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The Cluster Concept in Multiple Hadron Production

Independent emission of groups of hadrons describes the essential features of high-energy scattering.

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Collisions of strongly interacting subnuclear particles (hadrons) at relativistic energies are distinguished by the creation of additional particles. The study of the particle production process has been one of the central concerns of high-energy and cosmic ray physics for many years. Recently the evolution of a phenomenological description of multiple production, which began with pioneering studies in cosmic rays, has accelerated dramatically with the accumulation of detailed experimental results. These have been obtained using the 70 GeV proton synchrotron at Serpukhov, USSR, the 500 GeV Fermilab proton synchrotron at Batavia, Illinois, and the CERN Intersecting Storage Rings (ISR) at Geneva, Switzerland. The head-on collisions of 30 GeV protons which may be studied at the ISR are equivalent to collisions of 2000 GeV protons with a stationary target. With the passing of the survey phase of experimentation in the new energy regime, it is appropriate to summarize in general terms what has been learned and what new questions have been identified.

Despite prodigious experimental and theoretical effort, no unified theory of high-energy collisions has yet emerged. Instead there exists a variety of rather different schemes, each emphasizing one or another aspect of the data and describing a limited set of phenomena. One of the most fruitful of these descriptions rests on the concept of hadronic clusters. According to this picture, particle production is a two-step process in which correlated groups of particles called clusters are emitted and subsequently decay independently into the observed secondary hadrons. Experimental evidence for the existence of clusters is entirely circumstantial. Nevertheless there is a consensus that an average cluster decays into three to four pions and has much in common with the prominent meson resonances. The motivation and indications for the cluster concept and the aspirations for theories based upon it form the substance of this article.

Character of High Energy Collisions

The total cross section, or probability for two hadrons to interact, is approximately constant over a wide range of energies, but the reactions which take place vary considerably. At very low center of mass (c.m.) energies (1), elastic scattering is preeminent. At higher energies inelastic processes account for a major fraction of the total cross section. Over a significant range of intermediate energies most of the inelastic scattering leads to two (stable or unstable) particle final states. Many of the hadron resonances were discovered in studies of such quasi-two body final states in the early nineteen-sixties. Multiple production, which is the focus of this article, dominates at c.m. energies above about 8 GeV.

The primary observables of high-energy collisions are the momenta (or at least directions) of the emerging particles and information, usually incomplete, about their identity. The three chief categories of particle detectors: photographic emulsions, hydrogen-filled bubble chambers, and electronic counters as commonly used are ionization devices--highly efficient for the detection of charged particles but rather insensitive to electrically neutral particles. As a consequence each event is only partially observed in most experiments.

The necessity to cope with an ignorance of many of the details of multiparticle final states has led to the notion of *inclusive reactions*. Instead of measuring in full the kinematic parameters of every particle in an event, it is useful to characterize final states by the explicit occurrence of a small number of particles with specified momenta, together with any number of undetected particles. Thus a single-observed-particle inclusive cross section gives the probability to detect one secondary with specified momentum, plus anything else. In this language the total cross section is a no-observed-particle inclusive cross section.

Several important general features of multiple production have been identified.

1. The momenta of secondary particles perpendicular to the axis defined by the direction of the colliding particles are severely limited, and small compared to the "longitudinal" momenta. The mean value of the <u>transverse momentum</u> is approximately 350 MeV/c, independent of the energy of the colliding particles. Because the momentum vectors of the outgoing particles are strongly collimated along the initial beam direction, it is useful to idealize particle production as a one-dimensional process in momentum space (2). A useful kinematic variable is the (longitudinal) rapidity, $y=(1/2)\log[(E+p_{\ell})/(E-p_{\ell})]$, where E and p_{ℓ} are the energy and longitudinal momentum of the observed particle. The rapidity has some important virtues. First, rapidity differences are preserved under Lorentz boosts along the beam direction. The concept of particles with similar or dissimilar momenta is therefore given a Lorentz invariant meaning. Second, with rapidity as the longitudinal momentum variable the Lorentz invariant phase space volume element d^3p/E separates neatly into transverse and longitudinal parts as $\pi dp_t^2 dy$. The one-dimensional picture emerges when the transverse degrees of freedom are neglected. Finally, for relativistic particles the rapidity is closely approximated by a "pseudorapidity" variable $\eta=-\log(\tan\theta_{lab})$, for which only the directions of the emerging particles need be measured. These properties

lead to a suggestive analogy with a one dimensional gas, with the kinematical boundaries of rapidity in correspondence with the walls of a container, and the density of hadrons per unit rapidity corresponding to the number of gas molecules per unit "volume." For proton-proton collisions at c.m. energy W, the length of the allowed rapidity interval is $Y = 2 \log(W/M)$, where M is the proton rest mass (about 1 GeV). About eight units of rapidity are available for study at present day accelerators.

2. On the average, a "leading particle" which retains most of the attributes of the beam particle emerges with half the energy of the incident projectile. [A similar statement holds for the target particle.] Thus in collisions initiated by a proton beam it is routine to find a fast secondary proton or neutron emerging along the beam direction. The <u>leading particle effect</u> can also be regarded as a limited inelasticity of hadron collisions: averaged over many events, the c.m. energy expended in particle production is only about one-half of the energy of the colliding particles.

3. The mean number of secondaries increases slowly with energy. At accelerator energies most of the produced particles are known to be pions, the least massive strongly-interacting particles. If all secondaries were produced at rest in the c.m. system, the multiplicity

would grow linearly with the c.m. energy. In fact the observed growth is more gradual; it is nearly logarithmic, as shown in Fig. 1(a). The changing character of the processes which compose the nearly constant total cross section is illustrated in Fig. 1(b), which displays the semi-inclusive "topological" cross sections for inelastic production of a fixed number of charged particles plus any number of neutrals. These rise and fall with increasing energy, but sum to the slowly varying inelastic cross section.

4. A short-range order of multiparticle final states is manifested in several ways. The memory of the attributes of the beam and target particles persists only in restricted fragmentation regions which extend about two units of rapidity from the rapidity boundaries. Likewise charge correlations and the other clustering phenomena that we will discuss are enforced over a short, and roughly energy-independent, interval in rapidity.

5. Outside the fragmentation regions, in the so-called central or pionization region, the structure of multiparticle events does not depend upon the nature of beam or target. For example, excluding the projectile fragmentation region, pion-initiated events at high energies are largely indistinguishible from proton-initiated events. This is sometimes called the

factorization property.

6. Inclusive cross sections have been found to scale in the fragmentation regions, in the sense that they are approximately independent of the incident energy, being functions only of the Feynman variable $x = 2\, p_{\ell}/W$. In the pionization region cross sections are observed to increase gradually with increasing energy.

7. The structure of events is relatively stable as the energy changes. The rapidity density of produced pions is almost energy independent. In terms of the one dimensional gas analogy, the length of the container (the rapidity interval) grows as the energy increases, but the density of gas is fixed, and correlations among the molecules are unchanged.

These seven generalizations are simplified idealizations which are subject to numerous caveats and to quantitative refinement. They nevertheless provide a reliable outline of all the gross characteristics of multiple production now known. One further phenomenological construct is often of value. It is the separation of many-body events into two classes:

1. inelastic diffraction, the quasielastic production of fixed final states (such that fragments of the target have fixed laboratory momenta independent of the

incident energy), predominantly of low mass and multiplicity, each with a cross section that is nearly constant at high energies; and

2. nondiffractive production accounting for the bulk of the inelastic cross section, the cross section to produce any specific channel being strongly energy dependent.

The explicit models to be discussed below apply specifically to the nondiffractive component.

History of the Cluster Concept

The tendency of produced hadrons to merge into correlated systems at definite energies was first observed in the early fifties when resonances were discovered in pion-nucleon scattering experiments. However, the hypothesis that multiple production is a two-step process was not advanced until 1958. It arose from the analysis of experimental data obtained by cosmic ray physicists in the study of collisions initiated by primary particles with energies around 1000 GeV. A class of processes was found in which particles in the pionization region appeared to emanate from two isotropically decaying centers, called fireballs. Each fireball had a mass estimated at 3-4 GeV/c^2 and decayed into seven or eight pions.

A year later, cosmic ray experiments with 300 GeV primaries revealed events which could be explained by the creation of a single fireball possessing similar properties, though with a slightly broader mass distribution. At these energies, individual events were found in which the angular distribution of secondaries lacked forward backward symmetry in the c.m. Such asymmetrical showers were ascribed to the motion of the fireball.

The statistical or hydrodynamical picture (3) which was at that time the most popular approach to multiple production could not explain these results. But soon ideas about the peripheral nature of hadron collisions evolved into the one-pion exchange model for two-body collisions, which was in turn generalized into the multiperipheral cluster model (4). According to this idea, the virtual particle exchanged between colliding hadrons radiates groups of correlated pions. This chain of clusters is shown schematically in Fig. 2. The limited transverse momentum of secondaries and the leading particle effect follow from the damping of momentum transfer characteristic of virtual particle exchange. The other important properties of multiple production have natural explanations in this picture as well.

A new wave of interest in the structure of multiparticle events arose about five years ago after the discovery at the then new accelerators of strong short-range rapidity correlations among produced pions. Soon afterwards the azimuthal, charge, and fixed multiplicity correlations were studied. Early comparisons of experimental features with those expected in the cluster picture were made on the basis of a simplified version, or caricature, of the model, named the <u>independent cluster emission model</u> (ICEM). Inspired by multiperipheral results and by the parton model ideas developed to interpret inelastic electron-nucleon scattering (5), theorists assumed clusters to be produced with uniform probability over the entire rapidity interval. So that calculations could be carried out analytically, the properties of the clusters themselves were postulated very roughly: all clusters were taken to be identical and to decay isotropically into a fixed number of pions. In addition, the constraints of energy and momentum conservation were imposed only in an average sense. The ICEM does not pretend to treat such problems as the energy dependence of total cross sections or the relation between elastic and inelastic scattering which are usually addressed in the framework of the multiperipheral approach. It does, however, provide a faithful representation of the properties of inelastic events suggested by the multiperipheral model. On the basis of the comparison of ICEM predictions with experiment it was suggested that the <u>average cluster</u> has a mass of no more than about 1.5-2 GeV/c^2 and decays into three or four pions.

More elaborate multiperipheral calculations in which clusters of varying masses are allowed and the conservation laws and dynamics of the interaction are taken rigorously into account tend to indicate that such figures could arise as an average of the contributions of prominent resonances with heavier clusters or fireballs. These studies suggested, furthermore, that different experiments might be sensitive to various sorts of clusters. This may account for the variability of the properties imputed to clusters. At rather low energies and for low multiplicity events at high energies, it is mostly the light resonances that dominate, but for the higher multiplicities favored by cosmic ray studies the part played by heavy clusters might be enlarged.

Concluding this brief history, we may say that the questions regarding clustering effects have been answered on the phenomenological level in the present range of accelerator energies. Much work remains to clarify the nature of the clustering phenomenon and, particularly, the existence, decay properties and other attributes of extremely massive clusters.

Experimental Evidence for Clusters

To explain now the effects of clustering of secondary pions were discovered, we shall discuss several <u>methods of cluster detection</u>. It is impossible to describe them all here. However, only a few of the nearly twenty techniques are in active use.

As we have already mentioned, hadronic clusters are not directly observed. Their existence is suggested indirectly by effects such as correlations. Two circumstances make the isolation of individual clusters difficult. First, the decay products of two or more clusters in an event can overlap in rapidity, making a unique separation almost impossible. Second, an isolated group of particles may occur as a fluctuation, particularly if neutral particles go undetected. To exclude a fluctuation interpretation it is necessary to identify and collect many similar (fully analyzed) events, which is not an easy matter.

The cosmic ray studies which gave rise to the two-center hypothesis were restricted to events in which clusters appeared to be well separated in pseudorapidity. The statistics and precision of these early studies were quite modest. Consequently we must regard their results as more suggestive than definitive.

The occurrence of clustering effects in an unbiased sample of inelastic events was demonstrated for the first time by measurements of inclusive two-pion correlations. The probability to observe in a single event one pion at rapidity y_1 and a second pion at rapidity y_2, together with anything else, is recorded. If the pions were produced independently, this joint probability would be equal to the product of the probabilities to find pions at rapidities y_1 and y_2 in different events. In the absence of dynamical and kinematical correlations the correlation function defined as the difference of the two-particle inclusive distribution and a product of single-particle inclusive cross sections should vanish (6). Experiments have shown that this difference is noticeably greater than zero at coincident rapidities $y_1 = y_2$ and decreases exponentially with the separation of pions $|y_1 - y_2|$. Thus all correlations are concentrated within a limited interval of about two units of rapidity (see Fig. 3). This observation provided a strong argument in favor of the cluster concept.

The more particles are contained in a cluster, the stronger is the correlation at $y_1 = y_2$. The correlation length is related to the angular distribution of pions created in the cluster decay. Comparison of experimental data with theoretical formulas has shown that independent emission of individual particles is excluded by experiment, but that excellent agreement results if particles are produced by clusters which decay isotropically into 3-4 pions on the average.

Information of a more detailed nature can be extracted from analogous distributions for events with fixed numbers of charged particles (<u>semi-inclusive correlations</u>). When analyzed in the ICEM framework, data on semi-inclusive correlations yield a measure of the width of the multiplicity distribution for cluster decay, in addition to its mean. The inferred average properties of clusters are unchanged but at low multiplicities clusters closely resembling resonances are produced while at the highest multiplicities (accounting for perhaps 10% of the inelastic cross section) higher multiplicity clusters seem called for. This trend is evident in Fig. 4. It is intriguing that this tendency was observed at the CERN ISR at energies equivalent to about 1000 GeV primaries, i.e. the regime in which fireballs were first detected in cosmic rays.

A slightly different form of the two-particle correlation idea was exploited in the rapidity gap method. The main idea behind this approach is that the distance in rapidity between neighboring particles is related at small separations to the mean density of particles, and at larger separations to the density of clusters. Therefore from a knowledge of densities of pions and clusters one can easily determine the average number of pions per cluster. Once again the same value of 3-4 pions per cluster was inferred. Similar estimates were obtained from other methods as well. Thus the average characteristics of clusters are now well established.

As useful as a description of multiple production in terms of the average properties of clusters is, it is an obvious oversimplification to regard all clusters as identical. Some particles may well, in principle, be produced independently, and it is known that two-pion resonances such as the ρ meson are produced copiously. To the extent that these low-multiplicity objects are produced directly, the spectrum of cluster masses and decay multiplicities must extend well above the average values.

To study this possibility it is necessary to investigate many-particle correlations. The simplest generalization of correlation functions to three and more pions results in cumbersome multidimensional distributions. It is much more suitable to generalize the rapidity gap technique by considering distributions of rapidity intervals which contain 1, 2, ... pions. The maxima and widths of the distributions of rapidity intervals are connected in the ICEM with the decay properties of clusters. Comparison with experiment confirmed the mean values mentioned above and, in accordance with semi-inclusive results, showed that heavier clusters appear to be important in high multiplicity events.

Analytical calculations using the ICEM played an important part in establishing the average properties of clusters. However for more detailed studies the ICEM is compromised by the omission of conservation laws, the leading particle effect, and the transverse motion of clusters. A more complete treatment can be done only by computer calculations employing Monte Carlo techniques. When that level of computational complexity is reached, the more realistic -- and more ambitious -- multiperipheral model becomes the preferred tool.

Outlook

What is the nature of these hadronic clusters for which so much indirect experimental evidence has been compiled? Are they actual dynamical objects or are they illusions caused by the interplay of kinematical restrictions and fluctuations? Do they, in other words, provide an accurate physical description of high energy collisions or merely a convenient "as if" mnemonic? Although clustering phenomena are firmly established, the cluster interpretation remains unproved. However, the observed stability of cluster properties favors their existence, and in most theoretical schemes they are treated as real.

In the multiperipheral model, high energy multiple production is viewed as a sequence of low energy interactions among virtual particles. In this light it is quite natural that the low-mass clusters reproduce the spectrum of meson-meson scattering, including the well-known meson resonances. The nature of the conjectured high-mass clusters is far less clear. One may imagine them to represent an average of overlapping heavy resonances and continuum states, not intrinsically different from their less massive counterparts. Indeed, such a model implies some degree of correlation among clusters of arbitrary size, which makes the notion of an individual cluster slightly nebulous. But this sort of microscopic interpretation, even if correct, might not provide great economy or insight. It may be that clusters can be described most economically as collective excitations of hadronic systems with many degrees of freedom. In this event, theoretical techniques traditionally brought to bear on nonrelativistic many-body problems will supply new insights into their nature. Alternatively, it may be possible to make explicit the suggestive connection with the quark parton model description of the hadron jets observed in inelastic electron-proton collisions. This would yield a unified description of the full spectrum of clusters.

Either development would raise the clustering phenomenon to a general property of hadronic matter. It should then be observed not only in hadronic reactions but also in lepton-induced reactions in which hadronic final states are formed. First indications of clustering effects are already visible in proton-antiproton annihilation and in electron-positron annihilation into hadrons at high energies. New opportunities for experimentation with colliding electron-positron beams of up to 40 GeV c.m. energy, which will appear soon, undoubtedly will shed new light on the apparent similarity of many particle reactions initiated by different beams.

In conclusion, the cluster concept has led to many important insights, and further study of the phenomenon of clustering is certain to provide clues for the deeper understanding of the strong interactions.

Footnotes

1. In collisions of relativistic particles with a stationary proton target, the c.m. energy is $W=[2M(E_{1ab}+M)]^{\frac{1}{2}}$, where E_{1ab} is the beam energy and M is the proton mass. At very high energies, W is approximately the square root of twice the beam momentum, in GeV units.

2. Were particles emitted isotropically in the c.m. system we should regard particle production as a three-dimensional process. There are regimes, in low-energy annihilation reactions and in the decays of massive particles, in which the three-dimensional picture seems appropriate.

3. The hydrodynamical approach was initiated by L. D. Landau, Izv. Akad. Nauk SSSR. Ser. Fiz. 17, 51 (1953). A recent survey is given by P. Carruthers, Ann. New York Acad. Sci. 229, 91 (1974).

4. The multiperipheral model was introduced by D. Amati, A. Stanghellini, and S. Fubini, Nuovo Cimento 26, 896 (1962).

5. R. P. Feynman, Photon-Hadron Interactions (W. A. Benjamin, Reading, Mass., 1972).

6. If all effects of energy and momentum conservation may be neglected (a good approximation in the pionization region), the correlation function can depend only on the rapidity difference $|y_1-y_2|$.

7. Fermilab is operated by Universities Research Association, Inc., under contract with the United States Energy Research and Development Administration. The

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Figure Captions

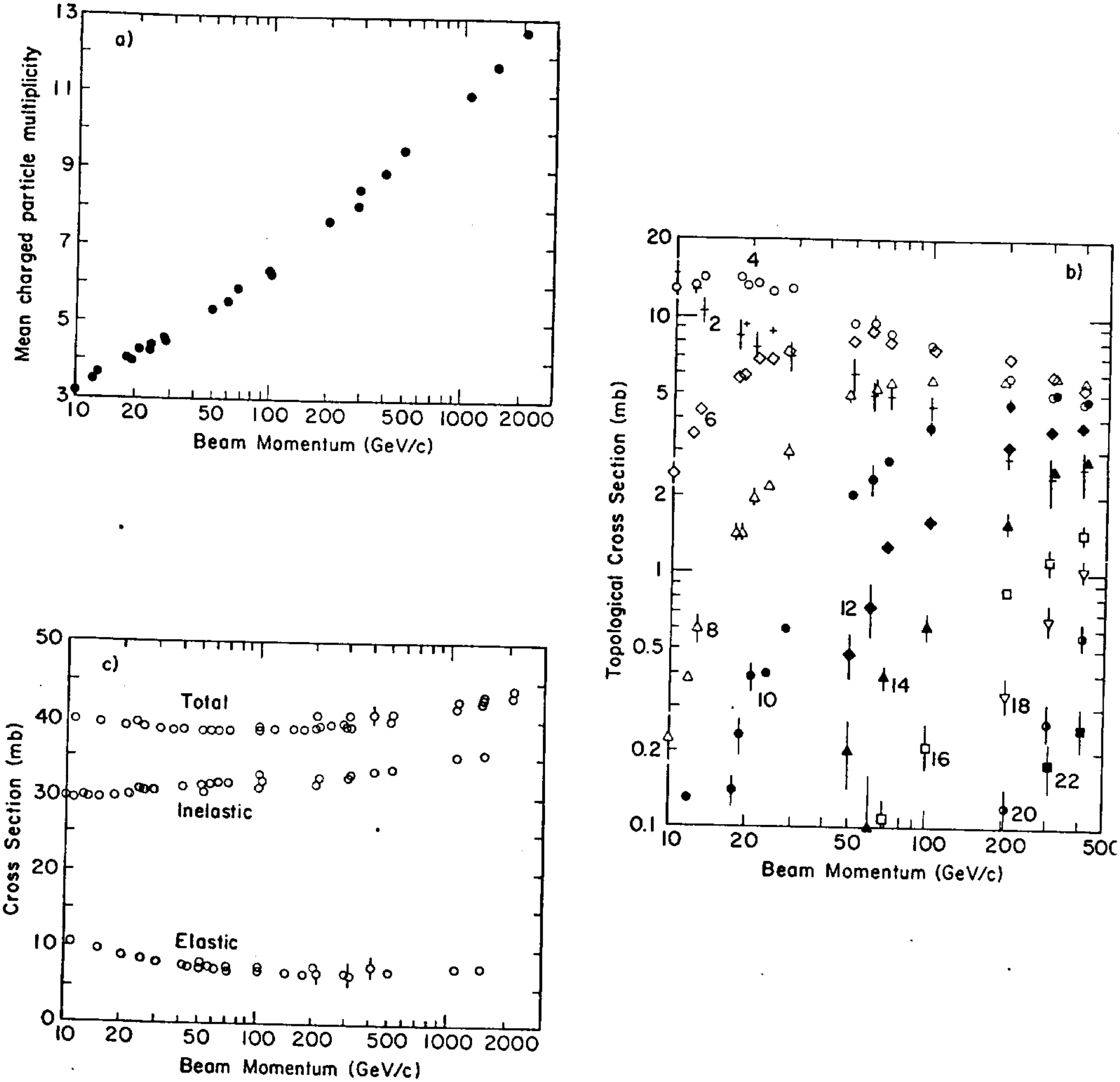
Fig. 1: Some gross features of proton-proton collisions at high energies. (a) The mean multiplicity of secondary charged particles is displayed vs. the beam momentum. (b) Evolution of the "topological" cross sections with increasing beam momentum. Also shown (c) are the total inelastic cross section (the sum of the topological cross sections), and the elastic and total cross sections.

Fig. 2: The multiperipheral cluster mechanism for particle production. The blobs, representing hadronic clusters, are emitted by a virtual particle (dashed line) exchanged between the colliding hadrons.

Fig. 3: The rapidity correlations of two pions produced in p p collisions at a c.m. energy of 62 GeV, as a function of the pseudorapidity difference, for $\eta_1=0$. The data are from S. R. Amendolia, et al., Nuovo Cimento 31A, 17 (1976).

Fig. 4: The dependence of $\langle K(K-1)\rangle/\langle K\rangle$ upon the number of charged prongs n, as measured in p p collisions at W=62 GeV [from Amendolia, et al., op. cit.]. Here K is the number of charged decay products of a cluster. The dashed line shows the expected dependence if clusters are three-particle ($\pi^+\pi^-\pi^0$) resonances. The increase observed above $n/\langle n\rangle=1.5$ suggests the growing importance of high-multiplicity clusters. A Poisson distribution for the number of decay

products would result in a linear growth of <K(K-1)>/<K> with n/<n>.



a)
Mean charged particle multiplicity
Beam Momentum (GeV/c)
b)
Topological Cross Section (mb)
Beam Momentum (GeV/c)
4
2
6
8
10
12
14
16
18
20
22
c)
Cross Section (mb)
Total
Inelastic
Elastic
Beam Momentum (GeV/c)

Fig. 1

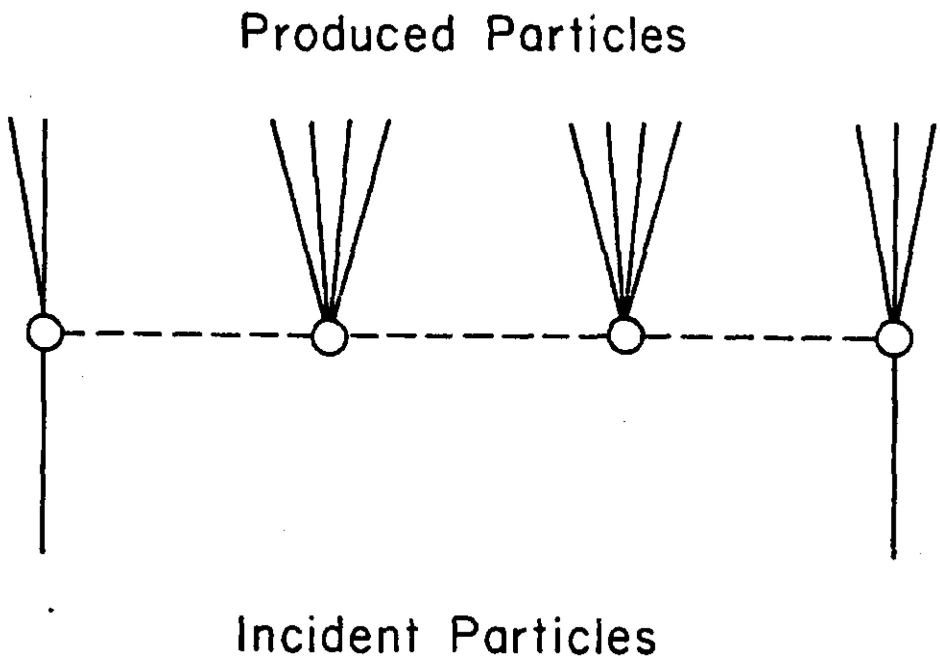


Fig. 2

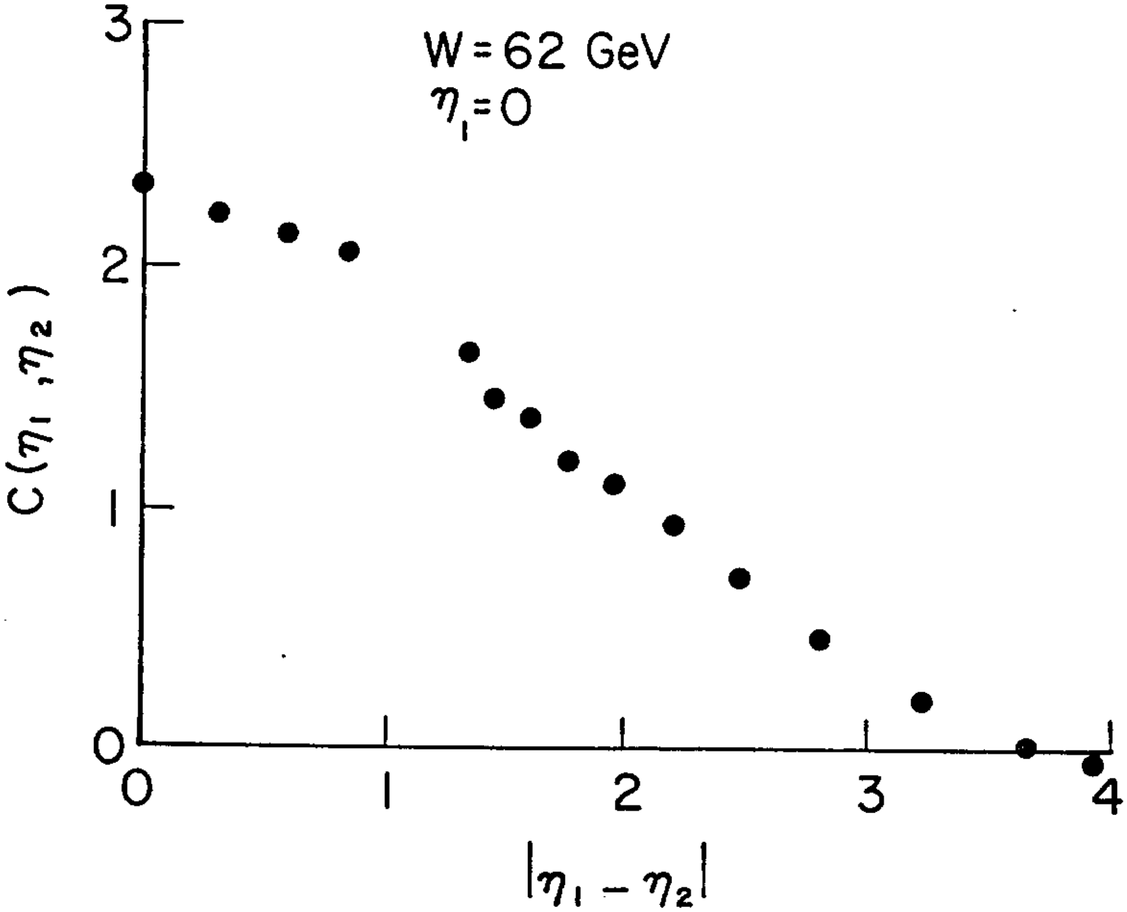


Fig. 3

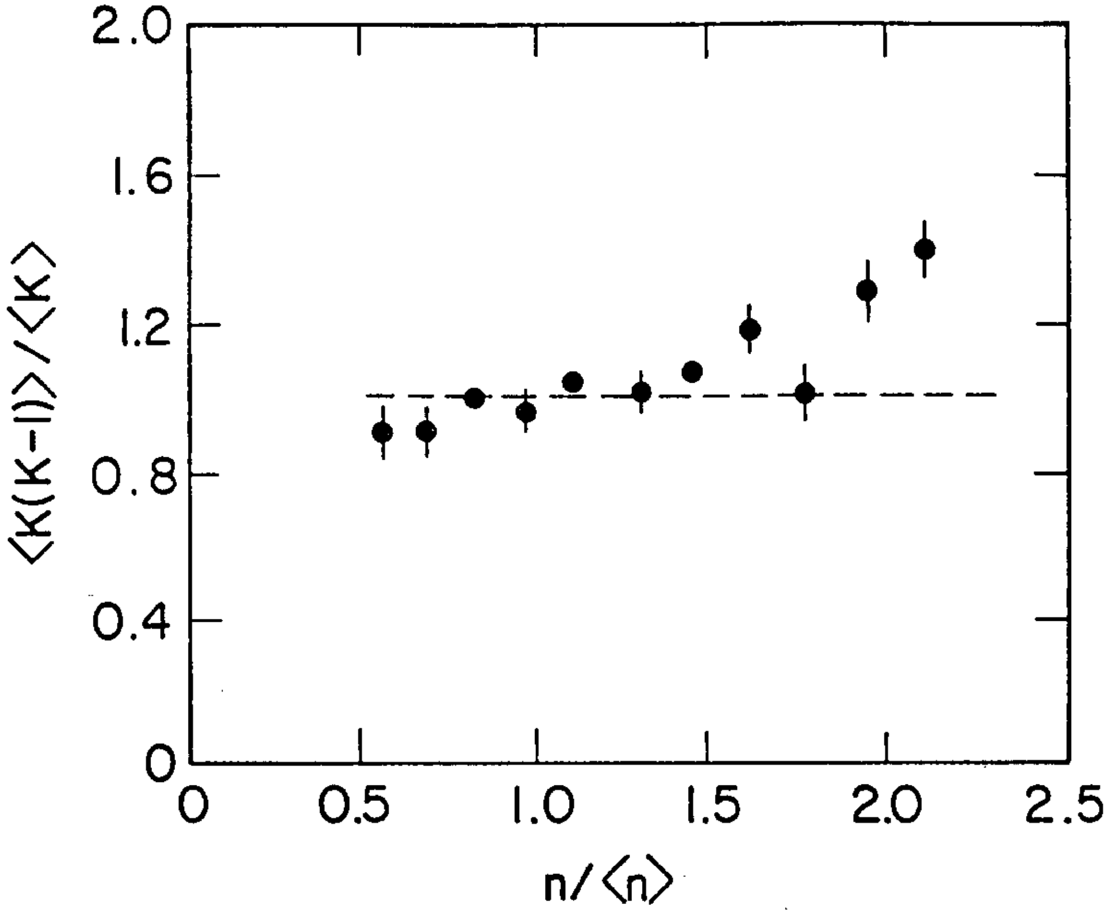


Fig. 4