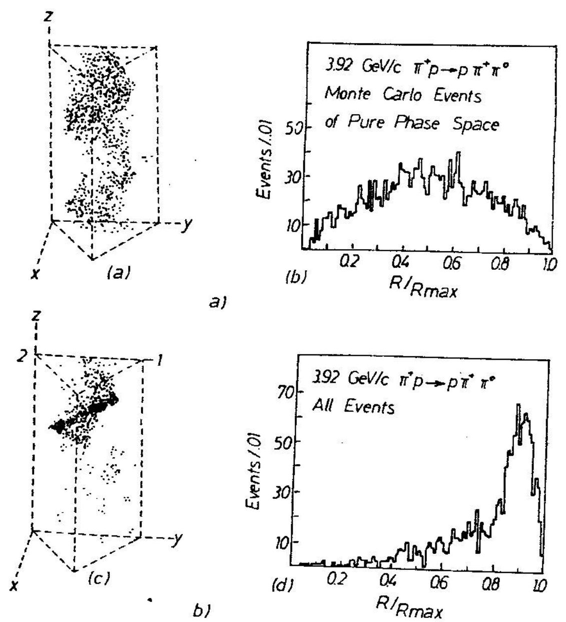

Fig. 14. **a.** Distribution of three-body reactions in a prisma-plot and the $R/R\ max$ distribution for Monte Carlo events. **b.** The same for real events $\pi^+p \rightarrow p\pi^+\pi^0$ at 3.92 GeV/c [14].

the suggested and the real final states [15]. The resulting selections distributed the original sample of the reaction into final states practically without any background. Some effective mass distributions of particles before and after the selection are seen in Fig. 15. It seems that the study of exclusive reactions in a multidimensional space of complete kinematics may be the only way to solve most of the physical problems connected with the production of resonances and dominant dynamics. The prisma-plot method may probably be generalized to the more sophisticated selection of the final state according to the suggested dynamics maped by the Monte Carlo sample produced with a given amplitude.

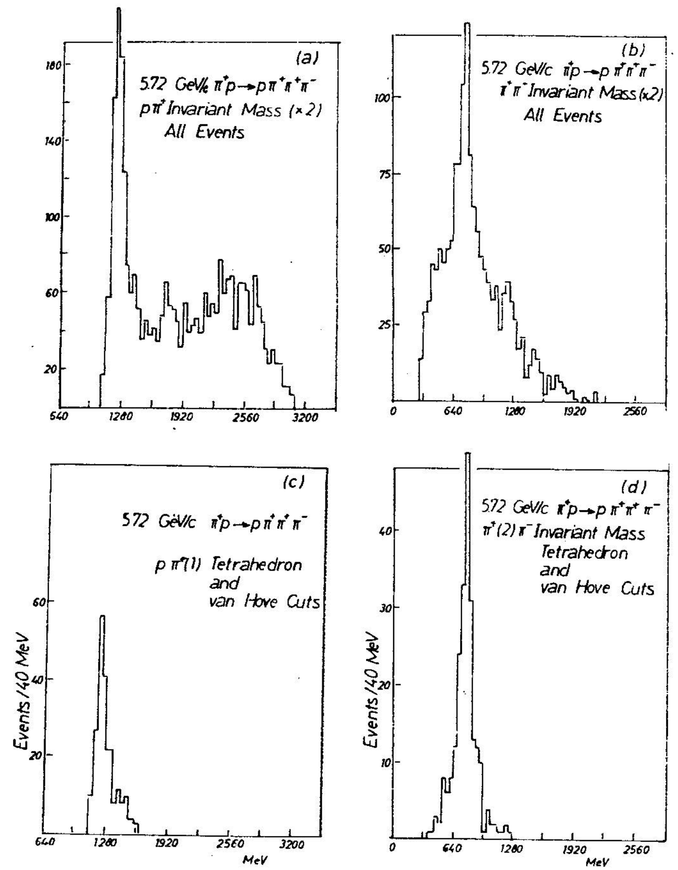

Fig. 15. Unselected and selected mass distributions obtained by means of the prisma-plot technique for four-body reactions [15].

V. MODELS AND THEORETICAL APPROACH

A theoretical approach to multiparticle reactions has been tried since the days of early cosmic ray studies. Let me mention the Heisenberg model [16] of multiparticle production and the Landau hydrodynamical approach [17]. A summary of recent models has been published [18], let me mention here only a few basic principles.

The multiperipheral future was developed from two-body or quasi-two-body reactions assuming the factorization of amplitude

$$A(s, t_i, s_{in}) = \prod_{i=1}^{n-1} A_i(s_i, t_i), \qquad (11)$$

where $A_i(s_i, t_i)$ is the amplitude of virtual two-body reactions. If all strong correlations among the secondary particles are neglacted and the energies and subenergies of particles s_i are large enough (strong ordering limit), the kinematic realation holds

$$s_1 s_2 \ldots s_{n-1} \leqslant s t^{n-1}, \qquad (12)$$

where s_i are subenergies of two particles and t is the average momentum transfer. Just using e. (12) and taking $s_1 \approx s_2 \approx \ldots \approx s_{n-1} = s_0$ we can obtain a logarithmic increase of multiplicity

$$n \leqslant c \ln s, \qquad (13)$$

where $c = [\ln (s_0/t)]^{-1}$. An elengat way of multiperipheral description was given in the Chew-Pignotti model [19], where all correlations and transversal momenta were neglected and the cross section for n-particles gave a simple intergrable form

$$\sigma_n \approx g^{2n} e^{(2\alpha-2)Y} \int \prod_{i=1}^{n-1} dy_i \delta(Y - y_{n-1}), \qquad (14)$$

$$\sigma_n \approx g^{2n} e^{(2\alpha-3)Y} \frac{Y^{n-2}}{(n-2)\,!}, \qquad (15)$$

where α is an effective trajectory, g^2 is the coupling constant at each vertex and Y is connected with the primary energy, $Y = \ln s$. In order to obtain a constant total cross section $\sigma_T = \sum \sigma_n$ we have to requier the constraint $2\alpha - 2 + g^2 = 0$, which leads to the simple form

$$\sigma_n \approx G^4 e^{-g^2 \ln s} \frac{(g^2 \ln s)^{n-2}}{(n-2)\,!}. \qquad (16)$$

This is nothing else than the simple Poisson distribution with an average

multiplicity $\langle n \rangle = g^2 \ln s$. The model predicts equally well the independence of the rapidity distribution from primary energy and forms the plateau [20]

$$\frac{d\sigma}{dy} = \sum_n \sum_i \frac{d\sigma_n}{dy_i} \approx s^{(2\alpha-2+g^2)}. \qquad (17)$$

The model is only a very crude approximation neglecting the transversal momenta effects but can explain some typical observations.

In the diffractive model [21] the two semitransparent colliding objects are described. The produced particles are created by fragmentation or excitation of those colliding objects and the cross section of a given reaction remains independent from primary energy. The geometrical picture of the reaction is give by the amplitude

$$a(\boldsymbol{k}) = \int [1 - S(\boldsymbol{b})]\, e^{i\boldsymbol{b}\boldsymbol{k}}\, d^2 \boldsymbol{b}, \qquad (18)$$

where $\boldsymbol{k}$ is a two-dimensional momentum transfer, $k^2 = -t$, the $\boldsymbol{b}$ is the impact parameter in the transversal plain and $S(\boldsymbol{b})$ is a transition function depending on the density of the matter inside a hadron. As the energy increases final limits for σ_{el} and $d\sigma/dt$ are reached. Similarly, due to the Lorentz contraction of the hadrons the limiting distribution of the secondary particles is obtained. One of the consequence of the model is an asymptotic behaviour of the partial cross section σ_n. Plateaus in the distribution rapidity and the logarithmic increase of multiplicity can be obtained as well.

The thermodynamical picture of reactions has been suggested by Hagedron [22] and is based on the bootstrap idea of successive decays of Fire-Balls. The estimated hadron density for such a mechanism has the form

$$\varrho(m) \approx c m^a e^{m/T_0}, \qquad (19)$$

where c is an arbitrary constant, $a \leqslant -\frac{5}{2}$ and T_0 is the maximum temperature of the hadron matter ($T_0 = 160$ MeV in equilibrium). To explain the peripherality and limitation of transversal momenta the assumption of a general velocity function has been made. This function fitted by experiment, however, is independent from the primary energy of the colliding particle. With this simple description all basic features of multiparticle reactions such as scaling properties, logarithmic multiplicity increase, and correlations among the particles can be explained.

A very simple approach to the phenomenological description as attend in the NOVA model [23] which assumes that of two colliding particles on is excited and emits isotropically the sesondary particle. A sufficiently broad spectrum of the masses of excitation has been selected to justify the logarithmic increase of multiplicity (multiplicity is proportional to the excited mass) and the additional assumption of peripheral distribution of the NOVA system was introduced:

$$\varrho(M, t) \approx \frac{e^{-\beta(M-M_{min})}}{(M - M_{min})^2} e^{B(t-t_{min})}, \tag{20}$$

where β and B are arbitrary constants. Many experiments have been compared with this simple description but the conclusion is that at least 20 % of events could be explained only by excitation of the two interacting particles (two NOVA's).

A field theory approach to multiparticle processes has been made with partial success [24]. It can explain the constant ratio between the elastic and the total cross section $\sigma_{el}/\sigma_T = \frac{1}{2}$, but the total cross section increases with the primary energy as $(\ln s)^2$. Such theories, however, have a pleasant feature of unitarity in the final eikonal representation.

Recent studies of reactions and inclusive distributions of secondary particles seem to support the concept of two different mechanisms of particle production at high energy. One of them may be represented by multiperipheral features and the second by the diffraction dissociation. This is the way which qualitatively explains a non-Poisson multiplicity distribution, and the existence of diffraction dissociation events at high energies. The estimation of this two-component theory gives the 22 % of diffraction dissociation and the rest of the multiperipheral type mechanism.

Since the number of experiments in multiparticle reactions is increasing, we may soon learn the complete dynamics of the elementary particle production.

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