

The background of the entire page is a photograph of a complex particle detector, likely a bubble chamber or cloud chamber, showing various components, wires, and a large yellow cylindrical section. A red circular seal of the Massachusetts Institute of Technology (MIT) is positioned to the right of the text 'MIT AND THE'.

MIT AND THE

NOVEMBER REVO

ESTABLISHING THE
STANDARD MODEL
OF PARTICLE PHYSICS

LUTION

by Peter Fisher & David Kaiser

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FIFTY YEARS AGO, the worldwide community of particle physicists rapidly converged on what we now call the “Standard Model.” Since that time, the Standard Model has passed every experimental test, and it continues to guide our investigations of three of the four fundamental forces of nature: electromagnetism, the weak nuclear force, and the strong nuclear force—encompassing all physical interactions except gravity. Over the years, theoretical physicists have used the Standard Model to calculate predictions for specific quantities, and in some cases those predictions match the latest high-precision experimental measurements to parts-per-trillion accuracy. In short, the Standard Model is the single most quantitatively precise scientific theory in human history. The banality of its title belies the grandeur of the accomplishment.

One of the most significant milestones in building the Standard Model occurred early in November 1974, when physicists announced the discovery a new particle, known as the “ J/ψ ,” an event that was quickly dubbed the “November Revolution.” That breakthrough, and several others along the way, has strong ties to MIT. These efforts exemplify the power of open-ended, basic research—and underscore the need to remain open to surprises.

THE BACKDROP: Suggestive Symmetries in the Sixties

At the close of the Second World War, when physicists in many parts of the world hoped to return from war-related projects to basic research, the set of known subatomic particles numbered just seven: electrons and positrons, protons and neutrons, photons, and positive and negative mesons (soon dubbed “muons”). Some theorists entertained notions of other possible particles—Wolfgang Pauli had reluctantly introduced the idea of a “neutrino” in a now-famous letter to colleagues in 1930, apologizing for his “desperate” attempt to make sense of the energy carried off by

electrons in radioactive decays, among other puzzles—but no solid evidence supported such speculations.

The situation changed rapidly soon after the war. In the United States, the brand-new federal Atomic Energy Commission—successor to the wartime Manhattan Project—financed the rapid-fire construction of new particle accelerators: thirteen new accelerators came online between 1946 and 1954 alone, including MIT’s own synchrotron, completed in 1950. These new machines operated at considerably higher energies than their prewar counterparts, probing interactions with energies of hundreds and soon thousands of MeV [million electron volts], well above the typical binding energies of nuclear matter. Nearly as soon as these new accelerators came online, physicists began finding a flood of new particles. In 1953, theorist Freeman Dyson quipped that hardly a month went by without the announcement of a new particle discovery. Around that same time, Edward Teller felt moved to versify:

*There are mesons π and there are mesons μ
The former ones serve us as nuclear glue
There are mesons τ , or so we suspect
And many more mesons which we can’t yet detect [1].*

By 1960, experiments around the world had yielded more than one hundred new particles, in a dizzying mishmash dubbed the “particle zoo.”

Physicists sought patterns amid the outpouring. Some of the new particles only seemed to be produced in combination with others—a phenomenon quickly designated “associated production.” Theorists wondered if perhaps there were additional properties of the particles, analogous to familiar charge and spin, which might account for these patterns. For example, the new K mesons always seemed to appear with Λ particles or Σ particles. Just a few years past his doctoral studies, Murray Gell-Mann (MIT PhD 1951), along with Abraham Pais, wondered if a new quantum number, which they called “strangeness,” needed to be conserved, much as electric charge was conserved. If the K mesons had equal and opposite “strangeness charge” to the Λ s and Σ s, maybe they always came careening out of particle scatterings together because then the net “strangeness” of such interactions would remain zero.

Within a few years, Gell-Mann and (separately) Yuval Ne’eman found that certain combinations of these new “charges” could account for even larger patterns. In 1960, Gell-Mann introduced his “Eightfold Way”—the name a playful homage to Buddhists’ path to nirvana—by which he could arrange clusters of the new particles in simple patterns, by assigning each of them various properties (baryon number, strangeness charge, isospin, and so on). Dozens of seemingly independent particles suddenly snapped into place when plotted in abstract mathematical planes like “hypercharge” versus “isospin,” all governed by discrete symmetry groups.

Emboldened by the patterns, Gell-Mann famously predicted at a conference at CERN in July 1962 that a new particle would be found with specific properties, based on a gap in an otherwise-full grouping of nine other new particles. The new particle, Gell-Mann declared, should have hypercharge -3 and isospin 0 , with a mass around $1680 \text{ MeV}/c^2$ —and about eighteen months later, experimentalists at Brookhaven National Laboratory identified exactly such a particle, which Gell-Mann had named the Ω^- , with a mass within 0.4% of Gell-Mann’s prediction.

Inspired by such successes, Gell-Mann (by then a professor at Caltech) and George Zweig (a postdoc at CERN) independently proposed—within 13 days of each other, early in January 1964—that the symmetries among nuclear particles could be associated with three constituent particles. Citing James Joyce’s notoriously obtuse novel *Finnegans Wake* among his brief set of just eight references, Gell-Mann called these new hypothetical particles “quarks”; Zweig named them “aces.” By carefully assigning values of hypercharge, strangeness charge, isospin, and electric charge to each of these three hypothetical constituents, Gell-Mann and Zweig could account for all of the symmetric groupings among particles in Gell-Mann’s “Eightfold Way.” A proton, for example, could be mapped to two “up” quarks and one “down” quark, while a neutron could be associated with two downs and an up. A positive pion could be associated with an up quark paired with an anti-down quark (the antimatter cousin of a down quark). Particles with strangeness charge, like the K meson, included at least one “strange” quark, while the Ω^- could be represented as a bound state of three strange quarks.

“It is fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities). ... A search for stable quarks at the highest energy accelerators would help to reassure us of the non-existence of real quarks.”

—MURRAY GELL-MANN

Although the quark idea may seem routine today, it was by no means an obvious suggestion back in the 1960s. For starters, Gell-Mann and Zweig had to assign fractional electric charges to the quarks—even though no fractional charges had ever been observed. The dynamics of how such particles might interact with each other also remained a complete mystery. Gell-Mann himself hedged, calling his brief article “A *schematic* model of baryons and mesons.” In the conclusion he wrote, “It is fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities). ... A search for stable quarks at the highest energy accelerators would help to *reassure us of the non-existence of real quarks*.” Zweig found out even more dramatically just how unrealistic his colleagues considered the new idea: neither of his 1964 papers on “aces” was accepted for publication. To this day, they exist as unpublished preprints on the CERN server [2].

Even as most physicists remained skeptical that quarks were real, several were impressed by the power of discrete symmetries to bring order to the jumble of new particles. Over the course of the 1960s, Sheldon Glashow, Steven Weinberg, and Abdus Salam each independently introduced models that combined the weak nuclear force with electromagnetism into a single “electroweak” force. In these models, the interactions remained symmetrical—that is, unchanged—even if various particles were swapped for one another in a pattern that could vary across time and space. Such models are known as “local gauge theories.”

The theorists hypothesized that some new, force-carrying particles skittered among the known particles, enforcing the overall symmetry. Like the familiar photon from electromagnetism, the new particles would each carry one unit of spin; but unlike the photon, three of them (which Weinberg labeled the W^+ , W^- , and Z^0 particles) would need to be massive, to account for the short-range nature of the weak force. Weinberg wrote his landmark 1967 article, “A model of leptons,” while on sabbatical at MIT, before joining the MIT faculty.

By the time Weinberg (and, separately, Salam) wrote their articles on electroweak theory, they could incorporate recent work on spontaneous symmetry breaking. This last step was critical, since their model required the force-carrying W and Z particles to be massive; but if they simply assigned masses to these particles from the start, the mass terms would break the very symmetries that the new particles were meant to preserve.

So Weinberg and Salam borrowed a trick that several others had recently worked out: they incorporated yet another hypothetical field, this one with zero spin, whose self-interaction potential allowed for multiple, degenerate ground states at non-zero values of the field. When the field settled into one of these lowest-energy states, the motion of any other particles that interacted with it, such as the W and Z particles, would be affected. In particular, their interactions with the molasses-like spin-0 field would make them lumber through space as if they were massive. Building on critical work by Jeffrey Goldstone from 1961, Peter Higgs, François Englert and Robert Brout, and Gerald Guralnik, Carl Hagen, and Thomas Kibble introduced versions of this spontaneous symmetry-breaking mechanism in 1964, tailored to local gauge theories in which forces were governed by so-called “non-Abelian” symmetry groups [3]. (Goldstone joined the MIT faculty in 1977, and Guralnik had completed his undergraduate studies at MIT in 1958.) A few years later, Benjamin Lee dubbed this mass-bestowing spin-0 particle the “Higgs boson.”

By the late 1960s, several suggestive hints were in hand about the basic constituents of the microcosmos. Perhaps particles like protons and pions were actually composites, built out of quarks; maybe nuclear forces like the weak force were mediated by spin-1 particles like the W s and Z ; perhaps an all-pervasive Higgs field made these (and other) particles behave as if they were massive. But there was no consensus about any of these hints. Nor was it clear that the theoretical framework even made sense: it all appeared to break down when applied to high-energy phenomena, and the analogy to electromagnetism decidedly failed for particles that interacted strongly with each other, even at low energies.

SEEKING DEEPER STRUCTURE:

The SLAC-MIT Deep Inelastic Scattering Experiments

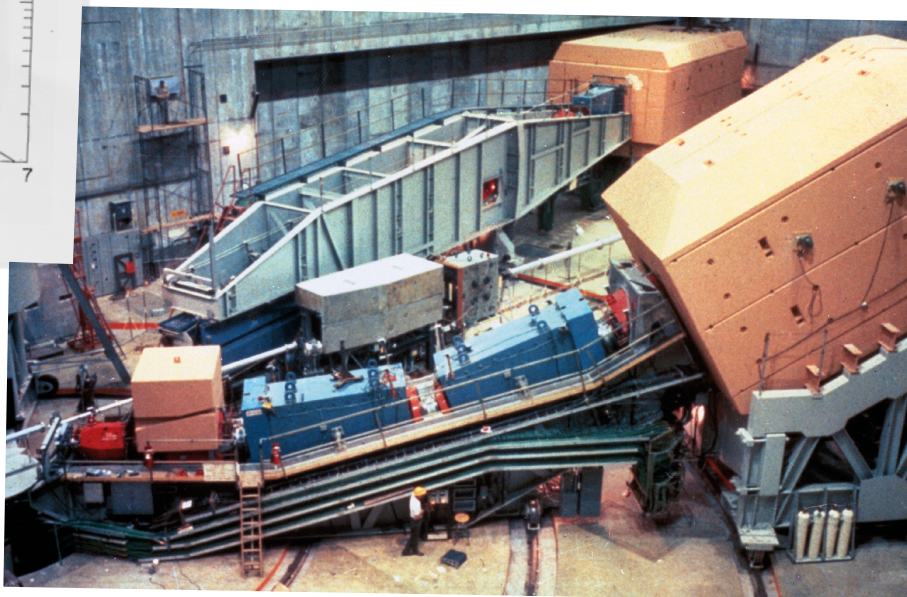
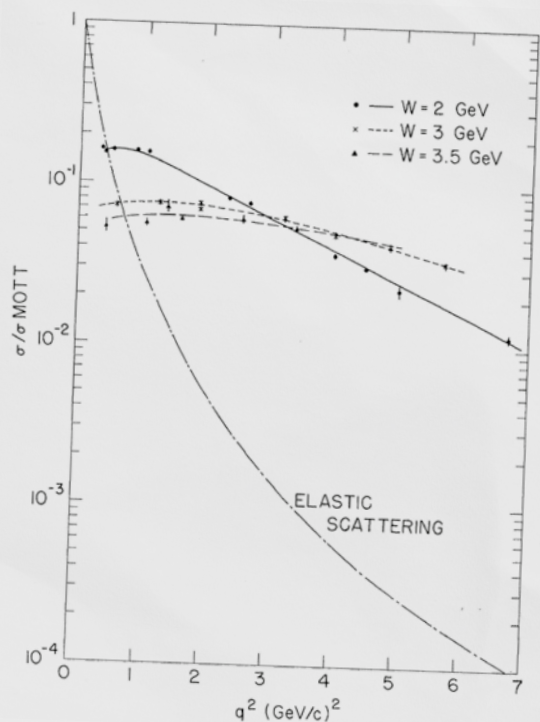
Beginning in 1962, the U.S. Atomic Energy Commission began construction of an even larger particle accelerator in the hills near Stanford University in California. Unlike most of the previous generation, the new machine would string a series of powerful electromagnetic cavities along a straight line—stretching for two miles—to accelerate electrons to unprecedented energies before smashing them into fixed targets. The



Figure 1.

TOP: The two-mile "linac" (linear accelerator) at SLAC. Electrons accelerated down the linac are directed by magnets into experimental stations housed in buildings near the bottom of the image. **CENTER:** Data from one of the group's first papers, showing the prediction (dashed curve) of interaction strength as a function of momentum transfer from the electron to the proton, if the proton were a smooth, spherical ball of charge. The data points indicate much higher interaction strengths, indicating the presence of concentrated scattering sites—internal structure—within the proton.

BOTTOM: One of the spectrometers for the deep inelastic scattering experiments. The target—a small tube, about 7 cm in diameter and 14 cm long, containing hydrogen gas—is beyond the left edge of the image. The scattered electrons' momenta were measured as they traveled through the two blue magnets and into the detectors inside the orange shielding. Each spectrometer rode on circular rails so they could measure electrons at different angles from the incident beam. **SOURCES:** (top and bottom) © SLAC National Accelerator Laboratory; (middle) M. Breidenbach *et al.*, "Observed behavior of highly inelastic electron-proton scattering," *Physical Review Letters* 23, no. 16 [20 October 1969]: 935–939, on 935, © American Physical Society.



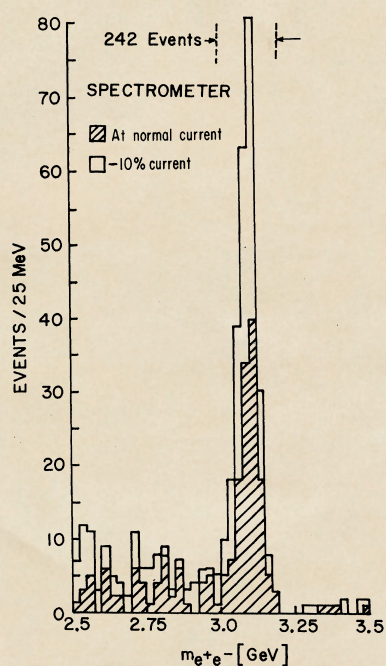
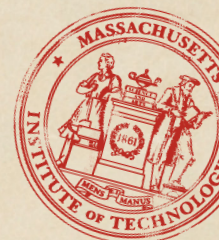


Figure 2.

The MIT-Brookhaven experiment, 1974. **TOP LEFT:** Photograph of the twin-arm spectrometer used to measure the energies and momenta of the electrons and positrons produced by protons hitting the beryllium target, which lies below the image. **ABOVE RIGHT:** Annotated photograph of the spectrometer, showing each arm containing magnetic and position sensors to measure each particle's momentum, followed by detectors to identify the particle as an electron or positron and measure its energy. **BOTTOM LEFT:** Publication histogram of the electron-positron events as a function of energy, showing a sharp peak around 3.1 GeV, indicating the decay of a J particle of that mass. **SOURCES:** Courtesy Professor Samuel Ting; Samuel C.C. Ting, "The discovery of the J particle: A personal recollection," *Reviews of Modern Physics* 49, no. 2 (April 1977): 235–249, on 241, © American Physical Society; J. J. Aubert *et al.*, "Experimental observation of a heavy particle J ," *Physical Review Letters* 33, no. 23 (2 December 1974): 1404–1405, on 1404, © American Physical Society.

Stanford Linear Accelerator Laboratory, or SLAC, began operation in 1966.

One of the first experiments at the new accelerator was directed by MIT's Jerome Friedman and Henry Kendall, along with Richard Taylor at SLAC. The group's original proposal, submitted in January 1966, was to scatter high-energy electrons off of liquid hydrogen targets. They aimed to measure the "form factors" of the protons inside the target nuclei when subjected to high-energy bombardment by electrons; these form factors described how magnetization and electric charge were distributed within a proton.

Their expectation was that the proton could be treated as a smooth, spherical ball of positive electric charge with a radius of around one fermi. (A fermi, also known as a femtometer, is 10^{-15} m.) In that case, the fast electrons from the accelerator should have been slightly deflected in their passage through a proton's sphere of charge. That would correspond to proton form factors that varied in a smooth way as a function of the electron's incoming energy and angle of scatter. Occasionally the electron-proton interaction would produce secondary particles, causing the electron to lose some energy, known as an "inelastic" process. In those cases, the types of particles produced could be determined by comparing the electron's energy before and after the scattering. The effort became known as the SLAC-MIT Deep Inelastic Scattering experiments. (See Figure 1.)

Between 1967 and 1969, the SLAC-MIT team carefully measured how the scattering rates varied with energy and angle with enormous magnetic spectrometers. Each spectrometer included powerful magnets to bend an electron's path following a collision, directing it toward detectors that could measure its momentum. One spectrometer was sensitive to energies up to 8 billion electron volts, while the other—which weighed more than 3,000 tons—could measure the scattered electrons' energies up to 20 billion electron volts. Each spectrometer was mounted on circular rails, like a railroad car, so it could be swiveled to take measurements at various scattering angles.

While the experimental group was still collecting data, neighboring theorists James Bjorken (MIT SB 1956, then based at SLAC) and Richard Feynman (MIT SB 1939, then a professor at Caltech) predicted that *if* a proton had internal, point-like structure—rather than behaving

like a smooth blob of charge—then electron-proton scattering at high energies should depend only on the ratio of the momentum transfer between the electron and proton and the electron's energy loss, but not on either quantity separately. Feynman argued that from the point of view of the speeding electron, racing toward the proton target, the proton would undergo relativistic length contraction, appearing to squeeze into a narrow pancake. Moreover, any internal forces occurring within the proton would essentially freeze from the electron's point of view, since (thanks to relativistic time dilation) the electron would "see" the proton's internal clock tick very slowly. Hence whatever complicated jumble of interacting, moving parts might live inside a proton would act, to the electron, as essentially free (non-interacting), stationary, point-like targets.

The SLAC-MIT experimental data showed exactly this scaling: protons really *do* have internal structure. In 1990, group leaders Jerome Friedman, Henry Kendall, and Richard Taylor shared the Nobel Prize in Physics.

Tellingly, Feynman dubbed the scattering sites inside protons "partons"—not "quarks." Gell-Mann's and Zweig's idea about constituent quarks concerned low-energy phenomena and required that the quarks (if real) interact very strongly with each other to remain bound inside particles like protons. Feynman's partons, on the other hand, served as high-energy scatterers that hardly interacted with each other at all. The dramatic results from the SLAC-MIT experiments, combined with Bjorken's and Feynman's clever analyses, quickly convinced the community that protons have internal structure, but *not* necessarily that quarks are real. Indeed, as late as 1972, Gell-Mann himself still referred to quarks as "fictitious." That would soon change.

THE NOVEMBER REVOLUTION:

A New Particle and New Clarity.

In 1970, Sheldon Glashow (of electroweak-theory fame, on the Harvard faculty) collaborated with two younger Harvard postdocs, John Iliopoulos and Luciano Maiani, to clarify a puzzling pattern from different experiments. They focused on weak-force decays of unstable particles like the K mesons. The original Gell-Mann–Zweig quark model had included three "flavors" of quarks: up, down, and strange.

Combined with the Glashow-Weinberg-Salam electroweak theory, the three-quark model suggested that K mesons should rapidly undergo radioactive decays known as “flavor-changing neutral currents”: the strange and anti-down quarks within a K meson would decay (via emission of W particles) into a pair of positive and negative muons. Yet such transitions appeared to occur about ten thousand times less frequently than predicted by these models.

Glashow, Iliopoulos, and Maiani demonstrated that if there existed a fourth flavor of quarks—akin to the up quark, but more massive—then there should be a near-perfect cancellation of the quantum-mechanical amplitudes governing such flavor-changing neutral currents. That near-cancellation would suppress the likelihood that K mesons would decay into pairs of muons.

Strikingly, the “GIM mechanism” suggested something even deeper: perhaps there existed a symmetry linking the known leptons (the electron, electron-neutrino, muon, and muon-neutrino, which do not “feel” the strong nuclear force) with the still-hypothetical quarks (which do). Upon incorporating the new “charm” quark, the trio argued, each lepton might be paired with a corresponding quark. The particles could be grouped in “generations”: the electron and its neutrino paired with the up and down quarks in the first generation; the muon and its neutrino paired with the charm and strange quarks in the second.

As Glashow, Iliopoulos, and Maiani completed their calculations, two new experiments began to take form. Neither had been pitched or planned with quarks in mind, let alone a possible fourth flavor. Rather, both experiments had been developed to test the interaction of light with matter. But in November 1974, when both groups announced their discovery of a new particle called the “ J/ψ ,” the implications for quarks seemed clear.

One of these experiments was based at Brookhaven National Laboratory on Long Island, New York, and led by MIT professor Sam Ting. Ting’s driving question concerned the conversion of photons into heavy nuclear particles, along with MIT junior faculty Ulrich Becker and Min Chen. Throughout the 1960s, physicists had measured such conversions into three new particles: the ρ meson, the ω meson, and the ϕ meson. Each carried the same quantum numbers as the photon (for example, each had one unit of spin and zero electric charge); but

unlike massless photons, each “heavy photon” (also known as “vector mesons”) had a large mass, comparable to that of a proton. The new particles decayed rapidly into pairs of electrons and positrons, by means of which physicists could measure how strongly ordinary photons interacted with the heavy photons—measurements that Ting and his group had performed during the late 1960s.

By 1971, Ting had grown puzzled: could there really only exist three heavy photons, each with around the same mass? Since the ρ , ω , and ϕ had been produced in proton-proton scattering experiments, he proposed to seek new members of the set in higher-energy proton collisions. He submitted a proposal to Brookhaven to use the Alternating Gradient Synchrotron, which could produce high-intensity beams of very energetic protons, with energies up to 30 billion electron volts. When the protons interacted with a beryllium target, they could produce new particles with masses up to about four times the mass of a proton. So many energetic particles would be produced that the target had to be segmented into ten plates, each around 1 cm² and spaced about 10 cm apart, to allow for heat dissipation.

Downstream from the target, Ting and his group designed and installed a double-arm spectrometer with which they could measure the energy and momentum of electrons and positrons. (See Figure 2.) The very high rate of particles entering the spectrometer meant that the data had to be recorded on a computer—a very early application of microcomputers in such experiments—and then analyzed on mainframe computers over the months after the data had been acquired. In addition to Ting, Becker, and Chen, the group included ten other physicists from MIT.

By late summer 1974, the team had identified a sharp, narrow peak at around 3.1 GeV: at that energy, the number of electron-positron events spiked, indicating that the energetic proton scattering had produced a new particle which quickly decayed into electron-positron pairs. Ting and his group decided to call the new particle “ J ,” since they had been inspired to search for such “heavy photons” by thinking about the electromagnetic current (typically denoted “ j ”) that couples matter to photons.

Over the same period, an experimental team at SLAC, led by Burton Richter (faculty member at Stanford University, MIT SB 1952, MIT PhD 1956), developed a

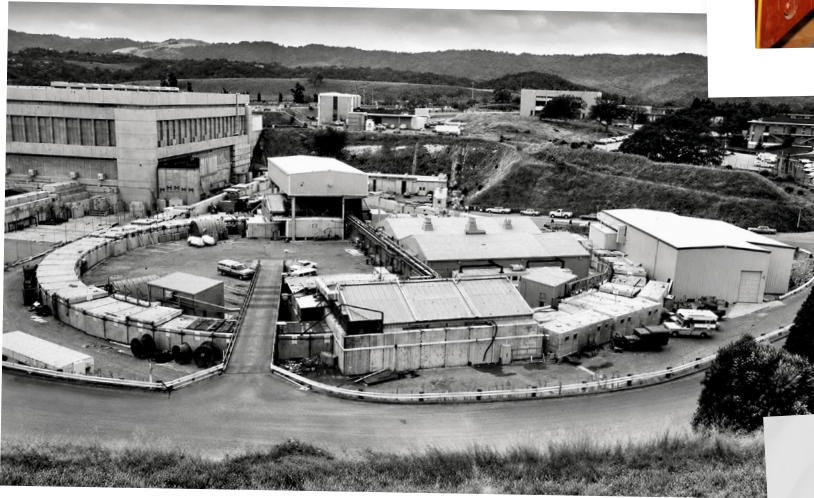
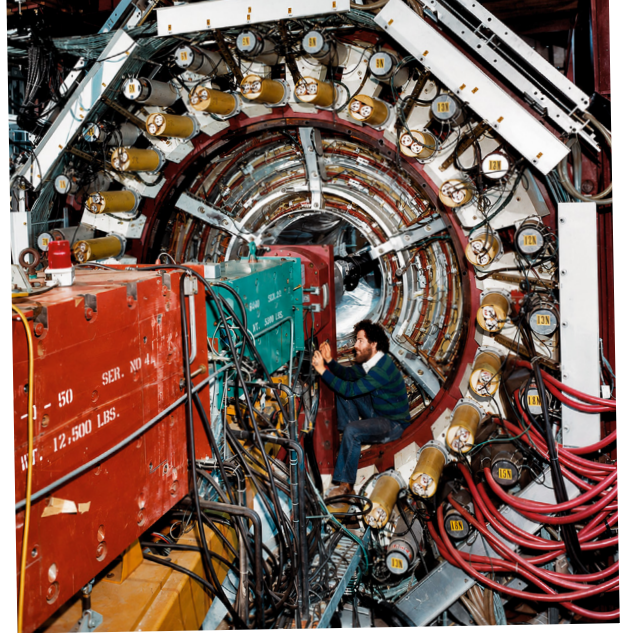
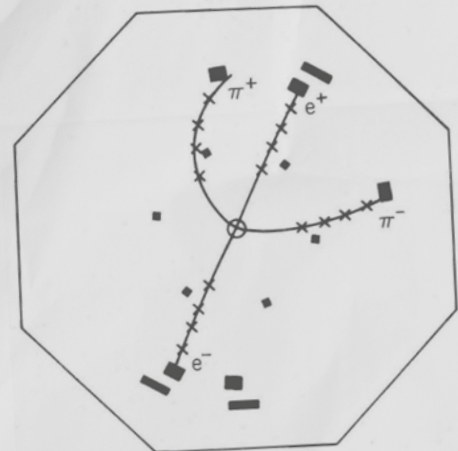


Figure 3.

TOP LEFT: The Stanford Positron Electron Asymmetric Ring (SPEAR) storage rings. Electrons were injected via the beam pipe visible tangent to the ring in the upper left; a second beam was injected from a location behind the building in the upper left. Within the ring, electrons circled counterclockwise and the positrons circled clockwise. Magnets focused the electrons and positrons into collisions in the building to the right, at a point surrounded by the Mark I detector. **TOP RIGHT:** The Mark I detector. The red focusing magnet in the foreground enclosed the beam pipe and the intersection point. The octagonal structure measured 3.5 m across and consisted of a 2 m diameter inner detector that measured charged particle momentum and trajectory, a 3 m diameter scintillator detector that measured particle velocity, the 3.3 m diameter solenoidal magnet, which created the magnetic field for the momentum measurement, and more scintillators that measured penetrating particles. **BOTTOM RIGHT:** Data display showing four particles emanating from the intersection point. The different symbols show the different measurements of each particle. Combining or "reconstructing" these data indicated they came from the decay of a ψ particle at the intersection point [4]. **SOURCES:** each image courtesy SLAC National Accelerator Laboratory.



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new kind of accelerator and detector. (Joining Richter on the SLAC team were several other MIT graduates, including Martin Breidenbach SB 1965, PhD 1970, and Roy Schwitters SB 1966, PhD 1971.) For the new detector, the SLAC group worked in collaboration with colleagues at nearby Lawrence Berkeley Laboratory to design the first comprehensive, cylindrically symmetric detector, which could register particles at nearly any angle from the beam direction—a big change from previous instruments that could only detect particles within narrow angles. The novel SLAC-LBL detector became known as the “Mark I” detector. The accelerator included a storage ring about 100 meters in radius that would be filled with particles from the 2-mile linac. The Stanford Positron Electron Asymmetric Ring (SPEAR) could hold high-energy electrons traveling in one direction, while positrons traveled within the same circular beam pipe in the opposite direction, each guided by a magnetic field. The electrons and positrons would counter-rotate for several hours, made possible by a very high vacuum within the machine. At one point on the ring, the Mark I detector surrounded the beam pipe. At that location, focusing magnets brought the electrons and positrons into collision.

When an electron-positron collision occurred, it yielded a spray of up to about ten particles that the Mark I detector could measure. (See Figure 3.) The large number of particles, whose momenta were measured across several channels, required that the Mark I detector—like the MIT-Brookhaven experiment—use a computer to record the data for subsequent (“off-line”) analysis. Much like the MIT-Brookhaven effort, the original proposal for the SLAC experiment did not mention anything about quarks; the focus had been on measuring properties of photons produced in electron-positron annihilation.

The SLAC team faced a different challenge than the MIT-Brookhaven group. Any new, short-lived particle that might be produced from the annihilation of a counter-rotating electron and positron would have an energy exactly twice that of the electron. Since the SLAC team did not know with any precision what the mass of the new particle might be, they had to adjust the electron beam in steps to “scan” the energy, working first in steps of 100 MeV. By summer 1974, the team found that runs in the vicinity of 3.1 GeV were giving statistically inconsistent results. A software glitch first seemed to be the likely culprit; by that autumn, some team members suspected hardware problems

and undertook a more fine-grained energy scan, using steps of just 1 or 2 MeV. The team did not yet know that the new particle—which their group dubbed the “ ψ ” meson, based on the arrangement of particle trajectories in their experiment—could only be produced when the electron-positron collision energy was within 0.05 MeV of the ψ particle’s mass, corresponding to just 1/20th of their step size. Fortunately for the group, imperfections in the SPEAR storage ring introduced a spread of 1 MeV in the beam energy, creating a small signal that physicists could then home in on.

The two groups completed their analyses around the same time in autumn 1974, and Ting and Richter announced their groups’ findings on November 11. Ting also shared a preview of his group’s results with colleagues at the Frascati Laboratory in Italy. With a clear indication of what energy to focus on, the Italian group was able to replicate the results within two days. All three groups published their results just three weeks later, in the same issue of *Physical Review Letters*. The dramatic announcement of the J/ψ discovery was quickly dubbed the “November Revolution.”

Even before the experimentalists’ papers had appeared in print, several theorists (including Glashow) submitted articles demonstrating that the J/ψ particle could be described as a bound state of a charm quark with an anti-charm quark, a state of matter soon known as “charmonium.” This interpretation gained traction when the SLAC group found evidence of an excited state of the ψ particle—which they dubbed the ψ' —about two weeks after they first identified the ψ . Just two years later, Sam Ting and Burton Richter shared the 1976 Nobel Prize in Physics for their groups’ discoveries.

FRAMING AND NAMING THE STANDARD MODEL

Beginning in 1972—while the MIT-Brookhaven and SLAC-SPEAR experiments were still under construction—Murray Gell-Mann and colleagues developed a new dynamical theory of the strong nuclear force. Cast in analogy to local gauge theories like electromagnetism and electroweak theory, the new model described quarks interacting by exchanging “gluons” [5] (analogous to photons and the W and Z weak-force carriers). They posited that each quark carried a new kind of charge, which, unlike electric

charge, could have three different values. Much as the three primary colors (red, green, and blue) can combine to yield white light, Gell-Mann and his colleagues dubbed the new feature “color” charge, and their new dynamical theory “quantum chromodynamics,” or QCD. Total color charge, they argued, must remain conserved in any interaction. Within months, Harvard PhD student David Politzer and, separately, Princeton PhD student Frank Wilczek and his advisor David Gross, demonstrated that the strength of the QCD interaction should fall at high energies—an effect they called “asymptotic freedom,” as Professor Wilczek describes in his contribution to this issue. Politzer, Wilczek, and Gross shared the Nobel Prize in 2004 for this work.

In July 1974, just a few weeks before the big announcement of the J/ψ discovery, Jean Iliopoulos (who had co-authored the GIM mechanism) delivered a plenary address at the 17th annual International Conference on High Energy Physics, held in London. His talk on “Progress in Gauge Theories” offered the first review of an emerging consensus on how various puzzle pieces might fit together. The “ultimate model,” he announced, could consist of the GIM-inspired fourth quark and resulting symmetry among lepton and quark generations, with forces governed by the Glashow-Weinberg-Salam electroweak theory and by QCD. He concluded with a flourish: “I am ready to bet now a whole case [of wine] that [...] the entire next Conference will be dominated by the discovery of the charmed particles.” [6] He won the bet.

Iliopoulos spoke of the “ultimate model”; Steven Weinberg casually referred to a “standard model” at conferences around that same time. At the 7th International Symposium on Lepton and Photon Interactions, held in August 1975 at SLAC—the first major conference after the November Revolution—participants readily adopted the new framework. The following month, Abraham Pais and Sam Treiman wrote of “a certain four-quark [electroweak] gauge model that we shall refer to here as the ‘standard’ model.” [7]

At the 1975 SLAC conference, some physicists went further, proposing that a third generation of particles might exist: new “top” and “bottom” quarks paired with a tau meson (akin to an electron but more massive) and an accompanying tau-neutrino. In rapid order, experimentalists announced evidence for the tau lepton in 1975 and the bottom quark in 1977. Evidence for the

other particles predicted by the Standard Model trickled in more slowly—the W and Z bosons detected in 1983, the top quark in 1995, the tau-neutrino in 2000—capped by the remarkable detection of the long-elusive Higgs boson in 2012.

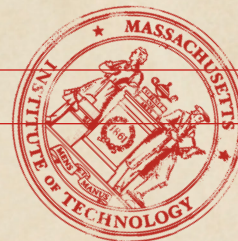
Open questions remain. As treated by the Standard Model, for example, neutrinos should be massless. Yet experiments since the late 1990s—for which several MIT physicists have played key roles—demonstrate clearly that neutrinos must have very tiny, nonzero masses. Perhaps even more urgent: a welter of astrophysical and cosmological evidence indicates that our universe is filled with some strange “dark matter,” which contributes about five times more to the cosmic energy balance than all of the Standard Model particles combined. Dark matter appears to nudge the motion of ordinary objects via gravity, while remaining impervious to all three of the forces (electromagnetism plus the weak and strong nuclear forces) described in such impressive detail by the Standard Model.

In the intervening fifty years, the Standard Model has withstood thousands of experimental tests that sought to find discrepancies and thereby drive a new theoretical advance. None have succeeded, despite forty years of advances in accelerator and detector technology. The latest accelerator, the Large Hadron Collider (LHC)—which is now undergoing a three-year upgrade to increase the amount of data collection tenfold—might reveal physics Beyond the Standard Model (BSM). Yet nothing is guaranteed, and CERN is studying a possible Future Circular Collider (FCC) that could come online in the 2040s.

No matter what comes next, the J/ψ era will stand as a unique time for many years. The teams that discovered real constituents inside protons, and new states of matter like the J/ψ , had not gone looking for such things. Each discovery required serendipity, an openness to surprise, as well as prepared minds. Fifty years ago, particle physics underwent a paradigm shift—following a playbook set forth by historian and philosopher of science Thomas Kuhn (MIT faculty 1979–91)—that changed our understanding of nature forever.

ACKNOWLEDGMENTS

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FOR FURTHER READING

01. Murray Gell-Mann, "Symmetry and Currents in Particle Physics," Nobel Prize Lecture (1969).
02. Samuel C.C. Ting, "The Discovery of the J Particle," Nobel Prize Lecture (1976).
03. Steven Weinberg, "Conceptual Foundations of the Unified theory of Weak and Electromagnetic Interactions," Nobel Prize Lecture (1979).
04. Jerome I. Friedman, "Deep Inelastic Scattering: Comparisons with the Quark Model," Nobel Prize Lecture (1990).
05. Henry W. Kendall, "Deep Inelastic Scattering: Experiments on the Proton and the Observation of Scaling," Nobel Prize Lecture (1990).
06. Frank A. Wilczek, "Asymptotic Freedom: From Paradox to Paradigm," Nobel Prize Lecture (2004).
07. Andrew Pickering, *Constructing Quarks: A Sociological History of Particle Physics* (Chicago: University of Chicago Press, 1984).
08. Robert P. Crease and Charles C. Mann, *The Second Creation: Makers of the Revolution in Twentieth-Century Physics* (New York: MacMillan, 1986; reprint, Rutgers University Press, 1996).
09. Michael Riordan, *The Hunting of the Quark: A True Story of Modern Physics* (New York: Simon and Schuster, 1987).
10. Laurie Brown, Michael Riordan, Max Dresden, and Lillian Hoddeson, eds., *The Rise of the Standard Model: Particle Physics in the 1960s and 1970s* (New York: Cambridge University Press, 1997).
11. Frank Wilczek, *The Lightness of Being: Mass, Ether, and the Unification of Forces* (New York: Basic Books, 2008).
12. David Kaiser, *Quantum Legacies: Dispatches from an Uncertain World* (Chicago: University of Chicago Press, 2020).

PETER FISHER, the Thomas A. Frank (1977) Professor of Physics, was appointed associate provost and associate vice president for research in October 2022. He also serves as head of MIT's newly established Office of Research Computing and Data. Fisher served as head of the Department of Physics from 2013 to 2022 and led the Experimental Nuclear and Particle Physics Division from 2002 to 2013.

Fisher has extensive experience in classical and quantum electrodynamics, including carrying out the most precise tests of the theory, and has over 300 publications in the field. He has also served as an expert witness in court cases related to electromagnetism. He has led a DARPA study of wireless energy transmission between spacecraft as part of the System F6 program, and is a founder of WiTricity, a startup developing wireless energy transmission for commercial use. He also serves as Vice Chair of the JASONS.

He has taught electromagnetism at both the undergraduate and graduate levels and was an instructor for the MIT Physics Undergraduate Laboratory, which includes several components related to electromagnetic radiation. Fisher serves as a referee for several journals, including *Physical Review*, *Physical Review Letters*, and *Nuclear Instruments and Methods*. He served on several national panels and advisory groups, including the Particle Physics Program Prioritization Panel that defined the roadmap for experimental particle physics over 10 years, encompassing about \$8 billion in research funds from the Department of Energy and National Science Foundation.

His research interests are the experimental detection of dark matter, the development of new kinds of particle detectors, and large scale classical and quantum computing systems. He carried out one of the first dark matter searches and since then has searched for dark matter on Earth and in space, including inventing a new kind of detector, the Dark Matter Time Projection Chamber. He recently published a book, *What is Dark Matter?*, with Princeton University Press. Peter Fisher received a bachelor of science in engineering physics from the University of California at Berkeley in 1983 and a PhD in physics from Caltech in 1988.

DAVID KAISER is Germeshausen Professor of the History of Science and Professor of Physics at MIT. He is the author of several award-winning books about modern physics, including *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (2005), *How the Hippies Saved Physics: Science, Counterculture, and the Quantum Revival* (2011), and *Quantum Legacies: Dispatches from an Uncertain World* (2020). In MIT's Physics Department, Kaiser is based in the Center for Theoretical Physics—A Leinweber Institute, where he focuses on early-universe cosmology, primordial black holes, and foundations of quantum theory. He is Fellow of the American Physical Society and member of the Board of Trustees of the American Institute of Physics Foundation, and he has received MIT's highest honors for excellence in teaching. His work has been featured in *Science*, *Nature*, the *New York Times*, and the *New Yorker* magazine. His group's efforts to conduct a "Cosmic Bell" test of quantum entanglement, together with MIT's Alan Guth and Nobel laureate Anton Zeilinger, were featured in the documentary film, *Einstein's Quantum Riddle*.

REFERENCES

- [1] Dyson and Teller quoted in David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago: University of Chicago Press, 2005), 198.
- [2] Murray Gell-Mann, "A schematic model of baryons and mesons," *Physics Letters B* 8 (1 February 1964): 214–215; George Zweig, "An SU(3) model for strong interaction symmetry and its breaking," CERN preprints TH-401 and TH-412 (January 1964).
- [3] A "non-Abelian" symmetry group is one in which the order in which symmetry transformations are applied affects the final state of the system. The discrete Lie group SU(2), at the heart of the Glashow-Weinberg-Salam electroweak theory, is an example of a non-Abelian group.
- [4] The story is that ψ was chosen because the particle "signed its own name" on the event display shown in Figure 3 (right).
- [5] Ting and his group went on to discover evidence of gluons in 1979 with the Mark J experiment at the PETRA accelerator at DESY in Hamburg, West Germany.
- [6] Jean Iliopoulos, "Progress in gauge theories," in *Proceedings of the XVII International Conference on High Energy Physics*, ed. J. R. Smith (Chilton, UK: Rutherford Laboratory, 1974), III-89–116, on 100.
- [7] Abraham Pais and Samuel Treiman, "How many charm quantum numbers are there?," *Physical Review Letters* 35 (8 December 1975): 1556–1559, on 1556; their article was submitted on September 8, 1975.