The Inner Structure of the Proton

There is something small and hard inside. These objects, which may be the particles called quarks, are seen most clearly when a violent collision of particles gives rise to a "jet" of debris

by Maurice Jacob and Peter Landshoff

In the study of the atom and its parts one of the most influential of all experiments was carried out almost 70 years ago in Ernest Rutherford's laboratory at the University of Manchester. Two of Rutherford's students, Hans Geiger and Ernest Marsden, directed a beam of alpha particles, which are fast-moving helium nuclei, onto a thin foil of gold. With a screen of fluorescent material, which scintillates when it is struck by an alpha particle, they then counted the number of particles scattered at various angles as a result of encounters with the gold atoms. Most of the particles passed straight through the foil or were deflected by only a small angle; the average deflection was less than a degree. Surprisingly, however, a few particles were deflected sharply. About one in 20,000, for example, was deflected by 90 degrees.

It was Rutherford who supplied the interpretation of these findings. Since the foil was many atoms thick, and since most of the alpha particles traversed it unimpeded, he reasoned that an alpha particle must be able to pass through an atom with little disturbance of its trajectory. Hence the atom as a whole must be diffuse, with much empty space. The occasional scattering at wide angles, however, was evidence that there is something hard in the atom, which must be small since only a few of the alpha particles encountered it. Both the violence of the collisions and their rarity could be explained by assuming that the atom has an impenetrable, dense core where all its positive electric charge is concentrated in a small volume. In traversing the foil most of the alpha particles never approached one of these small cores close enough to be strongly influenced by it, but when a collision did take place, the alpha particle could be scattered in any direction, even straight back along its original path.

What Rutherford had discovered, of course, was the atomic nucleus. He had also introduced a method for investigating the constitution of matter, a method whose importance is undiminished today. In the decades following Rutherford's experiment it became apparent that the nucleus itself has a structure: it is made up of protons and neutrons. Now there is compelling evidence that the component protons and neutrons are not elementary objects; like Rutherford's atoms they are mostly empty space, but embedded within them are small, hard constituents. The constituents have been given different names in different contexts: they can be called either partons or quarks.

The internal structure of the proton is being explored today through experiments that are almost identical in form with Rutherford's. Collisions are arranged between various kinds of particles, and instruments measure the angular distribution of the scattered fragments. Again it is the particles emerging at large angles to the direction of the original beam that convey information about the finest details of the internal structure.

The modern experiments differ from Rutherford's chiefly in scale. The projectiles employed are not alpha particles emitted during the radioactive decay of a nucleus but electrons or protons raised to high energy by an accelerator. Secondary beams of other particles, such as neutrinos or pions, can also be created. The most energetic collisions come about when two beams of accelerated particles are made to collide head on. At high energy the particles do not merely bounce apart; instead much of their energy goes into creating new particles and antiparticles, often dozens of them, which fly away from the point of impact like debris from an explosion. The instruments that detect these particles are not simple fluorescent screens (although that principle is still in use) but elaborate electronic "counters," which not only register the direction a particle takes but also measure its energy, momentum and electric charge. There is a difference of scale in another sense as well. With energies several thousand times greater, the modern experiments can reveal structural features several thousand times smaller. Indeed, the resolving power of the highest-energy experiments is now about 10^{-16} centimeter, which is roughly a thousandth the diameter of the proton.

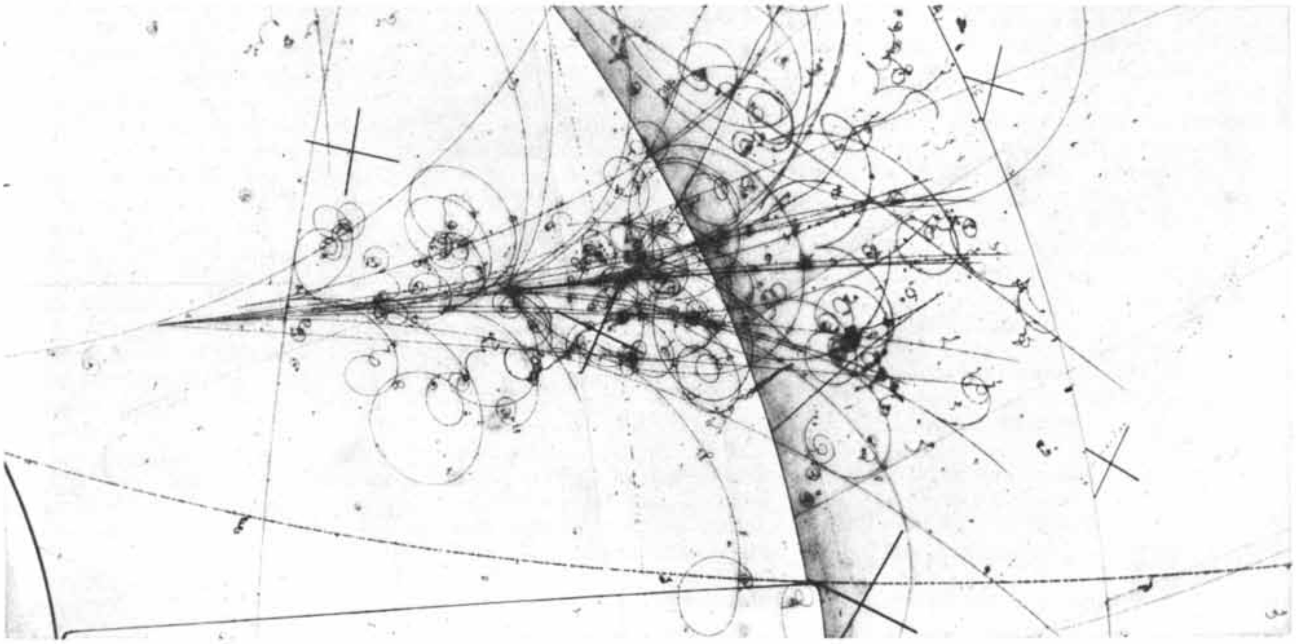
This fine structure becomes visible only in those collisions where some of the energetic fragments emerge at a large angle to the beam direction. As in the earlier atomic experiments, such "hard-scattering" events are comparatively rare. When two protons collide head on, for example, the emitted particles are almost always confined to two narrow cones centered on the axis defined by the two colliding beams. Occasionally, however, particles emerge from the point of impact roughly perpendicular to the beam axis. If one such particle is detected, at least several more usually accompany it. What is most intriguing is that when a fragment is shot to the side in this way, the particles are not scattered randomly in all directions; instead they are generally organized into well-collimated spurts of particles, which have been named jets. The wide-angle jets have the same significance for the structure of the proton as the wide-angle scattering of alpha particles had for the structure of the atom. They are evidence for something small and hard in the proton.

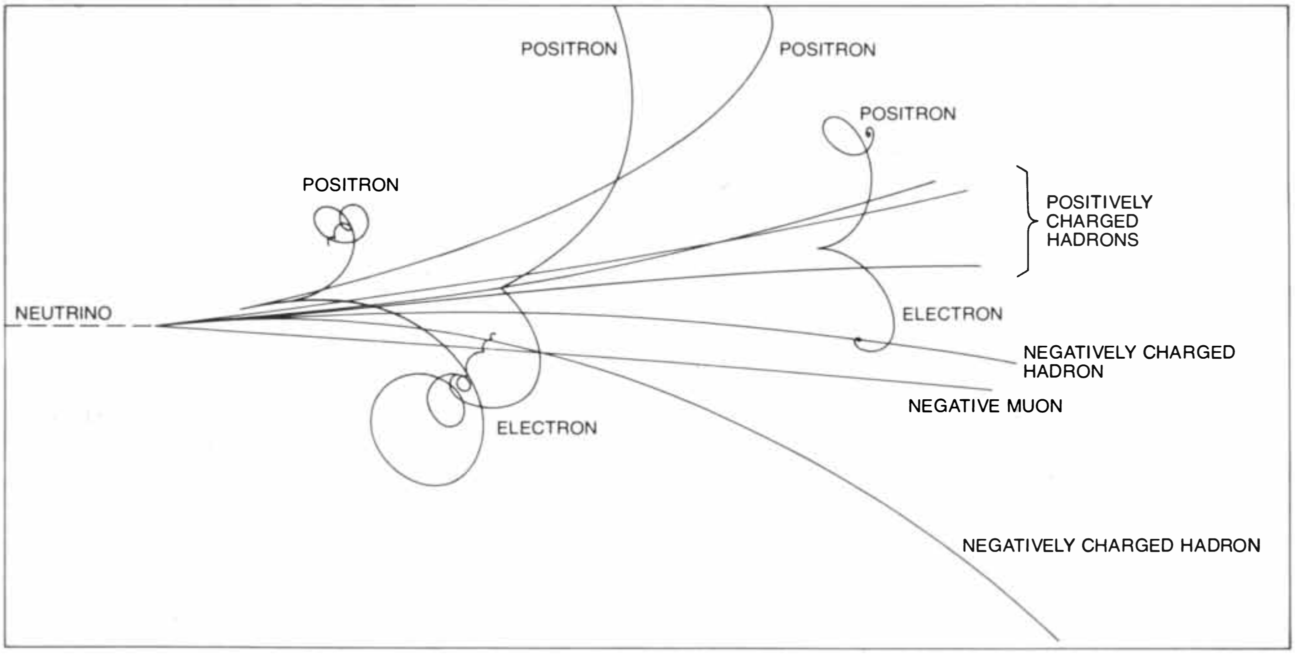
It has been known for some time that the proton is not a pointlike particle. It has a finite size, a diameter of about 10^{-13} centimeter. Although that is very small—indeed, it is smaller than an atom by a factor of about 100,000—it is still measurable. The same cannot be said of certain other particles, most notably the electron. If the electron has any extension, it has not yet been detected, and for now the electron can be regarded as a mathematical point.

In 1970 an experiment at the Stanford

Linear Accelerator Center (SLAC) provided the first direct evidence that the proton has not only size but also structure. In the two-mile linear accelerator at SLAC electrons were raised to an energy of some 20 billion electron volts. (One electron volt is the energy imparted to an electron, or to any other particle with one unit of electric charge, when it is accelerated through a potential difference of one volt. A billion electron volts is abbreviated GeV, the *G* standing for the prefix giga-.) The accelerated electrons struck protons and neutrons in the atoms of a stationary target. Instruments monitored the angular distribution of the scattered electrons and of other particles created in the collisions.

Although most of the electrons passed through the target with little change in direction, the number of widely scattered particles was greater than expected. It was greater than would be predicted if the proton were diffuse and homo-





JET OF PARTICLES emerges from a proton struck by a high-energy neutrino. The event is recorded in trails of bubbles, which form in superheated hydrogen along the path of a charged particle. The neutrino, which leaves no track because it has no charge, is transformed by the collision into a negatively charged muon, which can be observed. At the same time a stream of particles moves off in another direction. They are hadrons, a class of particles (such as the proton and the pion) that are thought to be made up of the more fundamental entities called quarks. From the curvature of the tracks in the magnetic field that permeates the bubble chamber it can be deduced that three of the hadrons carry a positive charge and two have a negative charge. In addition at least one neutral pion is emitted; it cannot be seen, but the products of its decay are pairs of electrons and antielectrons, or positrons, which leave distinctive spiral tracks. In the frame of reference in which the neutrino and the target proton collide with equal but opposite momentum, the scattered muon and the jet of hadrons would appear to emerge almost back to back. Such wide-angle scattering signals a violent process. The event can be explained by the hypothesis that the neutrino collides with a hard constituent of the proton, such as a quark; the quark is ejected, but as it escapes several other quarks and antiquarks materialize, creating the jet of hadrons. The photograph was made with the Big European Bubble Chamber at the European Organization for Nuclear Research (CERN) near Geneva. Some of the particle tracks are identified in the map below.

geneous. The excess of widely scattered particles implied that the proton has embedded within it objects whose diameter is no more than a fiftieth that of the proton as a whole. Richard P. Feynman of the California Institute of Technology supplied a name for these constituent objects: partons.

What was revealed in the SLAC experiments was the internal structure of the proton as illuminated by electrons. Since then similar studies have been done in which the target is illuminated by a beam of muons (which are much like electrons but have a mass 200 times as great) or by a beam of neutrinos (which are particles related to the electron and the muon but lacking all mass and electric charge). Electrons, muons and neutrinos are collectively called leptons, and they make excellent probes in physics experiments because they themselves seem to be pointlike and without structure. Deep-scattering experiments with all three kinds of lepton have given consistent results: occasional wide-angle scattering can be explained by collisions between the incident leptons and some hard constituent of the proton.

The scattering of leptons by protons gave the first experimental indication that the proton has definite structural constituents. Interactions among those constituents were first observed clearly in another series of experiments, begun in 1972, in which protons were scattered by protons. The experiments were carried out by three groups working at the Intersecting Storage Rings (ISR) of the European Organization for Nuclear Research (CERN) near Geneva. Collisions of protons with protons gave rise to infrequent events in which energetic particles appeared at a wide angle to the axis of the beams. These results were interpreted as evidence for the scattering of a constituent object in one proton by a constituent of the other proton.

Several years before the discovery of the parton and before the ISR experiments began, a structure had been proposed for the proton entirely on theoretical grounds. The proton and the neutron are members of the large family of particles called hadrons, which are distinguished from the leptons in that they are susceptible to the strong, or nuclear, force. It is the strong force that binds protons and neutrons together to form atomic nuclei, but the strong force has no effect on leptons; they simply do not "feel" it, much as an electrically neutral particle does not respond to an electric field. The proton and the neutron were the first hadrons known; in the 1940's another was discovered: the pion. In the 1950's a number of powerful accelerators began operating, and an unexpected multitude of new hadrons came to attention. It was this multiplicity of hadrons that stood in need of explanation; it seemed unlikely that all these particles could be equally elementary.

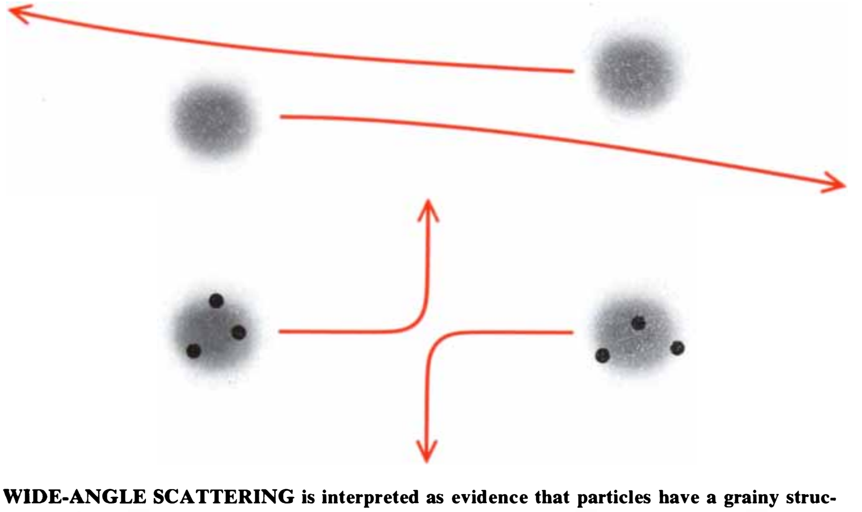
An explanation was proposed in 1963 by Murray Gell-Mann and by George Zweig, both of Cal Tech, who worked independently but reached similar conclusions at about the same time. They pointed out that all the known hadrons could be explained as combinations of just three kinds of more fundamental particles, which Gell-Mann named quarks. Some of the hadrons, including the proton and the neutron, were to be made up of three quarks; others, such as the pion, consist of one quark and one antiquark. The properties associated with the hadron as a whole are given simply by adding up the corresponding properties of the component quarks. In this way all the known hadrons could be accounted for as combinations of quarks. What is more, every allowed combination of quarks, with one exception, corresponded to a known hadron; the exception described a particle designated omega minus, which was discovered in 1964.

The quark model was formulated to explain the diversity of the hadrons; it says nothing explicitly about the internal structure of any particle. Nevertheless, when partons were discovered, there was a natural tendency to identify them with the hypothetical quarks. Several properties of the partons, such as their intrinsic spin angular momentum, have been measured and are consistent with the predictions of the quark model. What is more, the quark model itself has become more secure.

The three "flavors," or kinds, of quark proposed in 1963 were enough to construct all the hadrons then known. It was soon suggested, however, that there should be a fourth flavor, distinguished by a new property of matter called charm. The discovery in 1974 of the hadron designated *J* or psi provided strong evidence for the charmed quark, and a rich spectrum of other charmed hadrons was subsequently discovered. Since then particles that carry still another flavor have turned up. They are thought to incorporate a fifth flavor of quark; because the other four quarks seem to be organized in pairs it is assumed there is also a sixth flavor. All these new hadrons follow the pattern specified by the quark model. Each hadron seems to consist either of three quarks or of one quark and one antiquark, drawn from the set of five or six possible flavors. No particle that would require some other combination has been observed.

In addition to their flavors each of the quarks bears another distinctive property, which in the spirit of whimsy that characterizes the quark nomenclature has been given the name color. It is the colors of quarks that govern their binding together to form hadrons. There are three colors, and only certain combinations of them seem to be possible.

The role of color in binding together the quarks in a hadron is analogous to the role of electric charge in binding together the particles that make up an atom. A precise and well-tested theory describes the latter interaction: quantum electrodynamics. It depicts the attraction or repulsion between two charged particles as being communicated by the exchange of photons, or quanta of electromagnetic radiation. A theory constructed and named on the model of quantum electrodynamics has been formulated to describe interactions between colored quarks; it is called quantum chromodynamics. Here the force between the quarks is mediated by the exchange of gluons, hypothetical particles that "glue" the quarks together. Differences between electromagnetism and the strong interactions of quarks result largely from differences between



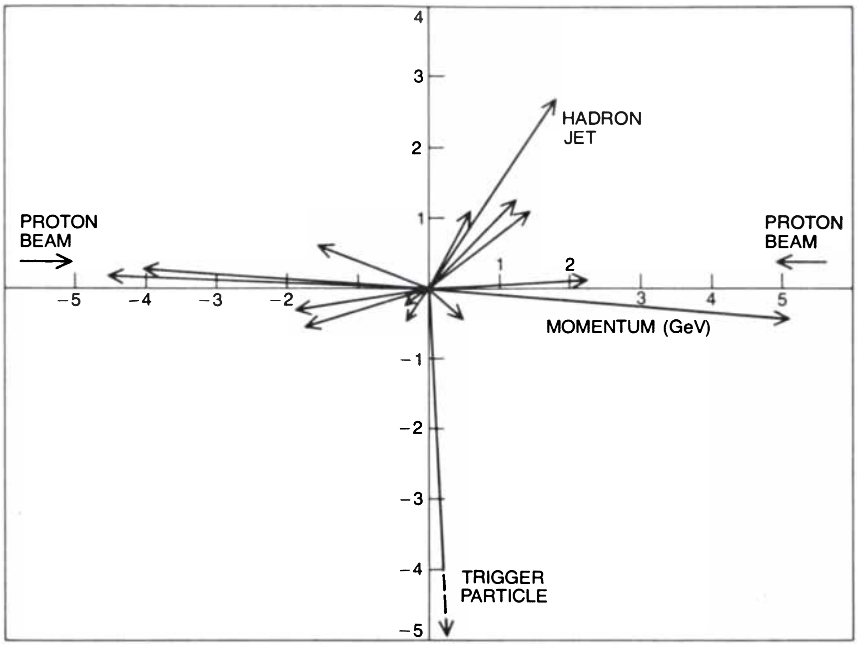
WIDE-ANGLE SCATTERING is interpreted as evidence that particles have a grainy structure, or hard constituents. When large, diffuse particles collide, they are little deflected from their paths. Such glancing collisions are also the most likely for particles that have hard constituents, but in the rare instances when the hard objects meet head on, they ricochet sharply.

the photon and the gluons. In the first place, whereas there is only one kind of photon, there are eight kinds of gluon. Furthermore, the photon communicates electromagnetic forces between charged particles but itself carries no electric charge; as a result a particle can emit or absorb a photon without changing its charge. The gluons, on the other hand, are themselves colored particles, and so they are subject to the very forces they transmit. Quantum chromodynamics has made a number of successful predictions, but it is a difficult theory with which to calculate precise results and it has not yet been confirmed with a precision even approaching that of quantum electrodynamics.

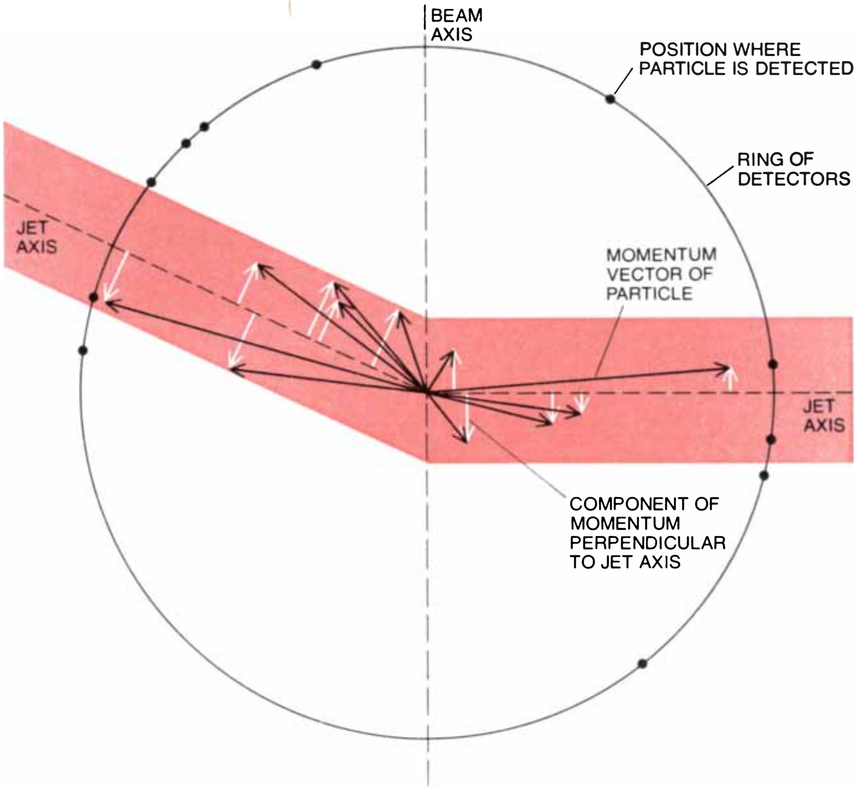
The existence of several hundred hadrons that correspond to allowed combinations of quarks, and the failure to observe even one hadron that cannot be explained as such a combination, represent powerful evidence for the quark model. Nevertheless, what might be considered the most direct and most compelling confirmation of the theory is still lacking: no one has yet isolated a quark. This failure is all the more puzzling in that deep-scattering experiments show the quarks within hadrons as moving about freely, as if they were only weakly bound together. It seems it should be easy to knock one out. When that is attempted, however, by bombarding a hadron with high-energy particles, the fragments that emerge are not quarks but ordinary hadrons, constituted of the standard combinations of quarks.

A possible explanation of this paradoxical behavior has been proposed in the context of quantum chromodynamics. It is hypothesized that the effective strength of the force between quarks is small at close range but grows much larger when the quarks are separated by more than about the diameter of a proton. This force law is just the opposite of the one that governs the more familiar forces of electromagnetism and gravitation, where the forces become weaker as the bodies recede from one another. Because of the peculiar form of the color force the quarks are little constrained inside a hadron, but the energy needed to extract a quark grows without limit as the separation increases.

So far it has not been proved with the tools provided by quantum chromodynamics that the quarks in a hadron are permanently or absolutely confined. There is still a possibility that experiments at higher energy may release a free quark. For now, however, physicists must live with the consequences of apparent confinement. One of these is that quarks cannot be examined in isolation; they must be studied in situ. Hence our best access to them is through wide-angle-scattering events in which a hard collision between a quark and a probe



HEAD-ON COLLISION OF TWO PROTONS yields several widely scattered hadrons. The protons approach each other with equal speed along the horizontal axis and meet at the center. A number of the emitted particles deviate little from the beam axis, but one particle emerges with high momentum at an angle of almost 90 degrees. The detection of this particle triggered the apparatus with which the event was recorded. The high transverse momentum of the trigger particle is partly balanced by a jet of hadrons. Not all the particles in the jet have necessarily been detected; the apparatus is not sensitive to electrically neutral particles, which generally account for about a third of the jet momentum. Only transverse jets are thought to result from the hard-scattering of quarks. The collision was observed with the Intersecting Storage Rings (ISR) at CERN. The length of each arrow is proportional to the momentum of the particle.

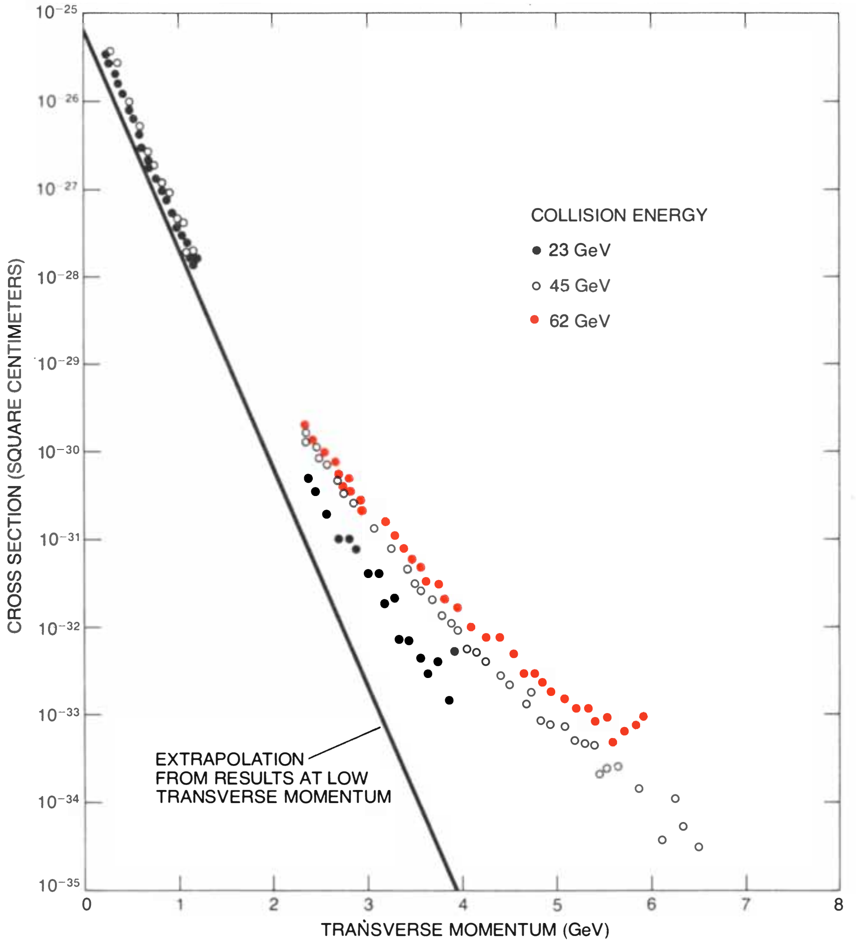


JET IS DEFINED in terms of the momentum of the constituent hadrons. If only the directions of the particles were recorded (by noting where they crossed a ring of detectors), they would be widely distributed. The jet becomes more coherent, however, when it is noted that the component of the momentum of a particle perpendicular to the axis of the jet seldom exceeds a threshold. Thus particles with large momentum are always closely aligned with the jet axis.

particle (which may be another quark or a gluon) gives rise to a jet of hadrons.

Collisions between particles are most easily visualized in the frame of reference where the center of mass of the colliding particles is regarded as being stationary. In this frame of reference the colliding particles approach each other with equal but opposite momentum; if they have the same mass, they collide head on with equal but opposite velocity. Like automobiles that collide head on and come to a dead stop, both particles give up all their kinetic energy.

In experiments where an accelerated particle strikes a stationary target the appearance of the event in the laboratory frame of reference is quite different. The center of mass is not stationary but is swept along in the direction of the beam, even after the collision. As a result the appearance of the event is greatly altered; for example, a jet of particles emitted at 90 degrees to the beam direction in the center-of-mass frame of reference is swept along with the moving particles, so that it appears to diverge from the beam by only a few degrees. In order to see the event in its simplest form one would have to race along parallel to the beam with the same speed as the center of mass. Although that is impractical, there are mathematical transformations that accomplish the same thing: they convert the directions and energies of particles observed in the laboratory into equivalent values in the center-of-mass frame. We shall discuss fixed-target experiments as if such transformations had been carried out.



PARTICLES WITH HIGH TRANSVERSE MOMENTUM are rarely emitted in proton-proton collisions, but at the largest observable values of transverse momentum there is an enhancement in their numbers. The yield of particles is given in terms of a cross section, or effective area, which measures the probability of an interaction. At transverse momenta below about 1 GeV (billion electron volts) the probability of emitting a particle declines steadily as the transverse momentum of the particles increases. At higher values of transverse momentum the probability continues to decline, but not as rapidly as would be predicted from an extrapolation of the results at lower transverse momentum. For example, the probability of observing a particle with a transverse momentum of 4 GeV is roughly 1,000 times greater than would be expected from the extrapolation. Moreover, the probability at low transverse momentum is almost independent of the energy with which the protons collide, whereas at high transverse momentum the collision energy has a strong influence. The anomalously large yields of high-transverse-momentum particles gave the first evidence for the hard-scattering of quarks by quarks. It was reported simultaneously by three groups of experimenters at the CERN ISR.

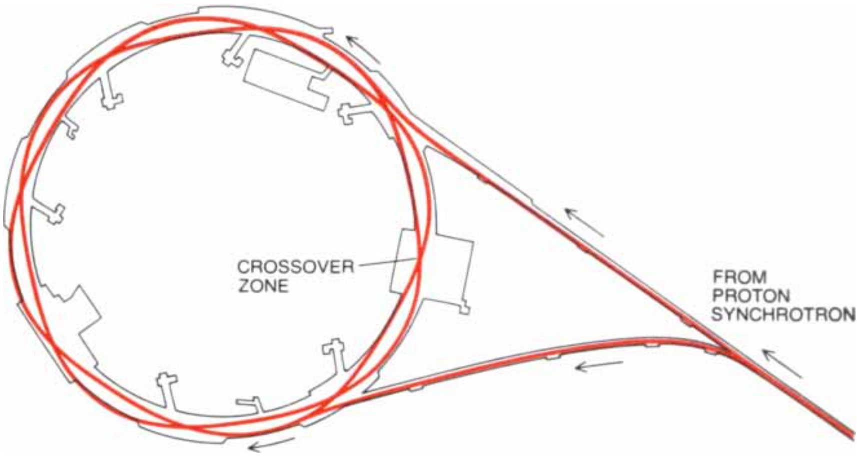
There is one type of high-energy-physics experiment in which the center of mass actually is stationary and the collisions have their simplest form even as they are observed in the laboratory frame of reference. They are events in which two particles are accelerated to the same momentum and are brought together head on. Such collisions can be arranged with particle storage rings, where beams of particles circulate in opposite directions and pass through each other on each revolution. The energy liberated by the collision is merely the sum of the energies of the two beams.

Collisions between electrons and their antiparticles, the positrons, are brought about in storage rings at a number of laboratories, including SLAC and the German Electron Synchrotron (DESY) near Hamburg. Both of these institutions have been operating electron-positron rings since the early 1970's, with maximum collision energies of roughly 10 GeV; both of them have also undertaken the construction of larger rings, capable of collision energies more than three times as great. The larger ring at DESY, which is called PETRA, has been operating since last spring. Still higher energies can be reached in collisions of protons with protons. The only facility for such collisions that is now operating is the ISR at CERN; it has a maximum energy of 63 GeV, the highest center-of-mass energy that can be reached by any instrument in particle physics.

The result of a head-on particle collision is perhaps easiest to interpret in the case of electron-positron interactions. Because the electron and the positron are particle and antiparticle they are both annihilated when they collide, yielding a state of pure electromagnetic energy. This state can be represented as a high-energy photon, but it is a photon with bizarre and paradoxical properties. A fundamental law of nature states that both energy and momentum must be conserved in all physical processes. In order for energy to be conserved in an electron-positron collision, the photon must carry off the several billion electron volts contributed by the annihilating particles. A photon can do that but, moving at the speed of light, it also has substantial momentum. The net momentum of the electron and positron, however, is zero, since they are moving with the same speed in opposite directions. Therefore the photon must have zero momentum and cannot move at all.

A way out of this quandary is provided by the uncertainty principle of quantum mechanics, which allows momentary fluctuations in the energy and momentum of a particle, provided they do not last too long or extend over too great a distance. Hence the photon can exist briefly even with its energy and momentum out of balance, but it must decay within a finite period into a set of particles that properly conserves energy and momentum. Such a photon is called a virtual particle, to distinguish it from a real photon, whose lifetime is unlimited.

The virtual photon can decay into any assortment of particles that conserves energy and momentum and various other properties that also must remain in balance, such as electric charge. These requirements can be met most easily if the virtual photon decays into a state made up of two particles, one being the antiparticle of the other. Energy can be conserved as long as the combined mass of the pair is no greater than the total energy of the electron and the positron. Momentum is conserved if the particle and the antiparticle move apart at the same speed but in opposite directions (which need not correspond to the axis of the electron and positron beams but can have any orientation in space). Electric charge and similar quantities are also conserved.



INTERSECTING STORAGE RINGS at CERN provide head-on collisions between protons in two counter-rotating beams. Protons supplied by a synchrotron are injected clockwise into one of the rings and counterclockwise into the other; they can then be maintained in a stable orbit for many hours. Each beam has a maximum energy of 31.5 GeV, so that the total collision energy is 63 GeV. Collisions take place in eight regions where the interlaced rings cross over.

At low energy one of the commonest decay schemes for the virtual photon results in the regeneration of another electron and positron, with the same energy as the original pair. Another possible outcome is the creation of two muons, one with a positive electric charge and the other with a negative charge. If the interaction region is surrounded by appropriate instruments, the electron pair or muon pair can be detected, with the characteristic signature of oppositely charged particles moving in opposite directions. A third possible decay sequence is of greater interest here. Provided the energy of the collision is sufficiently large, the virtual photon can decay to yield a quark and an antiquark. Significantly, however, the quark and antiquark do not, in their native state, reach the detectors. What is seen instead are two jets of hadrons, emitted back to back from the point of collision.

Any kind of hadron can appear in a jet, but pions are by far the commonest kind. At the collision energies available today a dozen or more particles can be emitted. Among them, in general, will be both positively charged and negatively charged particles as well as electrically neutral ones. Because most particle detectors rely on the ionization caused by the passage of a moving electric charge, the neutral particles escape detection in some experiments. If the neutral particles can be accounted for, however, it is always found that all conservation laws are obeyed by the complete ensemble of emitted hadrons. For example, the total charge of the hadrons is zero and so is their net momentum.

The conversion of a single quark-antiquark pair into a diverse array of hadrons is the most mysterious process in the creation of a jet. It may not be possible to describe it fully until the nature of the color charge is better understood. It is apparent that somehow the naked quark and antiquark "dress" themselves with other quark-antiquark pairs before they emerge to macroscopic distances, where they can be detected. As long as all the particles created in this process include equal quantities of matter and antimatter all conservation laws will be obeyed. Of course, there is still an energy constraint: the total mass of all the created particles cannot exceed the energy brought to the collision by the annihilated electron and positron.

The two kinds of quark that make up all the hadronic constituents of ordinary matter are designated u and d. Suppose the primordial pair created by the decay of the virtual photon consists of a u quark and its corresponding antiquark, which is labeled $\bar{u}$. Before these particles have separated any appreciable distance at least one more pair must be created. Suppose it is made up of a d quark and a $\bar{d}$ antiquark. The u quark can then become associated with the $\bar{d}$ antiquark, a combination that defines the structure of a positively charged pion. The remaining d quark and $\bar{u}$ antiquark constitute a negatively charged pion. In this case the final state would consist of just two particles, but in general there is additional pair creation, leading to a more complicated set of hadrons.

Quark pairs and muon pairs created in electron-positron annihilation seem to arise through the same process (namely through the decay of a virtual photon). It therefore seems reasonable that their average angular distribution, when it is calculated over many events, should also be the same. In testing this hypothesis we are handicapped because we cannot measure the direction taken by the quarks. It is known, however, that the set of all the hadrons descended from a given quark must conserve that quark's momentum. It is therefore possible to add up the momenta of all the hadrons in a jet in order to define the momentum vector for the jet as a whole. The direction along which this vector lies is the axis of the jet, and it should coincide with the direction of motion of the original quark. Experiments at SLAC and at DESY have compared the angular distribution of the jet axes with the distribution of muons, and they are in good agreement.

The total number of events in which muons are created and the number in which hadrons appear should also be related, and their relation should remain unchanged as the energy of the collision increases. In other words, the ratio of hadron events to muon events should approach a constant value regardless of the collision energy. The expected value of the ratio depends only on the total number of quark types and on their electric charges, and so it can be calculated directly from the quark model. Assuming that there are just the three quarks of the original Gell-Mann model, each of which comes in three colors, the predicted value of the ratio is 2. At energies below about 3 GeV that prediction is confirmed. Above 3 GeV significant numbers of charmed particles are created, so that the fourth, charmed quark must be included in the calculation. Adding the charmed quark (again in three colors) changes the predicted value to 10/3, which has also been confirmed experimentally. This remarkable accord between theory and observation has been found again on the next energy plateau, where another pair of quarks is introduced.

A jet of particles does not always look much like a jet at first glance. If the point of annihilation were surrounded by a spherical detector that would merely indicate the position of each hadron as it crossed the spherical surface, the particles making up each of the two jets might well be spread out over a wide area. The configuration of the jet becomes more coherent, however, if not only the direction but also the momentum of each particle is indicated. In general it turns out that the particles with the highest total momentum are closely aligned with the jet axis. The more widely scattered particles carry little momentum. Indeed, the jet can be defined in terms of this relation. A particle is considered to be part of a jet if the component of its momentum perpendicular to the jet axis is below a certain threshold. Under this rule a fast-moving, high-momentum particle must nearly coincide with the jet axis for it to be included, but for a slow-moving particle the direction is less critical.

The tendency for the particle momentum to be concentrated along the jet axis becomes more pronounced as the total momentum of the jet increases. This relation could be deduced from the simple observation that the number of particles in a jet increases more slowly than the total jet momentum. If the total momentum is, say, doubled, the number of particles will rise, but by a factor of less than 2. It follows that the average momentum per particle must be higher. If the perpendicular component of the momentum is not to exceed a threshold, then the momentum vectors of the particles must be more closely aligned, that is, they must bend closer to the jet axis.

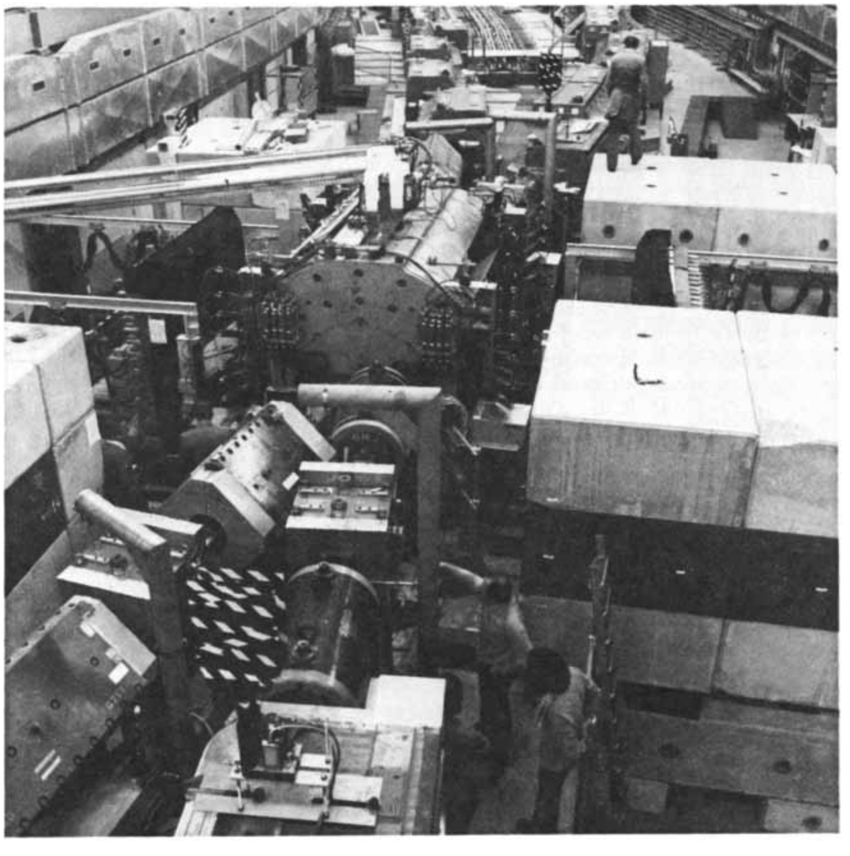
As it turns out, the average perpendicular momentum of the particles in a jet remains limited to about .3 GeV regardless of the total jet momentum. Although such a limit may seem mysteriously arbitrary, there is a plausible explanation for it: the perpendicular component of the momentum and the component parallel to the jet axis originate in different processes, which are largely independent of each other. The small, perpendicular component apparently results from interactions whose characteristic scale of length is comparable to the size of the hadron as a whole. The larger parallel component is associated with direct interactions of the pointlike quarks. This distinction becomes clearer in jets produced by proton-proton collisions, where both the quarks and the hadrons are present from the start.

So far we have been concerned mainly with experiments in which hadrons are bombarded by leptons or in which hadrons are created by the annihilation of leptons. It stands to reason that the quark structure of the hadrons should also be evident when the colliding particles are themselves hadrons. A jet of particles emerging from such a collision with high momentum transverse to the beam axis would then signal a direct, close-range interaction of two quarks. The most obvious interpretation of such events is that one constituent is expelled from each proton and subsequently gives rise to a jet of hadrons.

Precisely because hadrons have an internal structure, proton-proton experiments are more difficult to carry out and more difficult to interpret than experiments with leptons. When an electron is employed as a probe of the structure of the proton, at least the projectile is simple, apparently pointlike and well understood. A precise theory, quantum electrodynamics, describes its interactions. In proton-proton collisions both the probe and the target are complicated objects and the theory that describes them, quantum chromodynamics, is itself under test. In spite of these difficulties hadron jets in proton-proton collisions have been investigated in a long series of experiments over the past several years. In fixed-target experiments they have been studied with the large proton synchrotron at the Fermi National Accelerator Laboratory near Chicago. The most violent collisions have been observed with the ISR at CERN.

Given ideal apparatus an experiment with head-on proton collisions might not be too difficult. Detectors could be made to surround the interaction zone completely, so that every particle leaving the region would be intercepted. Every particle would be identified, including both the charged particles and the neutral ones, and their energy and momenta would be measured. What is more, every collision, no matter what its outcome, would be documented in this way, so that the interesting events could be picked out later for detailed analysis.

Real apparatus requires a number of compromises. The detector cannot encompass the entire solid angle surrounding the interaction zone and it cannot identify every particle, and so the reconstruction of events is often incomplete. Furthermore, it is not practical to record the outcome of every collision and to sort the results for interesting events after the fact. Even if the detector and the computers with which it communicates were capable of recording data at the necessary rate, years of labor would be required to sift the few hard-scattering events from the millions or billions of glancing collisions. Instead some criterion must be established for identifying a hard-scattering event as it happens. Then the detector is triggered only for those events that meet the criterion and



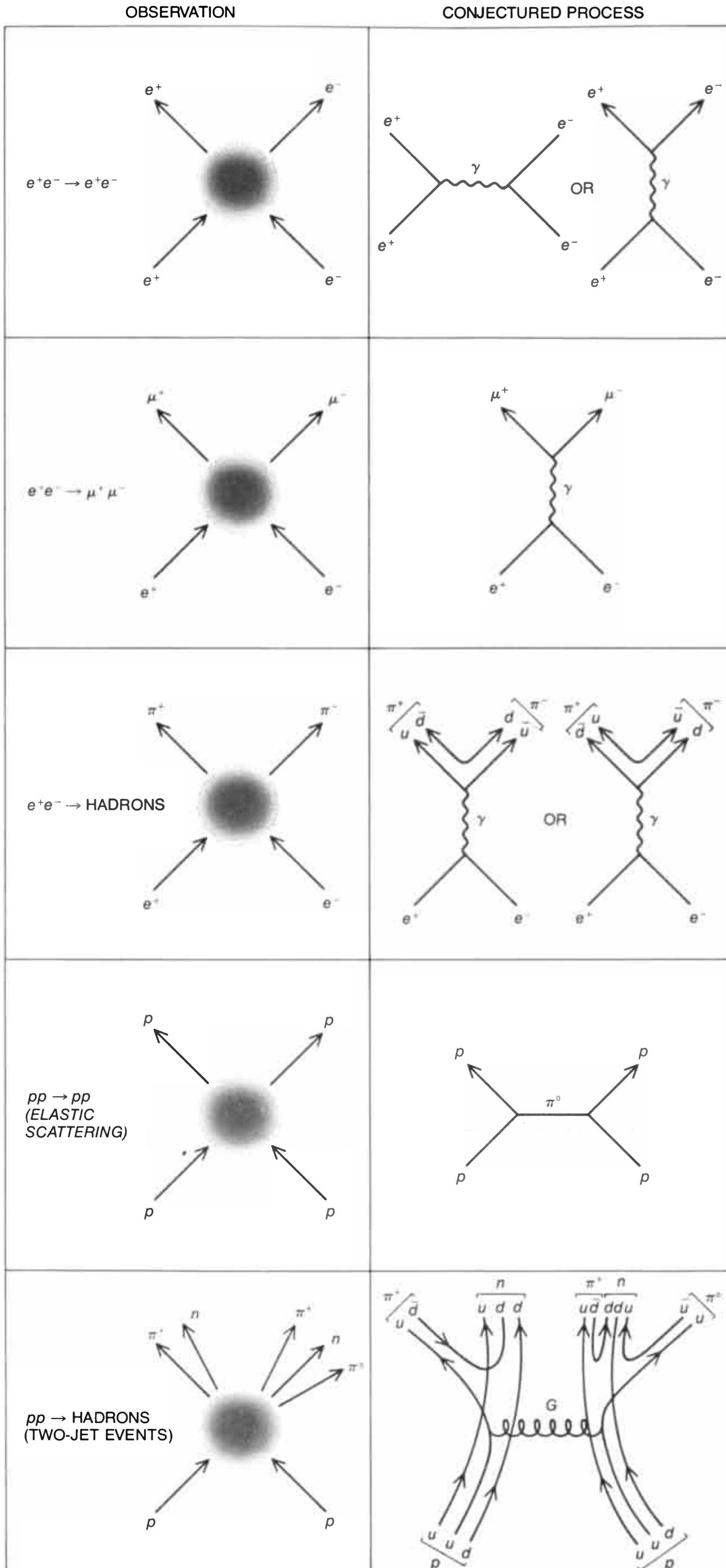
CROSSOVER ZONE at the ISR is instrumented with a large system of detectors for particles with high transverse momentum. The two proton beams circulate in pipes that are obscured by the magnets required to bend and focus the beams. The crossover itself is inside a larger magnet that makes up part of the detector system. The magnet bends the trajectories of the emitted particles so that their momentum can be measured. Electronic detectors bristle from the sides of the magnet and, at a greater distance, two large slabs of glass draped in black cloth serve as triggering detectors. Blocks of concrete and lead provide radiation shielding when the rings are operating. The experiment is being done by physicists from CERN and three universities.

all others are ignored. In most of the experiments conducted so far the triggering event has been the emergence of at least one particle with high momentum transverse to the beam axis. If the trigger threshold is set at 3.5 GeV, a few events per million are selected. Raising the threshold to 6 GeV reduces the fraction to a few per billion.

One drawback of such a triggering mechanism is that it rejects not only the glancing collisions but also a substantial number of head-on ones. If the threshold is set at 6 GeV, a jet with a total momentum of 6 GeV will be recorded only in the unlikely circumstance that all the momentum has been invested in a single particle. It is more likely that the momentum would be distributed among several particles (for example, three hadrons might have 2 GeV each), but none of these particles would be energetic enough to trigger the detector. The result is a bias in the data toward unusual events in which a single particle gets a major share of the total momentum.

Another form of trigger has recently been developed, first at Fermilab and then at CERN. It employs a type of detector called a calorimeter, which issues a triggering signal not when a single particle exceeds a certain momentum but when the total energy deposited in the calorimeter exceeds a preset value. By this means the rate at which acceptable events are recorded is increased by two or three orders of magnitude.

Although the study of jets is more



e^-	ELECTRON	n	NEUTRON
e^+	POSITRON	γ	PHOTON
$\mu^-\ \mu^+$	MUONS	$u\ d$	QUARKS
$\pi^-\ \pi^+\ \pi^0$	PIONS	$\bar{u}\ \bar{d}$	ANTIQUARKS
p	PROTON	G	GLUON

VIRTUAL PARTICLES serve as intermediaries between scattered quarks and other particles. Because virtual particles cannot survive long enough or travel far enough to be detected, their role must be deduced from the products of the interaction observed at long range. When an electron and a positron collide (*a*), they can merely bounce apart by exchanging a virtual photon. Alternatively the electron and the positron can annihilate each other, yielding a virtual photon that can then decay into a new electron-positron pair or into a positive and a negative muon (*b*). The virtual photon can also yield a quark and an antiquark (*c*), but unlike the electrons and the muons the quarks are never observed at long range. What are seen instead are pions or other hadrons; somehow the quark and the antiquark "dress" themselves in other quark-antiquark pairs. Collisions between protons are also mediated by virtual particles. If the collision is a glancing one (*d*), the exchanged particle might be a virtual pion. In hard-scattering events, however, the quarks themselves rather than the proton as a whole interact, and the quantum exchanged is called a gluon. Again pairs of quarks and antiquarks are created, giving rise to jets of hadrons (*e*). Symbols for the particles are identified in the key above.

straightforward in electron-positron annihilations than it is in hadron collisions, it is important that both kinds of experiment be carried out. In the first place there is great interest in cataloguing the similarities and differences between the jets produced by these very different reactions. The hadron collisions are of special interest because they provide a direct view of the interactions between quarks and gluons. For now the electron-positron storage rings yield jets of higher energy, but that lead should soon pass to experiments in which protons and antiprotons are brought into collision at energies roughly 10 times greater than those of the proton-proton collisions at the ISR.

Even after a high-transverse-momentum jet has been detected in the wake of a proton-proton collision it is not an easy matter to reconstruct the events that gave rise to the jet. The interaction itself is much more complicated than that of an electron and a positron. More particles are generally emitted: an average of about 16 at the highest energies employed with the ISR. The two jets do not necessarily appear back to back, even in the frame of reference defined by the center of mass of the two colliding protons. The reason is that the quarks are able to move almost independently inside the proton, and so a given quark does not carry a fixed, or even a predictable, fraction of the proton's total momentum.

The most disturbing influence on the interpretation of the proton-proton data is that the production of a transverse jet is not the only process going on in the collision. When an electron and a positron come together, the collision is either glancing or hard; when two protons collide, on the other hand, the collision can be both things at once! Glancing collisions are of course the commonest type. They result from interactions that involve only the diffuse, large-scale structure of the proton, and they give rise to particles whose momentum deviates little from that of the original, colliding particles. In other words, they give rise to longitudinal jets, which remain in close alignment with the beam axis. Hard-scattering events are thought to result from the direct collision of a quark in one proton with a quark in the other proton; a gluon may also collide with another gluon or with a quark. When quarks or gluons collide, however, the more diffuse parts of the protons still interact. As a result the transverse jets appear in addition to the longitudinal ones rather than instead of them. It is not always easy to decide which process gave rise to a given scattered particle.

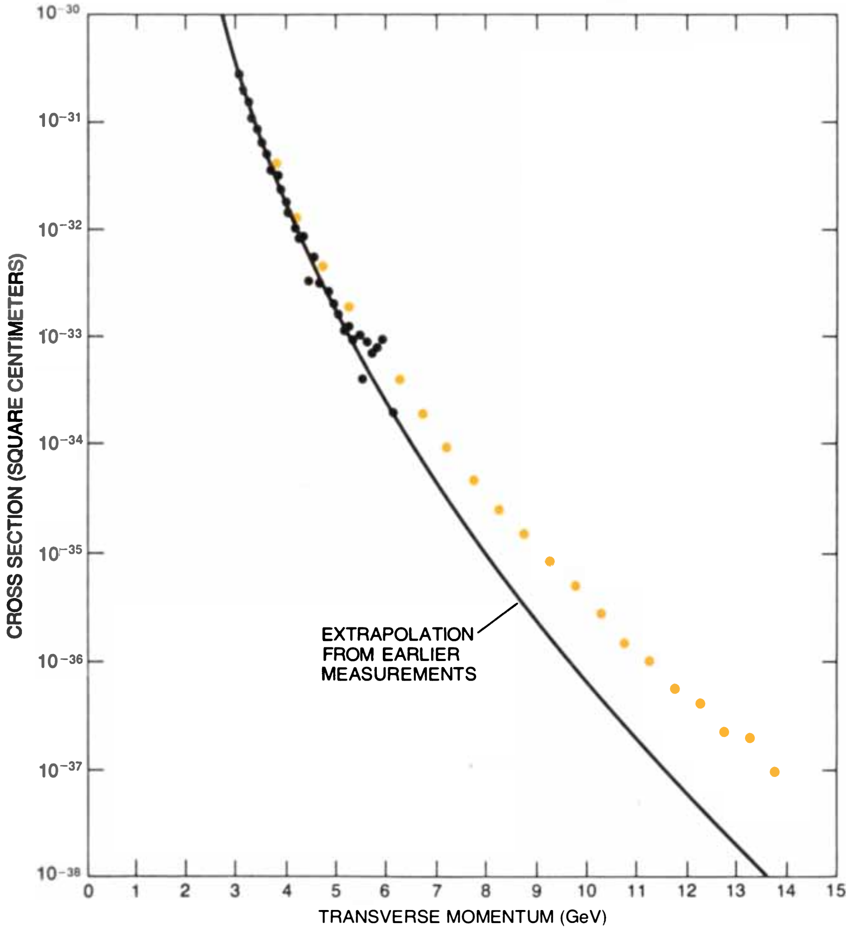
At the lower collision energies and the lower transverse momenta prevalent until a few years ago, the existence of jets could be demonstrated only by a statistical technique: by analyzing the correlations of hadrons appearing on opposite sides of the beam axis. With higher energies and with detector triggers set at higher momenta the analysis has become much simpler. It is possible to see a jet merely by looking at a diagram of the event. There is certainly no longer any doubt that transverse jets exist, both in electron-positron annihilations and in proton-proton collisions.

Analysis of the transverse jets observed at the ISR suggests that quark collisions have a number of similarities to lepton collisions. For the particles that make up the transverse jets (but not for those in the longitudinal jets) the allocation of momentum to components parallel to the jet axis and perpendicular to it is similar in lepton and in proton collisions. This finding suggests that the process whereby separated quarks dress themselves in quark-antiquark pairs may be the same in the two kinds of experiment. Further work will be needed, however, to confirm this conjecture.

The findings of the several experimental groups at the ISR have already provided strong evidence supporting a much earlier conjecture, called Feynman scaling (after Richard Feynman). The scaling hypothesis holds that on the average each hadron in a transverse jet should carry a fixed proportion of the total jet momentum (rather than a fixed quantity of momentum) as the total jet momentum increases. Thus the basic form of the jet and the way it breaks up into fragments should not vary with the momentum.

Now that hadron jets are well established, it is the nature of the constituents that give rise to the jets and the theory needed to describe those constituents that have become the focus of interest and controversy. Among theorists there is some disagreement over whether the results of the proton-proton experiments are in accord with the predictions of quantum chromodynamics.

It seems fair to say that the events seen so far are not in exact agreement with any detailed calculations that can be

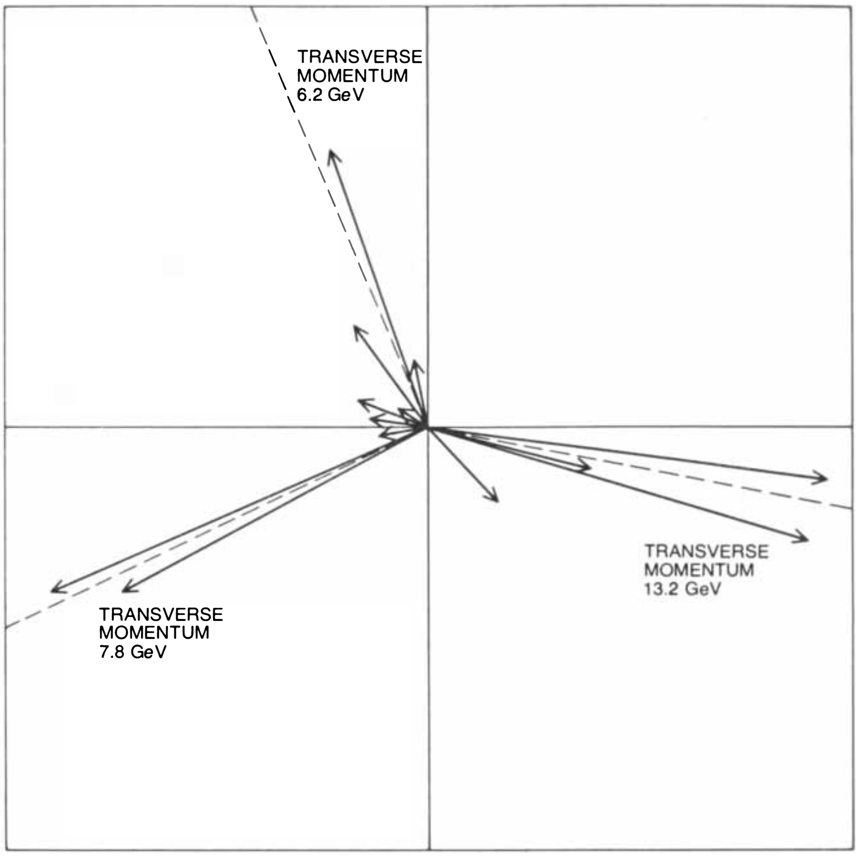


ENHANCED PRODUCTION of high-transverse-momentum particles has been found in recent experiments at the ISR to continue increasing at still larger values of transverse momentum. The earlier results are shown in black; the new data, in color, depart significantly from the rate of production extrapolated from the measurements at lower transverse momentum. The further anomaly could indicate that hard-scattering of quarks and gluons has become the dominant component of the proton-proton interaction. The data were recorded with the detector shown on page 72. The effect has been observed by two other groups working at the ISR.

done today in quantum chromodynamics. The discrepancy may result, however, not from a defect in the theory but from the limitations of available mathematical procedures. The strong forces that operate between quarks make it difficult to calculate exactly the behavior of a quark in many circumstances, even though that behavior is determined in principle by the theory. Detailed calculations are practical only in the special case of quarks that are very close together, where the color forces become weak. Collisions in which jets are emitted with high transverse momentum probe the quark structure at close range, but it remains to be seen whether the range achieved so far is small enough to be described by the theory.

In essence the experimental results observed up to now are more complicated than would be expected for the simplest possible interactions of point-like constituents. Some theorists think nonetheless that the events represent collisions of individual quarks and gluons and that the form of the jets will become simpler when events are observed at higher transverse momentum. Other theorists have suggested that the departures from theory have a more fundamental cause and that the jets observed so far reflect interactions of some more extended structures inside the proton, such as a bound system of a quark and an antiquark.

Where the two factions are in agreement is in their confidence that the form of the jets will become simpler at higher transverse momentum. Hints of such a simplification have already been observed in recent proton-proton experiments at the ISR, where the maximum transverse momentum has been pushed up to almost 14 GeV. For pions of the highest transverse momentum (greater than 6 GeV) the production rate was found to be enhanced slightly over the rate extrapolated from earlier results. This finding is consistent with the theoretical model in which the scattering of individual quarks and gluons obeys quantum chromodynamics in its simplest form.



THREE-JET EVENT was observed in electron-positron collisions at the PETRA storage ring near Hamburg. Two of the jets consist of five detected particles; the third has six tracks. Broken lines indicate the axes of the jets, defined by the average momentum of the detected particles. Like the two-jet events, the trijets are thought to originate with the creation of a quark and an antiquark. One of these particles then emits a real gluon, which decays to yield another quark-antiquark pair and hence another jet of hadrons. The event was recorded by physicists operating the TASSO detector; other groups at PETRA have also observed trijets.

The ultimate test of quantum chromodynamics will require experiments with jets of still higher transverse momentum; producing those jets will in turn require particle beams of still higher energy. New storage rings being planned or built now will provide the more energetic beams. At both CERN and Fermilab plans have been made to store counter-rotating beams of protons and antiprotons, with energies of from 250 GeV to 1,000 GeV, in large synchrotrons. A set of interlaced rings for proton-proton collisions, similar to the ISR in design but larger in scale, is under construction at the Brookhaven National Laboratory; it will have a maximum center-of-mass energy of 800 GeV, more than 10 times that of the ISR. A still grander project being considered in Europe is an electron-positron storage ring, to be called LEP, with a circumference of some 30 kilometers and a maximum center-of-mass energy of about 200 GeV.

In the meantime the PETRA storage ring commissioned last year at the DESY center has turned up the first few specimens of a new kind of hadron jet. Four groups of experimenters at PETRA, each working independently and with a different system of detectors, have observed electron-positron annihilations that give rise to three jets instead of the usual two. Quantum chromodynamics offers a possible explanation of such trijets. As in other lepton-induced events, a virtual photon decays to yield a quark and an antiquark, but one of these particles reduces its energy by spontaneously emitting a real gluon. The three particles then continue to separate, and each of them acquires its own escort of quarks and antiquarks, eventually forming a jet of hadrons.

In the 1950's the hope was that higher energy would make the physics of strong interactions simple. All the complicating effects that can now be attributed to the finite size of the hadrons would fall away, and the strong force would be as easily comprehended as electromagnetism. In terms of the objectives of the 1950's higher energy is here now, but the great simplification has not arrived in the way that was expected. It is only in those collisions where a large quantity of momentum is transferred from one particle to another that simplicity has emerged. These are also the collisions in which the structure of matter is probed at the smallest distances. Further progress will require still higher energies.

In the pursuit of this receding horizon, however, much has already been learned about the interactions, however complicated they may be, observed at energies accessible today. A new level in the structure of matter has been discovered. Hadron jets, together with other phenomena, have made us rich in experimental data. Quantum chromodynamics, even if it is only a theory in the making, has added a wealth of testable predictions. Enthusiasm runs high at the prospect that the two lines of work may soon converge.