The Search for Intermediate Vector Bosons

In theory these massive elementary particles are required to serve as the carriers of the weak nuclear force. They should be detected soon in the aftermath of collisions between protons and antiprotons

by David B. Cline, Carlo Rubbia and Simon van der Meer

One of the major achievements of modern physics has been the development over the past 15 years or so of a new class of unified theories to describe the forces acting between elementary particles. Until these theories were introduced the four observable forces of nature seemed to be quite independent of one another. The electromagnetic force governs the interactions of electrically charged particles; the weak nuclear force is responsible for such processes as the beta decay of a radioactive atomic nucleus; the strong nuclear force holds the nucleus together, and gravity holds the universe together. The most successful of the new theories establishes a link between electromagnetism and the weak force, suggesting that they are merely different manifestations of a single underlying force.

The unified electroweak theory is about to be put to a decisive experimental test. A crucial prediction of the theory is the existence of three massive particles called intermediate vector bosons (also known as weakons). The world's first particle accelerator with enough energy to create such particles has recently been completed at the European Organization for Nuclear Research (CERN) in Geneva. The accelerator was originally built to drive high-energy protons against a fixed target, but it has now been converted to a new mode of operation, in which protons and antiprotons collide head on. The colliding-beam machine has just completed its preliminary runs and is scheduled to resume operating next month with an elaborate new particle-detection system in place. If the intermediate vector bosons exist and if they have the properties attributed to them by the electroweak theory, they should be detected soon. They are currently the most prized trophies in all physics, and their discovery would culminate a search that began more than 40 years ago.

According to the prevailing view of the interactions of elementary particles, a force is transmitted between two particles by the exchange of a third, intermediary particle. Such a description is the essence of a quantum field theory. The idea of a field extending throughout space is needed to explain how particles can act on one another at a distance; it is a quantum field because it is embodied in discrete units, namely the intermediary particles. In electromagnetic and weak interactions the exchanged particle is a member of the family called the vector bosons. This term refers to a classification of particles according to one of their most basic properties: spin angular momentum. A boson (named for the Indian physicist S. N. Bose) is a particle whose spin, when measured in fundamental units, is an integer, such as 0, 1 or 2. "Vector" designates a boson whose spin value is equal to 1.

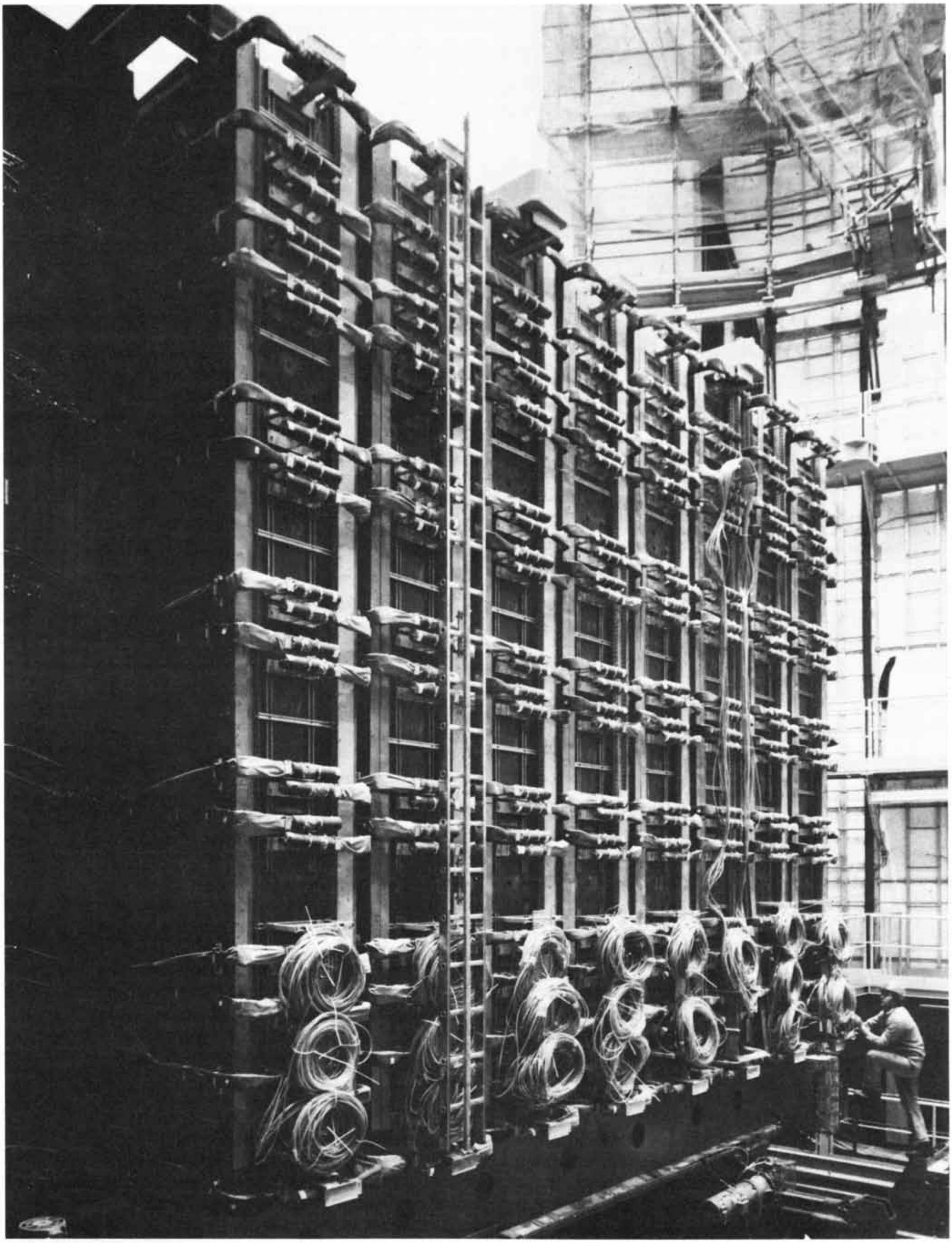
In the case of electromagnetism the exchanged vector boson is the photon, the massless and chargeless "wave packet" of electromagnetic energy that functions as the quantum of the electromagnetic field. Photons are easy to observe experimentally (in the form of light, for example), and from the study of their properties physicists have constructed the remarkably precise and comprehensive theory called quantum electrodynamics, or QED, which is the quantum field theory of the electromagnetic force.

The corresponding force carrier in weak interactions is the intermediate vector boson (intermediate simply because of its mediating role between particles). The existence of such a particle was first suggested in 1935 by the Japanese physicist Hideki Yukawa, who at the time was seeking a unified explanation of the two newly discovered nuclear forces: the strong and the weak. Yukawa noted that the range of a force should be inversely proportional to the mass of the particle that transmits it. For example, the range of the electromagnetic force is infinite, in accord with the masslessness of the photon. On the other hand, the two nuclear forces have only a limited range, and so Yukawa suggested they should be carried by particles with mass.

Specifically, Yukawa postulated the existence of a moderately heavy particle, later named the meson, the exchange of which gives rise to the strong attractive force between the proton and the neutron. The first particle of this type to be correctly identified, the pi meson (or pion), was discovered in 1947 in the shower of secondary particles generated by the collision of a cosmic-ray particle with an atom in the atmosphere; large numbers of mesons can now be made at will with particle accelerators.

The particles of the nucleus, including the mesons, are now thought to be composed of the more fundamental constituents known as quarks. The quarks are bound together by the strong force, but in this context the force has a form quite different from the one observed between protons and neutrons. The force between quarks is thought to be transmitted by the family of eight massless vector bosons called gluons. A property with the arbitrary name "color" is assigned to the quarks and the gluons and plays the same role in strong interactions as electric charge does in electromagnetic interactions. In recognition of this analogy the quantum field theory of the strong force is called quantum chromodynamics, or QCD.

The weak nuclear force has a still shorter range than the strong force that acts between protons and neutrons. The intermediate vector bosons of the weak force can therefore be expected to have a mass larger than that of the pi meson. Early attempts to detect the intermediary particles associated with the weak force were unsuccessful, presumably because the bosons' larger mass put them out of reach of the existing particle accelerators. Until the advent of the uni-

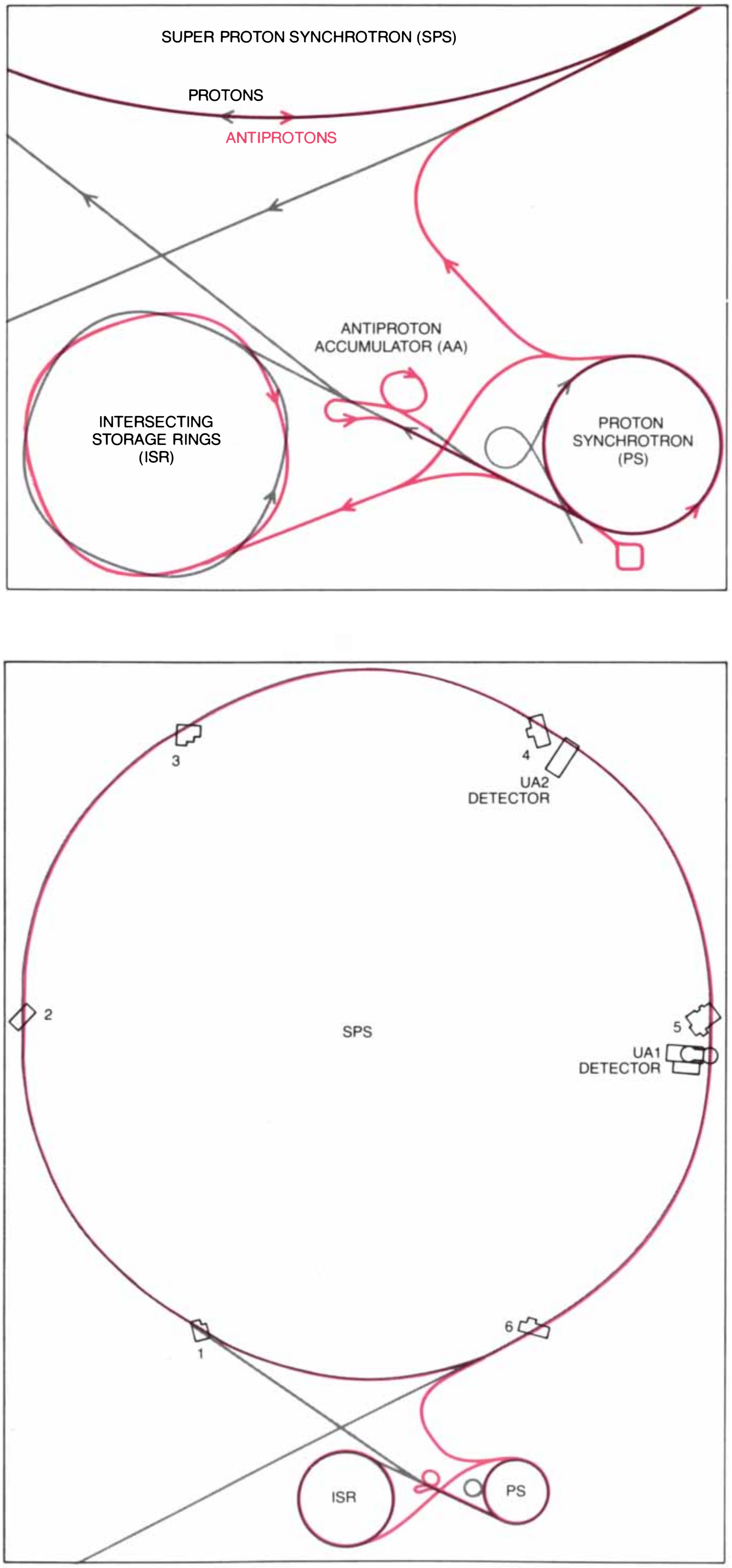


NEW PARTICLE DETECTOR at the European Organization for Nuclear Research (CERN) in Geneva was designed and built by a team of more than 100 physicists from 11 institutions in Europe and the U.S. The first observation of an intermediate vector boson is expected to be made with the aid of this device. The large, multipurpose detector, named the UA1 (for Underground Area One), is seen here in its "garage" adjacent to the largest particle accelerator at the CERN site: the Super Proton Synchrotron (SPS), which was recently converted into a proton-antiproton colliding-beam machine. When the detector is ready for operation, it is rolled to the left on rails into the path of the colliding beams. Electronic equipment covers the outside of the apparatus, obscuring the central detection chambers.

fied electroweak theory in the late 1960's and early 1970's, however, there was no good estimate of the mass of the weak-force particles.

The electroweak theory was developed independently by Steven Weinberg of Harvard University and Abdus Salam of the International Center for Theoretical Physics in Trieste, with major contributions by Sheldon Lee Glashow of Harvard and others. The theory, which can now be considered the "standard" account of electromagnetic and weak interactions, for the first time made specific and testable predictions about the properties of the intermediate vector bosons, including their mass. Furthermore, the theory required that there be three such particles, with electric charges of +1 (the W^+), −1 (the W^-) and zero (the Z^0). The best present estimate of the mass of the intermediate vector bosons, expressed in terms of their equivalent energy, is 79.5 GeV for the W^+ and W^- and 90 GeV for the Z^0. (The abbreviation GeV stands for giga-electron volts, or billions of electron volts; for comparison the mass of the proton is equivalent to a little less than one GeV.)

The idea at the heart of the standard theory is that electromagnetism and the weak force both stem from a single and more fundamental property of nature. At exceedingly high energy (high enough for W and Z particles to be made as readily as photons) events mediated by the two forces would be indistinguishable. This theoretical unification is accomplished by assigning the photon and the intermediate vector bosons to the same family of four particles. At energies accessible today there is no question that electromagnetic events are quite different from weak ones; more-



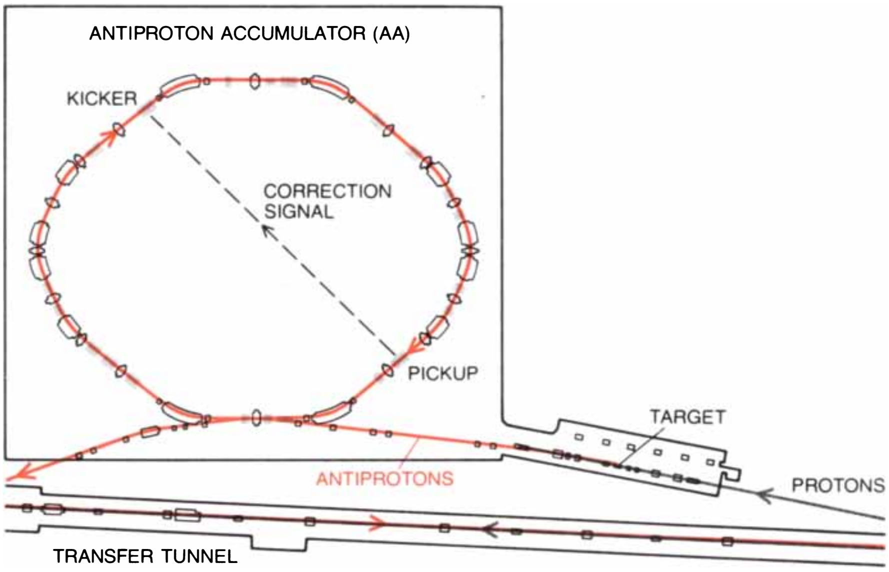
COUNTERROTATING BEAMS of protons and antiprotons are generated at CERN as the end products of a sequence of events in several interconnected accelerator rings. First a beam of protons (*gray*) is accelerated to an energy of 26 GeV (billion electron volts) in the Proton Synchrotron (PS). The protons are then directed at a metal target, producing (among other things) a few antiprotons with an energy of 3.5 GeV. The antiprotons (*color*) are collected and transferred to the Antiproton Accumulator (AA), where they are combined with previously injected antiprotons and concentrated in dense "bunches" numbering several hundred billion particles each. The antiproton bunches are next sent back to the PS ring, where they are accelerated to 26 GeV. The 26-GeV antiprotons are injected into the SPS ring, where protons of the same energy are already circulating in the opposite direction. The two beams are finally accelerated to 270 GeV each in the larger ring. The overall site plan (*bottom*) shows the location of the new particle detectors, which are placed in two long straight sections of the SPS ring where the counterrotating beams are brought into collision. The other rings shown are used for a variety of other experiments.

over, the photon and the *W* and *Z* particles seem to be unlikely siblings, since the first is massless and the other three are among the heaviest particles supposed to exist. The discrepancy is explained in the standard theory by the notion of a broken symmetry, which distinguishes between the forces as the energy is lowered in much the same way as a substance separates into different phases as the temperature is lowered.

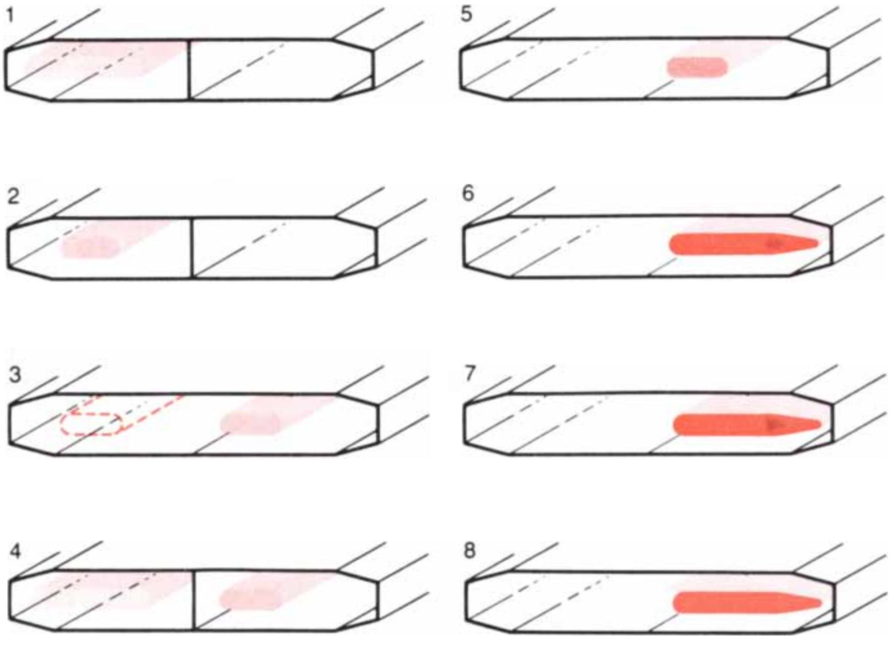
One approach to understanding the unified electroweak theory begins with an imaginary primordial state in which the photon and the intermediate vector bosons were all equally massless. It was the breaking of a symmetry of nature that endowed the W^+, the W^- and the Z^0 with large masses while leaving the photon massless. A mechanism for discriminating in this way among the carriers of the forces was first discussed in 1964 by Peter Higgs of the University of Edinburgh. Curiously, the Higgs mechanism is able to supply masses for the *W* and *Z* particles only by postulating still another massive particle, which has come to be called the Higgs boson. It is being sought along with the intermediate vector bosons.

The electroweak theory received important experimental support in 1973 from a discovery made at CERN and at the Fermi National Accelerator Laboratory (Fermilab) near Chicago. Up to then all known weak interactions of matter entailed an exchange of electric charge. For example, a proton might give up its charge of +1 to a neutrino (a massless particle with no charge). As a result the proton becomes a neutron and the neutrino is converted into a positron, or antielectron. All such events can be accounted for by the exchange of the charged intermediate vector bosons W^+ and W^-. The 1973 experiments revealed weak interactions in which the particles maintain the same charges they had before the event, as they do in electromagnetic interactions. A weak interaction of this type can be explained only by the exchange of a neutral intermediate vector boson (the Z^0 particle) or, in an equivalent description, by the operation of a neutral weak current [see "The Detection of Neutral Weak Currents," by David B. Cline, Alfred K. Mann and Carlo Rubbia; SCIENTIFIC AMERICAN, December, 1974]. In 1979 Weinberg, Salam and Glashow were awarded the Nobel prize in physics "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including . . . the prediction of the weak neutral current."

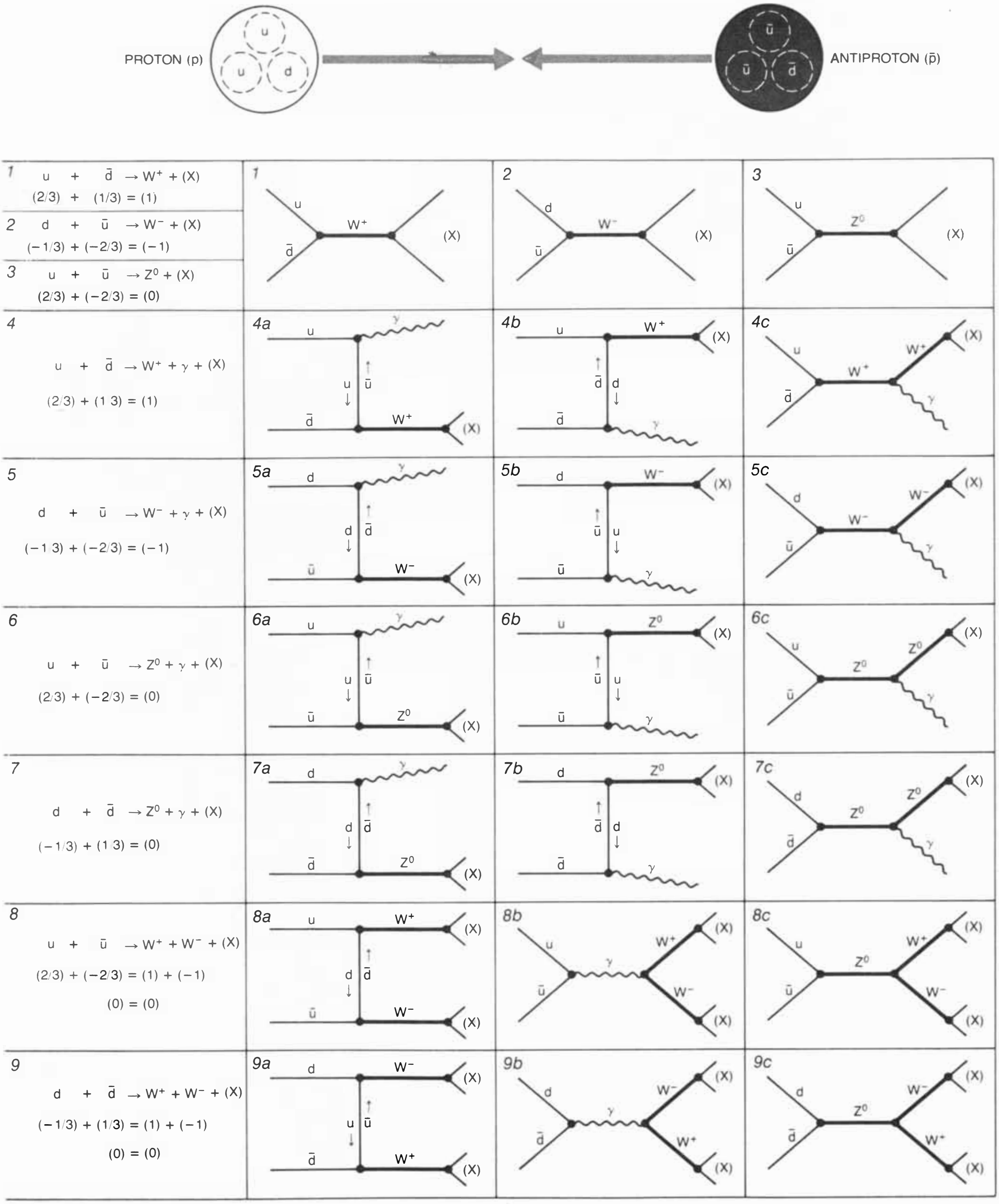
Once the existence of neutral weak currents had been fully confirmed it was only natural to try to find a way to detect the Z^0 as well as the W^+ and W^-. The task of creating particles with such a large mass, however, remained daunt-



ANTIPROTON ACCUMULATOR performs two functions essential to the CERN colliding-beam experiments: it "stacks" the successively injected bunches of antiprotons, and it "cools" them by a statistical process known as stochastic cooling. For cooling the ring incorporates a number of linked "pickup" and "kicker" devices (*gray shapes*) as well as the beam-bending and beam-focusing magnets (*white shapes*) found in any storage ring. In stochastic cooling a pickup at one section of the storage ring senses the average deviation of the particles from the ideal orbit; a correction signal is then sent across the ring to a kicker on the other side, arriving just in time to nudge the particles back toward the ideal orbit. One such link is indicated.



STACKING AND COOLING of antiprotons in the AA ring are illustrated in this sequence of cross-sectional diagrams. First a bunch of about 20 million antiprotons is injected into the ring and made to circulate on the outside of the wide-aperture vacuum chamber (*1*). During the injection this space is shielded from the rest of the chamber by a mechanically operated metal shutter. The injected particles are precooled by the stochastic method for two seconds, reducing their random motion by a factor of 10 in both the longitudinal and the transverse directions (*2*). The shutter is then lowered and the precooled antiprotons are magnetically shifted into the stack position in the main body of the chamber (*3*). The shutter is raised again and a second bunch of antiprotons is injected 2.4 seconds after the first one (*4*). The second bunch is subjected to the same procedure, ending up in the stack after being precooled (*5*). About an hour later, when 1,500 bunches have been injected and some 30 billion antiprotons have been precooled and stacked, a dense core begins to form in the stack (*6*). After 40 hours, when 60,000 bunches have been injected, approximately a trillion antiprotons are orbiting in the stack, most of them concentrated in the core (*7*). Magnetic fields are then actuated to extract the core, providing about 600 billion antiprotons for the colliding-beam experiments. The residue of some 400 billion antiprotons remains stacked in the AA ring and is available to start the formation of the next core (*8*). After another 24 hours the second core of 600 billion antiprotons will be cooled and ready for injection. In each case the inside of the ring is to the right.



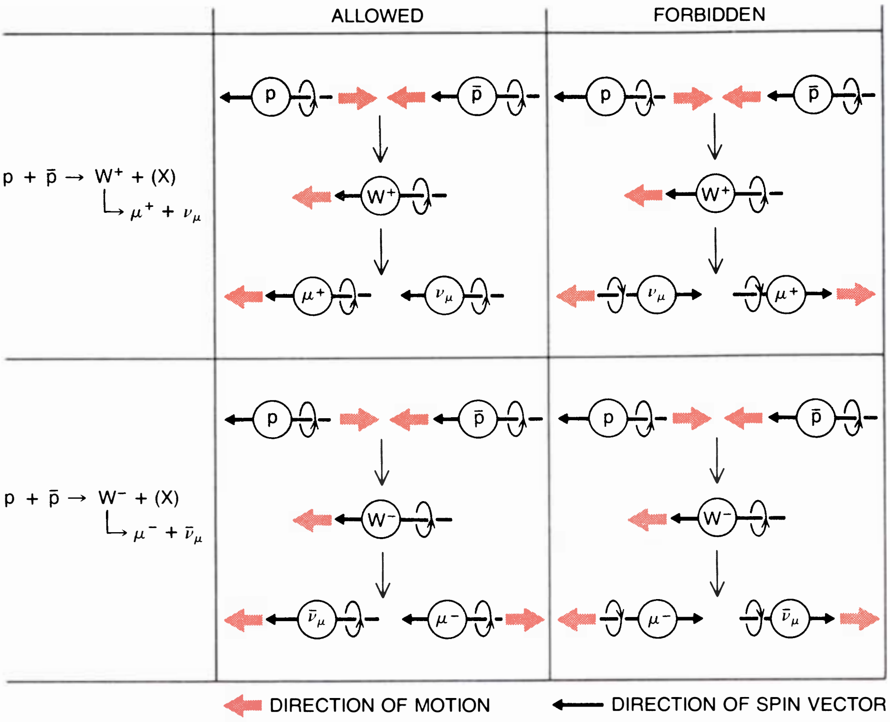
NEW PARTICLES are expected to appear in the aftermath of high-energy proton-antiproton collisions when a quark from the proton's structure interacts with an antiquark from the antiproton's structure. As the idealized drawing at the top indicates, the proton is presumed to consist of two "up" quarks (labeled u) and one "down" quark (d), whereas the antiproton has two "antiup" antiquarks ($\bar{u}$) and one "antidown" antiquark ($\bar{d}$). Quark-antiquark interactions that might contribute to the production of intermediate vector bosons are shown in symbols at the left and diagrammatically at the right. Three intermediate vector bosons are postulated: two charged particles (designated W^+ and W^-) and one electrically neutral particle (Z^0). All three are expected to be extremely short-lived and hence to be detectable only by virtue of their decay products, represented generically here by the symbol X. The first row shows the three most likely processes. The next four rows show processes in which intermediate vector bosons are created in association with energetic photons (γ). The last two rows show processes in which pairs of intermediate vector bosons are formed. (Where particles are shown moving in both directions along a vertical line the interaction can proceed by either mechanism.) The numbers in parentheses below the symbols at the left give the electric charge of each particle; the equations show that charge is conserved in all cases. Quarks are fractionally charged. Photons have no charge.

ing. The largest particle accelerators at the time were machines in which a single beam of protons is raised to high energy and then directed onto a fixed target. In the ensuing collision of a beam particle with a target particle most of the energy released goes into moving the two-particle system rather than demolishing it; only a small fraction of the beam energy is made available for the creation of new particles. The only chance of observing an intermediate vector boson, it seemed clear, would be in a colliding-beam machine, where the accelerated particles meet head on, transforming essentially all their energy into new particles.

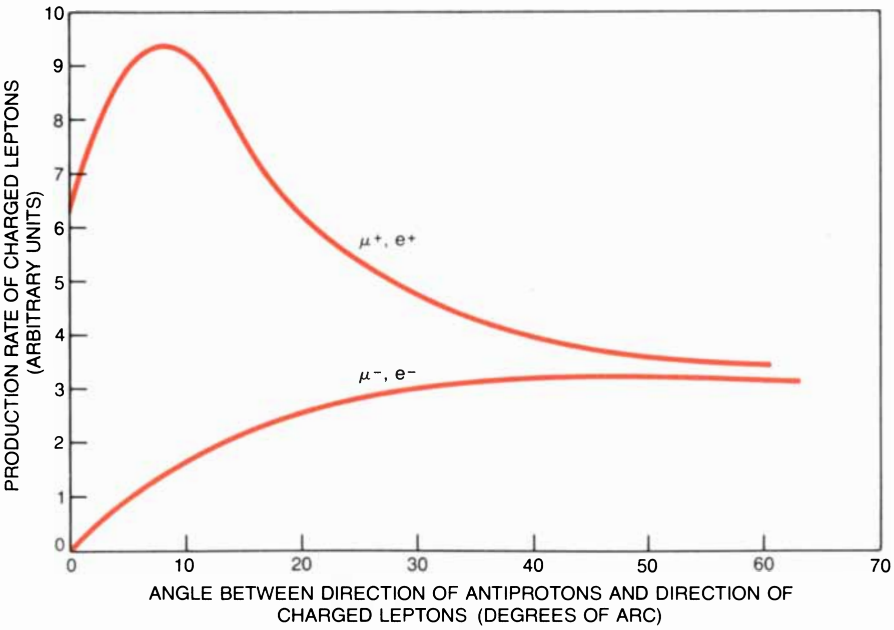
Storage rings for electrons and positrons had already been in operation for several years. The great advantage of employing electrons and positrons is that a single ring of magnets and radiofrequency cavities can simultaneously accelerate a particle and its antiparticle in opposite directions, so that counterrotating beams are formed in a single doughnut-shaped vacuum chamber. On the other hand, because electrons and positrons are very light they rapidly dissipate their energy when they are made to follow the curved path of the storage ring. It did not seem feasible then to build an electron-positron machine large enough to reach the energy of the intermediate vector bosons. The plan instead was to build storage rings in which protons would collide head on with other protons; two interlaced rings are needed to arrange such collisions. The first of these proton-proton machines were not scheduled to begin operating until the mid-1980's or later.

Then in 1976 two of us (Cline and Rubbia), together with Peter M. McIntyre, came up with an alternative idea. Instead of building an entirely new colliding-beam machine, we proposed, it would be feasible (and much cheaper) to convert an existing fixed-target proton accelerator into a colliding-beam machine by arranging to generate a counterrotating beam of antiprotons in the same annular space occupied by the original proton beam. Our suggestion was well received, and after a thorough review of the problems likely to be encountered in such a project it was decided to build proton-antiproton machines at two of the world's largest proton accelerators: the Super Proton Synchrotron (SPS) at CERN, which began operating at a peak energy of 400 GeV in 1976, and a more advanced version of a comparable machine at Fermilab that was then still in the planning stage.

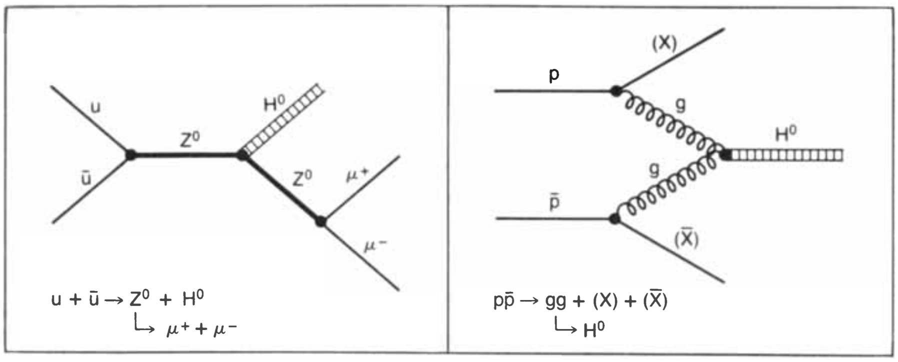
The CERN conversion was in many ways easier to accomplish, and it was completed by last summer, under the direction of Roy Billinge and one of us (van der Meer); the first proton-antiproton collisions at the designed peak energy of 270 GeV per beam were observed



DIRECTION OF SPIN of the particles involved in the production and decay of intermediate vector bosons has an important effect on the direction of motion of the decay products. The result is an asymmetry in the rate at which charged leptons are expected to be observed in different directions with respect to the incoming beams. (Leptons are particles such as electrons and muons that participate in weak interactions but not in strong ones.) For example, when a charged intermediate vector boson (W^+ or W^-) decays to form a muon (μ^+ or μ^-) and a muon-type neutrino (ν_μ or $\bar{\nu}_\mu$), most of the positively charged muons leave the collision in the direction of the incoming antiproton beam, whereas most of the negatively charged muons leave in the direction of the incoming proton beam (here left and right respectively). The observation of this effect, which is unique to interactions mediated by the weak force, would be taken as strong evidence for the fleeting existence of charged bosons among the decay products.



ASYMMETRY IS PREDICTED in the angular distribution of charged leptons emerging from proton-antiproton collisions in which charged intermediate vector bosons are created. Here the theoretical production rate of the charged leptons is given at various angles in relation to the direction of the antiproton beam. The effect is strongest in the forward direction (that is, at small angles with respect to the antiproton direction). Electrons (e^-) and positrons (e^+) as well as muons are expected to contribute to the effect, although the electrons and positrons interact with the materials of the detector more readily than muons do and hence are detected less frequently. The data points for the two curves were calculated for proton-antiproton collisions at a total energy of 2,000 GeV, the goal of the colliding-beam machine now under construction at the Fermi National Accelerator Laboratory (Fermilab) near Chicago.



HIGGS BOSON might also make its first appearance in the colliding-beam experiments at CERN or Fermilab. The discovery of this massive, uncharged particle (designated H^0) is considered the ultimate test of the "standard" unified theory linking electromagnetic interactions and weak interactions. Two processes that might lead to the production of Higgs bosons are illustrated. At the left a Higgs boson is created in association with a neutral intermediate vector boson. At the right a Higgs boson arises from the fusion of two gluons emitted during a grazing collision between a proton and an antiproton. (Gluons are the intermediary particles of the strong force that is thought to hold the quarks together inside the particles of the nucleus.)

in July. By late December, when the machine was shut down for the Christmas holiday, more than 250,000 such collisions had been recorded; because of the comparatively low rate at which intermediate vector bosons are expected to be produced in proton-antiproton collisions, however, it was not surprising that none were detected in these early runs. This situation is expected to change dramatically in the next round of experiments, in which the particle intensity of the beams, and hence the collision rate, will be increased by an order of magnitude or more.

The big proton-antiproton colliding-beam machine at Fermilab is still under construction and is scheduled to begin operating in 1985. Because it was originally designed to accelerate a single beam of protons to an energy of 1 TeV, or a trillion electron volts, it was named the Tevatron. In its reincarnation as a colliding-beam machine it is expected to be able to produce collisions with a total energy of 2 TeV (2,000 GeV), as opposed to 540 GeV for the CERN machine. When the Fermilab machine is completed, it will have the further distinction of being the first large accelerator to employ a ring of superconducting magnets.

How does one go about generating opposed beams of matter and antimatter in a storage ring? The hardest part in the two present instances is to accumulate a dense enough "bunch" of antiprotons to ensure a large number of collisions with the counterrotating protons. Unlike protons, antiprotons are not readily available from any natural source; they must themselves be created in high-energy collisions. A beam of high-energy protons is directed at a metal target, and antiprotons created in collisions with the target atoms are steered magnetically into a specially designed storage ring. The process is extremely inefficient; on the average one comparatively low-energy antiproton is produced for every million or so high-energy protons striking the target. To put this production rate in perspective, it has been calculated that in order to obtain a useful number of proton-antiproton collisions in the colliding-beam machine at CERN one must collect bunches of antiprotons (and protons) each made up of at least 100 billion particles. Successive bunches of antiprotons are collected and "stacked" every 2.4 seconds; at this rate it takes about 24 hours to accumulate a few hundred billion antiprotons for the colliding-beam experiments at CERN.

Creating enough antiparticles is not the only problem. As the antiprotons emerge from the target they have a range of velocities and directions. Viewed in their own frame of reference the antiprotons form a gas, and their random motions are indicative of a temperature. If the temperature is too high, some of the particles will strike the walls of the accelerator and the beam will be dissipated. Therefore some method is needed to "cool" the antiproton beam (that is, to reduce its random motions) in order to keep it as concentrated as possible before it enters the accelerator ring.

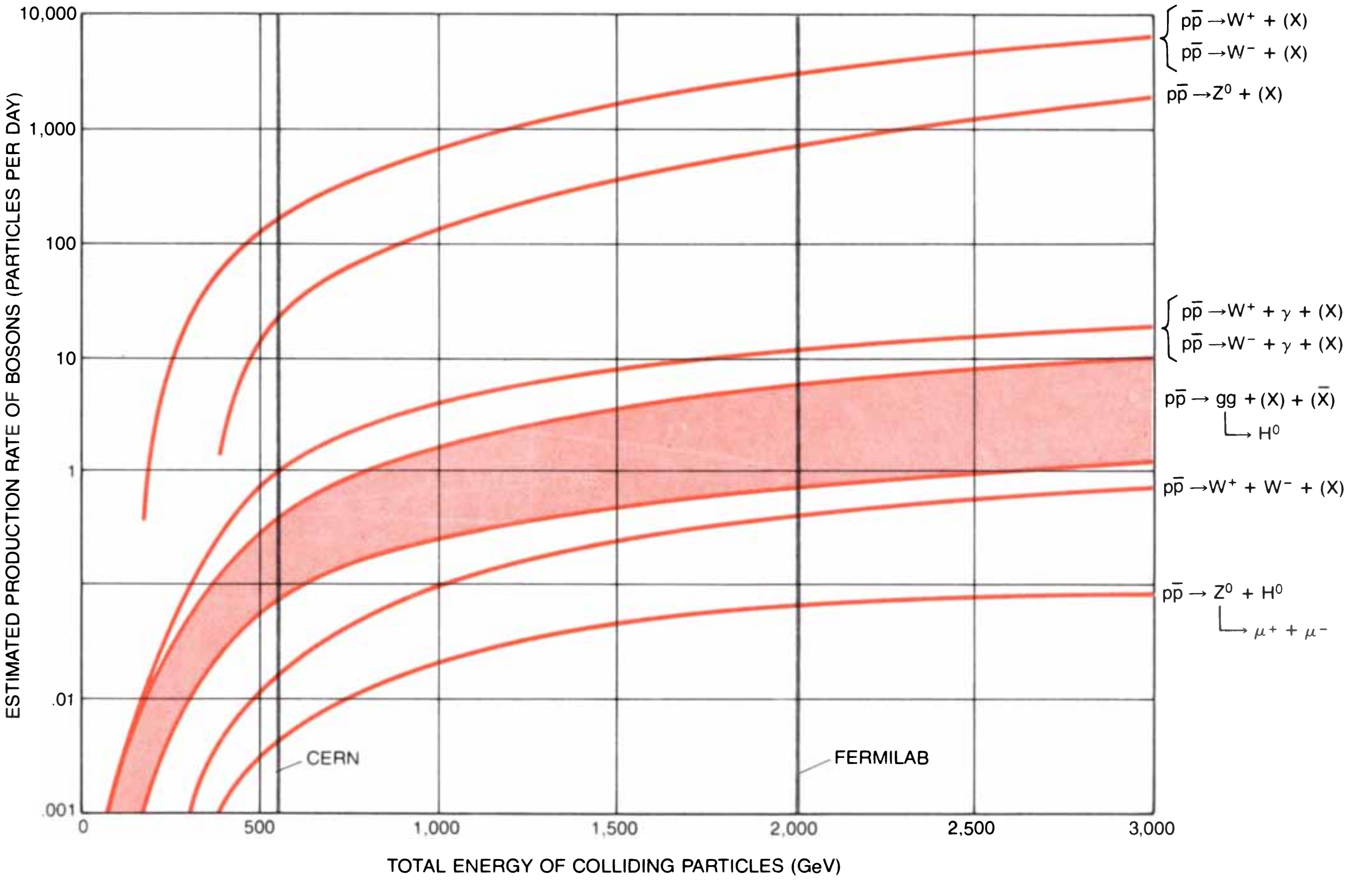
One such beam-cooling technique, called electron cooling, was first proposed more than a decade ago by Gersh I. Budker of the Institute of Nuclear Physics at Novosibirsk in the U.S.S.R. Basically it operates by mixing a "cool" beam of electrons (one in which all the particles have the same velocity and direction) with the "hot" antiproton beam for a short distance. In the process some of the random thermal energy of the antiprotons is transferred to the electrons. Mixing the antiproton beam repeatedly with fresh electron beams can cool the antiprotons significantly, provided their energy is not too high to start with. As it happens, the CERN scheme calls for an antiproton beam whose energy is initially too high to be cooled effectively by this method, and it is no longer being studied for this purpose. Electron cooling is still under consideration, however, for a role in the Fermilab project.

Another beam-cooling method, better suited to the requirements of the CERN proton-antiproton machine, was invented in 1968 by one of us (van der Meer). This method, called stochastic cooling (because it relies on a statistical process), utilizes a "pickup," or sensing device, in one section of a storage ring to measure the average deviation of the particles from the ideal orbit. The measurement is converted into a correction signal, which is relayed across the ring to a "kicker" device on the other side. The kicker applies an electric field to its section of the ring in time to nudge the center of mass of the passing particles back toward the ideal orbit. Although the particles move with nearly the speed of light, the correction signal can arrive in time because it takes the shorter path across a chord of the cooling ring.

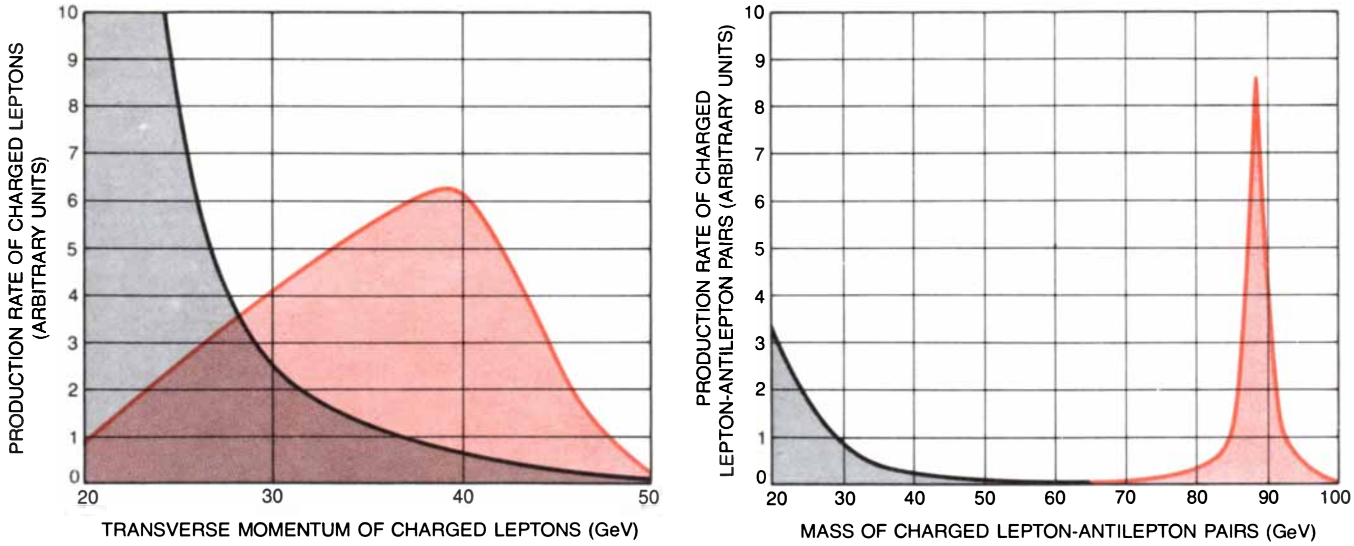
Both beam-cooling techniques have been tested successfully in the past few years at Novosibirsk, CERN and Fermilab. As a result there is every reason to believe full-scale antiproton collector rings such as the ones at CERN and Fermilab will work as planned. Beam cooling is becoming a routine part of accelerator technology.

For the experiments at CERN the particles are directed through a complex sequence of interconnected beam-manipulating devices. First a beam of protons is accelerated to an energy of 26 GeV in the Proton Synchrotron (PS), the original accelerator ring at CERN, completed in 1959. The proton beam is then directed at a copper target, producing a spray of particles, including a small number of antiprotons with an energy of 3.5 GeV. The antiprotons are collected and transferred to a wide-aperture storage ring called the Antiproton Accumulator (AA), where they are first precooled by the stochastic method and then moved to a slightly smaller orbit, where they are stacked with the previously injected bunches and subjected to further cooling. After a few hundred billion antiprotons have been collected they are sent back to the PS ring, where they are accelerated to 26 GeV before being injected into the SPS. Meanwhile protons at 26 GeV from the PS ring are injected into the SPS ring in the opposite direction. The counterrotating beams are finally accelerated to 270 GeV each in the SPS ring. The beams collide at two interaction sites, where the large particle detectors are placed [*see illustration on page 50*]. The interactions are so rare that the beam lifetime of several hours is not affected by them.

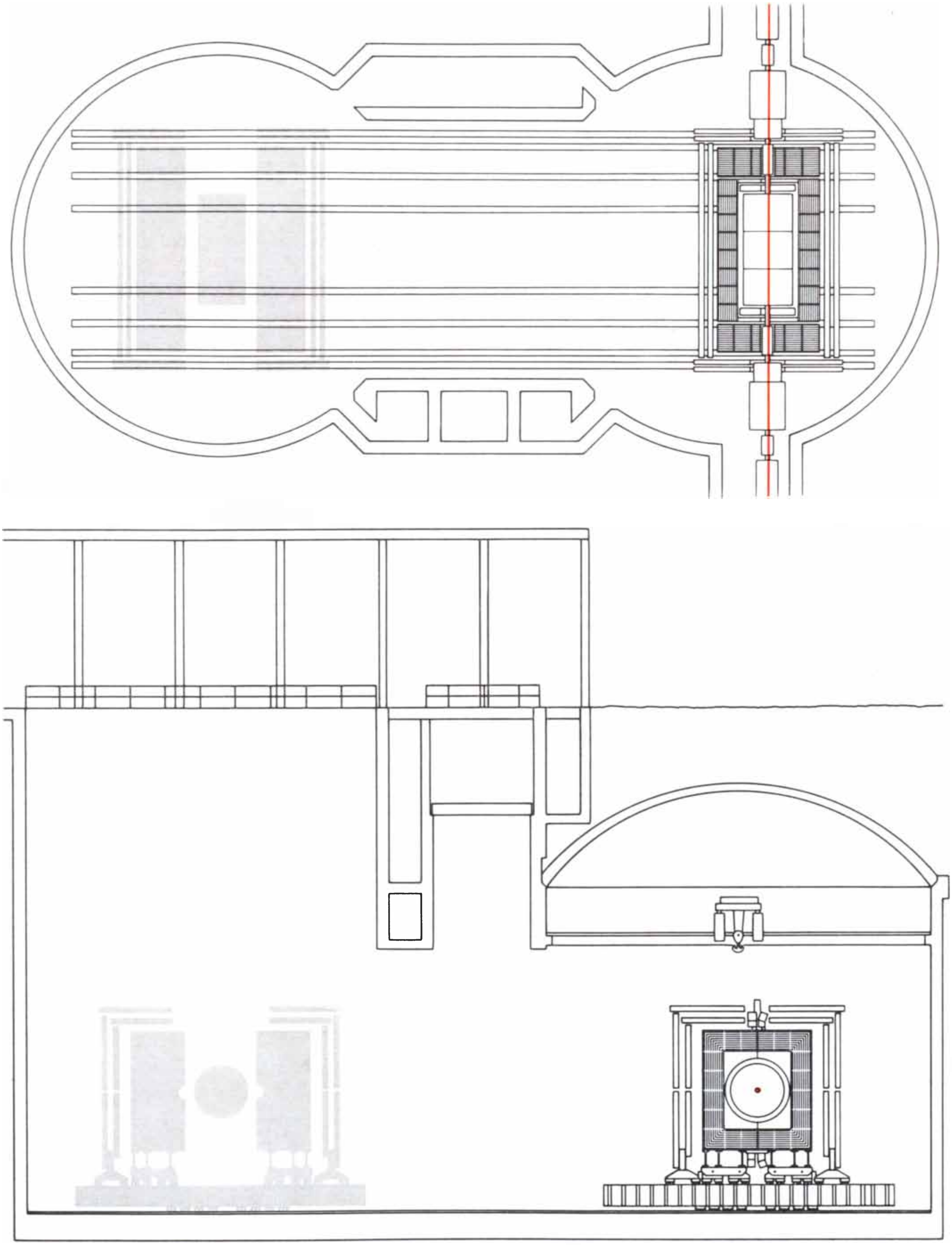
At present the Fermilab plan calls for



ESTIMATED PRODUCTION RATES of intermediate vector bosons and Higgs bosons by various collision processes vary as a function of the total energy of the colliding beams. The curves indicate the rate calculated for each process for one day of operation at the designed collision rate of the CERN and Fermilab colliding-beam machines. (The actual detected rate will be lower because of various experimental background effects.) The two vertical gray lines indicate the designed total energy of the proton-antiproton collisions at CERN and Fermilab. The processes that result in the production of a charged intermediate vector boson accompanied by an energetic photon are expected to serve as sensitive indicators of the magnetic properties of the W^+ and W^- particles. The process in which a Higgs boson is produced by the fusion of two gluons has a less predictable rate than the other processes and so is represented by a range of values.

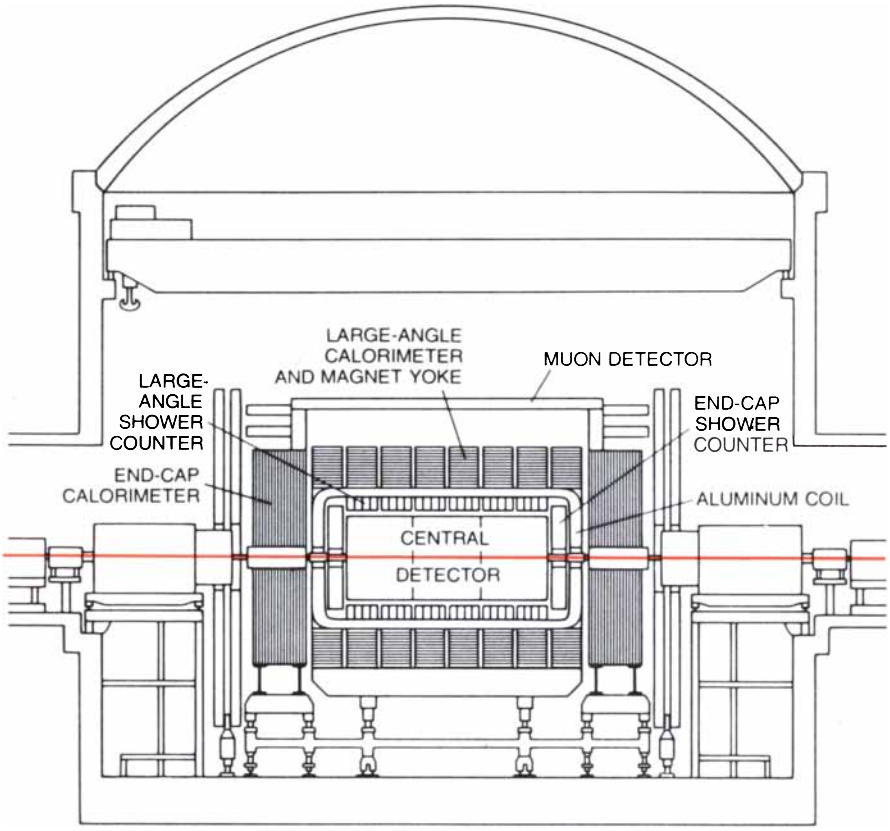


TELLTALE SIGNALS of the production of intermediate vector bosons (*color*) are expected to stand out above the background "noise" (*gray*), particularly at large angles with respect to the beam axis. The graph at the left shows the calculated mass spectrum of the charged leptons that would be emitted with a large transverse momentum from proton-antiproton collisions in which charged intermediate vector bosons are created. The peak in the signal is predicted to appear at about half the estimated mass of a charged intermediate vector boson. The background rate of leptons expected from other sources related to the collision process has no peak and is lower than the rate expected from the decay of the W^+ and W^- particles. The graph at the right shows the calculated mass spectrum for the decay of a neutral intermediate vector boson into a pair of charged leptons. The spectrum in this case has a peak near the predicted mass of the Z^0 particle (90 GeV). The negligible background noise makes this process the one in which the Z^0 is most likely to be discovered.



UA1 DETECTOR IS INSTALLED in a cavernous experimental area approximately 25 meters underground. In both the plan view (*upper diagram*) and the corresponding end view (*lower diagram*) the detector is drawn in black line when it is in its operating position straddling the beam pipe of the SPS and in gray tone when it is parked in its garage. The UA1 is by far the largest detector ever built for a colliding-beam experiment: it is 10 meters long by five meters wide and weighs 2,000 tons. It was built at a cost of roughly $20 million.

a more intense antiproton source than the one in operation at CERN. Protons with a higher energy will be used to make the antiprotons at Fermilab. Several alternative schemes are being investigated. One would rely on a combination of stochastic cooling and electron cooling to accumulate 100 billion antiprotons in less than an hour. The antiprotons would be injected into the Tevatron ring, accelerated to an energy of 1,000 GeV and made to collide with counterrotating 1,000-GeV protons in two experimental areas. The first area, where construction is scheduled to start soon, is designed to house a very large detector.



SIDE VIEW of the UA1 detector shows it in place in the SPS beam line. Experimental components for various purposes, including the search for intermediate vector bosons, are labeled.

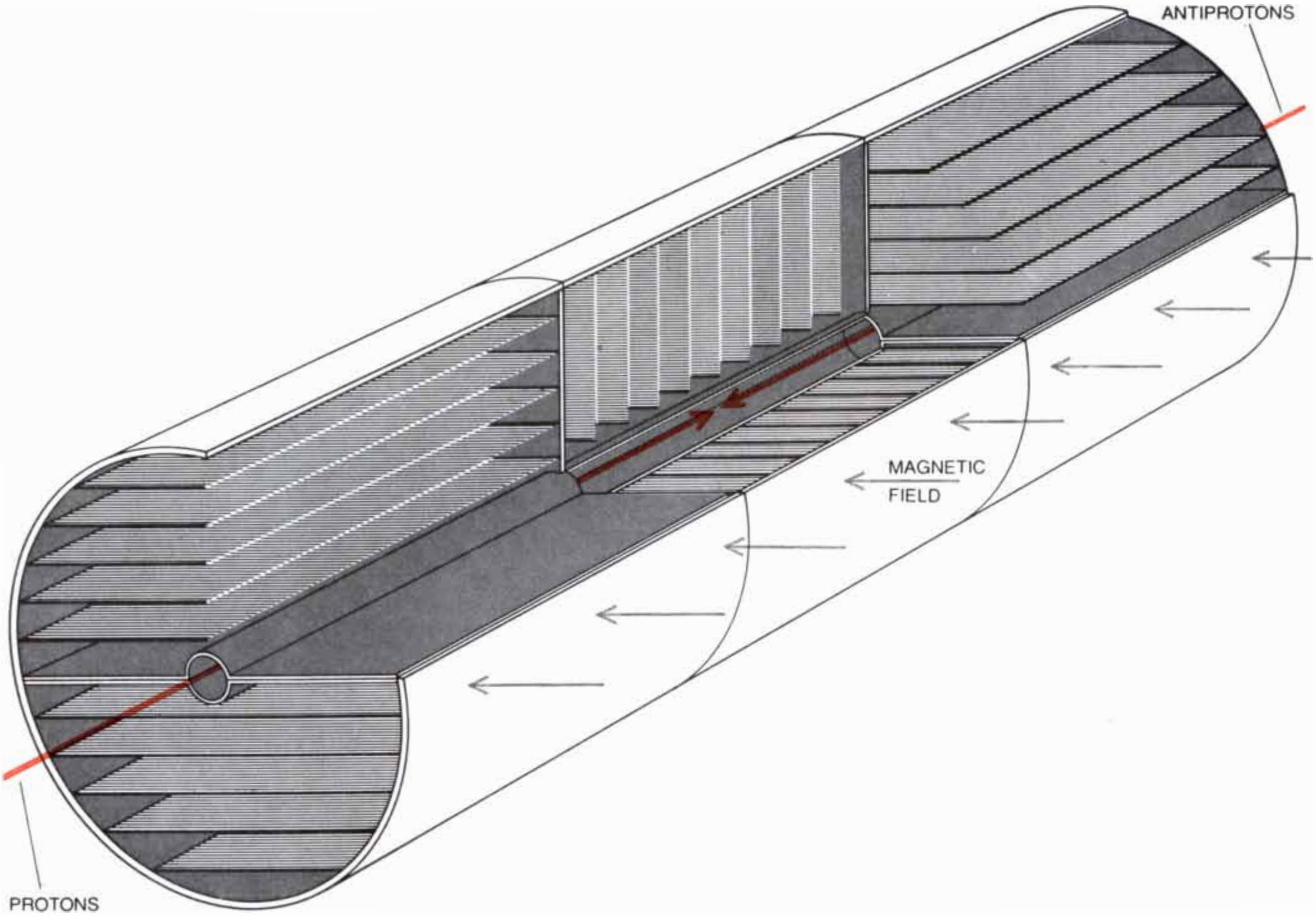
According to the electroweak theory, intermediate vector bosons can be created in proton-antiproton collisions by a variety of mechanisms in which a quark from the proton's structure interacts with an antiquark from the antiproton's structure. Both the proton and the antiproton are assumed to be made up of three constituent particles; in the whimsical nomenclature of the QCD theory the proton is said to harbor two "up" quarks (labeled *u*) and one "down" quark (*d*), whereas the antiproton has two "antiup" antiquarks ($\bar{u}$) and one "antidown" antiquark ($\bar{d}$). When a quark and an antiquark collide, they annihilate each other, creating a burst of energy that can rematerialize as new particles, including intermediate vector bosons. In some cases a single intermediate vector boson is expected to appear (accompanied by other kinds of particles); in other cases a pair of intermediate vector bosons is predicted [*see illustration on page 52*].

The expected production rate of W^+, W^- and Z^0 particles in proton-antiproton collisions varies as a function of an experimental parameter called the luminosity, which is defined as the number of high-energy particles per square centimeter per second passing through the cross section of the interaction region. The designed luminosity of the CERN machine, assuming the injection of 600 billion antiprotons per bunch, is 10^{30} particles per square centimeter per second. Given the same number of antiprotons per bunch, the Fermilab machine should attain a luminosity of 4×10^{30} particles per square centimeter per second (owing to its higher energy and hence smaller beam size). It can be calculated that at such luminosities the production rate of W^+, W^- and Z^0 particles, both singly and in pairs, should be high enough for them to be detected fairly often, perhaps as often as thousands of times per day [*see top illustration on page 55*]. Just before the CERN machine was shut down in December it briefly reached a luminosity of 10^{28} particles per square centimeter per second, putting it at the threshold of where one would expect to catch the first glimpse of an intermediate vector boson. (The initial operating experience with the CERN collider has also shown that proton-antiproton collisions could in principle be obtained at luminosities of 10^{31} particles per square centimeter per second or higher, provided enough antiprotons are available.)

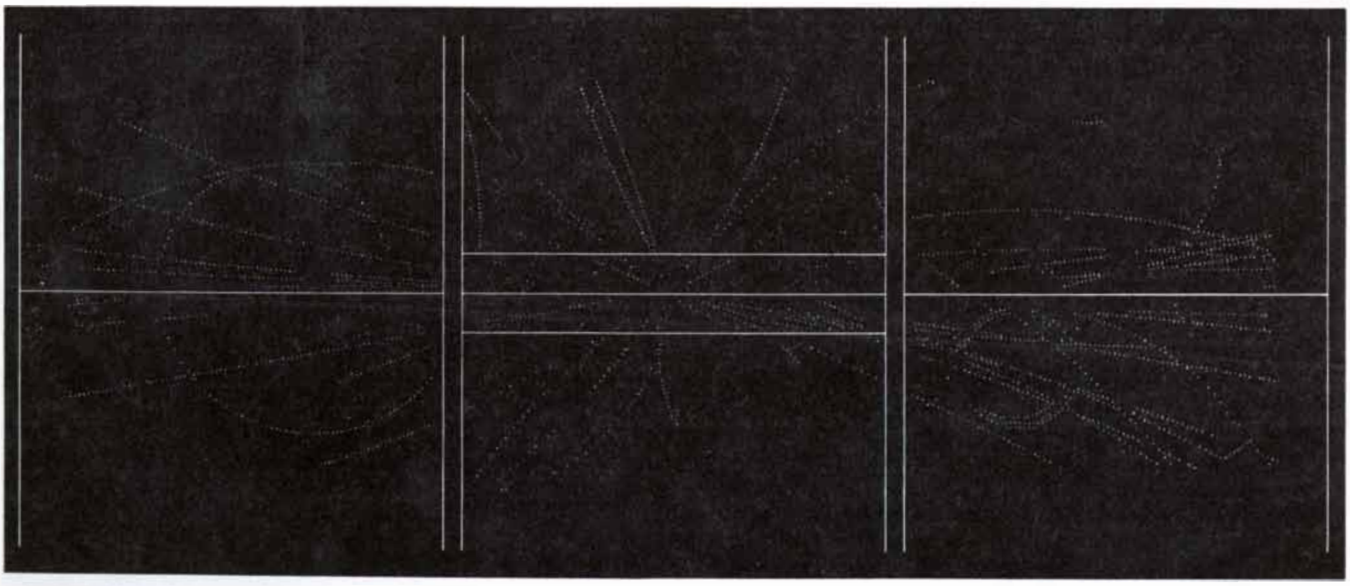
How will intermediate vector bosons produced in such collisions make their presence known? The lifetime of the particles is expected to be exceedingly short. In approximately 10^{-20} second they should decay spontaneously to form a variety of other particles, mainly quark-antiquark pairs and lepton-antilepton pairs. (Leptons are particles that respond to the weak nuclear force but not to the strong one.) Charged leptons such as electrons and muons can be detected by various means. In general the object is to detect the charged leptons from the decay of the intermediate vector bosons and to compare their production rate or other properties with the values expected from other causes arising in the collision process. The signal, in this case the angular distribution of leptons from the decay of W^+, W^- or Z^0 particles, is expected to stand out above the background "noise" of leptons from other sources, particularly at large angles with respect to the beam axis [*see bottom illustration on page 55*].

One unmistakable indication of the presence of intermediate vector bosons would be the appearance of a marked asymmetry in the rate at which leptons are detected in the forward and backward directions (measured arbitrarily with respect to the direction of the antiproton beam). Leptons that arise directly from strong or electromagnetic interactions of the beam particles should be completely symmetrical. According to the electroweak theory, however, decaying intermediate vector bosons should emit positively charged leptons predominantly in the forward direction and negatively charged ones predominantly in the backward direction. The expected lepton asymmetry, which is unique to events mediated by the weak force, results from the spins of the particles involved in the production and decay of intermediate vector bosons [*see illustrations on page 53*]. The observation of this effect will be taken as strong evidence that the long-sought intermediate vector bosons have finally been discovered. Their other properties can then be measured.

The ultimate test of the correctness of the electroweak theory would be the observation in the debris of proton-antiproton collisions of the Higgs boson. The discovery of this particle would demonstrate not only that electromagnetism and the weak force are unified but also that the unification is of the kind prescribed by the standard electroweak theory. A full discussion of



CENTRAL DETECTION SYSTEM of the UA1 consists of three cylindrical "drift" chambers, each containing an array of closely spaced wires and a gas at low pressure. In all three chambers the wires are strung horizontally. In the central chamber the horizontal wires are arranged in vertical planes; in the two flanking chambers they are arranged in horizontal planes. A charged particle passing through the chamber ionizes molecules of the gas, which then drift to the wires, depositing their charge. The pattern of charges appearing on many wires is recorded electrically and can later be analyzed by a computer to reconstruct the trajectory of the particle on the face of a cathode-ray tube. The chambers are approximately three meters in diameter. The wires are spaced about three millimeters apart.



VISUAL RECORD of a proton-antiproton collision that took place late last year in the central detection system of the UA1 was made by photographing a computer-generated display. The event is the same one that appears on the cover of this issue of SCIENTIFIC AMERICAN. More than 250,000 events of this type have been registered so far in the computer. Millions more will be recorded when the search for intermediate vector bosons resumes at CERN next month. The applied magnetic field bends the paths of the charged particles.

the experimental technique required to detect the Higgs boson is beyond the scope of this article. Proton-antiproton collisions could give rise to Higgs bosons, however, and the estimated rate of production is high enough for them to be discovered by means of their characteristic decay products in either the CERN or the Fermilab colliding-beam machines.

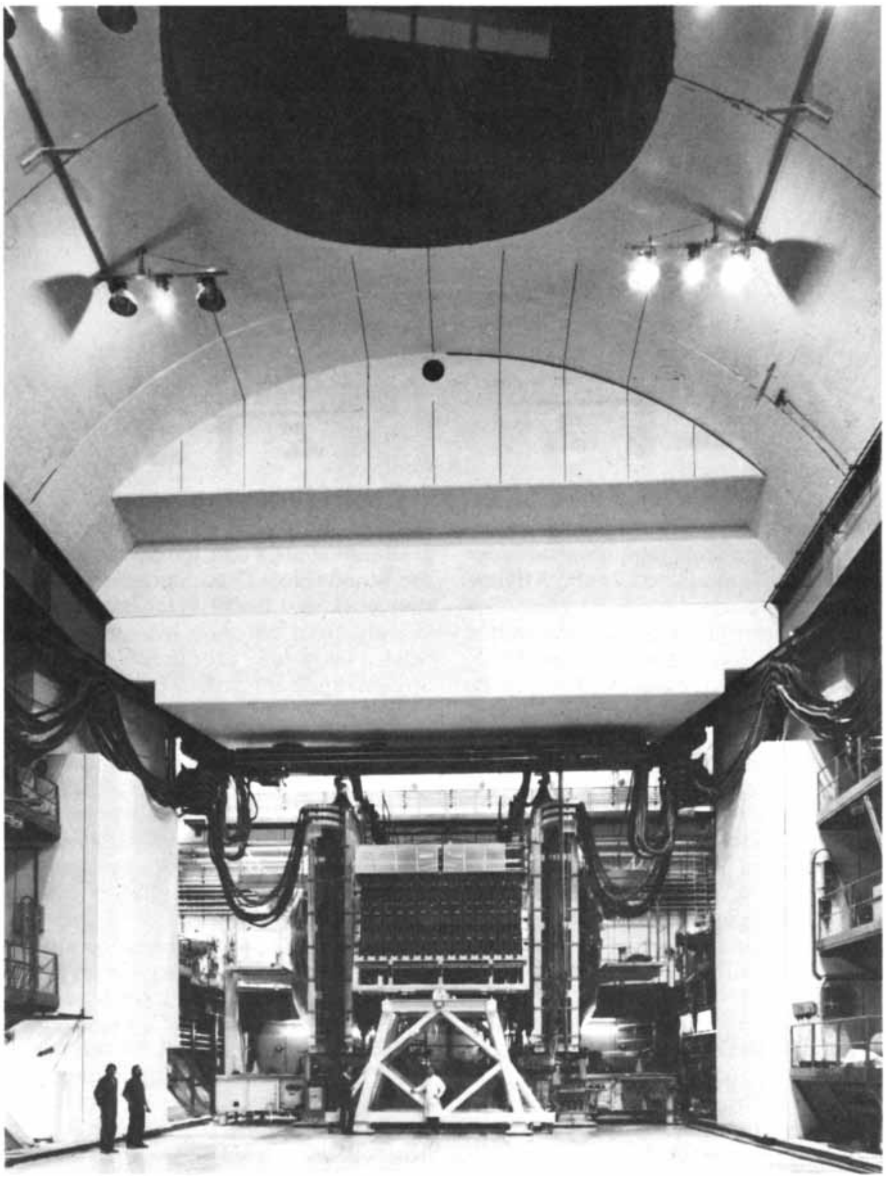
Several large detectors have been designed to search for the decay products of intermediate vector bosons and Higgs bosons. One of these devices, named the UA1, is now finished and ready for next month's resumption of the search at CERN. The detector is the result of a collaborative effort by a team of more than 100 physicists from 11 institutions in Europe and the U.S.: the University of Aachen, the Annecy Particle Physics Laboratory, the University of Birmingham, CERN, Queen Mary College (London), the Collège de France (Paris), the University of California at Riverside, the University of Rome, the Rutherford Laboratory, the Saclay Nuclear Research Center and the University of Vienna. It is 10 meters long by five meters wide, and its total weight is 2,000 tons. The underground hall in which it is installed is large enough for the detector to be rolled back into a "garage" when it is not in place in the path of the colliding beams.

The UA1 detector is a multipurpose device, designed to sense many kinds of particles and to collect information over a wide solid angle surrounding the point where the beams collide. It measures the energy of the particles by several means, including the curvature of their paths in a magnetic field. A large dipole magnet applies the main magnetic field horizontally throughout a volume of 85 cubic meters.

Inside the magnet, surrounding the beam tube, there are three "drift chambers," each containing an array of closely spaced wires and a gas at low pressure. An electrically charged particle passing through the chamber ionizes molecules of the gas; the ions then drift to the wires, where they deposit their charge. From the pattern of charges appearing on many wires the trajectory of the particle can be reconstructed. The central drift chamber has its wires arranged in vertical planes; the two flanking chambers have their wires arranged in horizontal planes. Signals from particles crossing the wire planes can be processed by a computer to yield an image of the decay products on the face of a cathode-ray tube [*see illustrations on opposite page*].

Surrounding the three drift chambers are various other detectors. Just outside the innermost detector is a lead calorimeter, a device that measures the amount of energy deposited in it by a charged particle such as an electron. The calorimeter is enclosed in turn by a series of iron plates interleaved with scintillation counters to measure the energy of heavier particles such as pions by means of their interactions with iron atoms in the plates. Finally, on the outside of the apparatus there are several large chambers for the detection of muons that pass through both the lead and the iron plates.

Another large detector, the UA2, is designed more specifically to search for intermediate vector bosons. It has no magnetic field but instead relies on a large array of calorimeters similar to those in the UA1 detector to measure the energy and direction of the emerging particles [*see illustration above*]. Detectors comparable to the UA1 and the UA2 are planned at Fermilab. If intermediate vector bosons exist, we believe these detectors will be adequate to discover them and to investigate their properties, thereby confirming the unified electroweak theory. If Higgs bosons exist, they might also be detected, thereby providing further support for the theory. Of course, it is still possible that the electroweak theory is incorrect and that none of these particles is real. One way or the other, the answer should be known soon.



ANOTHER LARGE DETECTOR, the UA2, has recently been completed at CERN. It was designed more specifically to search for intermediate vector bosons. Unlike the UA1, it has no magnetic field. It is installed in a second experimental area, built more than 60 meters underground, some distance away from the UA1. The detector is shown in place in the SPS beam line; when it is not in operation, it is rolled back into the large work area in the foreground. The large cylindrical shaft at the top is used to lower bulky components from the surface.