Cracking the Particle Code of the Univers

The Hunt for the Higgs Bos

JOHN W. MOFFA

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To Patricia, with lo

In April 2008, I traveled to Geneva for a week to visit the new facilities at the European Organizatio for Nuclear Research, known as CERN—the large hadron collider (LHC), the biggest and most expensive scientific experiment ever built. My wife Patricia and I stayed in Ferney-Voltaire, just across the border from Switzerland. From our hotel window, we could see the jagged white caps of th Jura Mountains rising over the charming little French town. Driving each day to CERN on a narrow country road, we crossed the French–Swiss border twice, and enjoyed the views of meadows, farms, and villages.

This was a pilgrimage that I had intended to make for years. I wanted to see with my own eyes the enormous particle accelerator whose experiments promised to answer important questions and settle long-standing disputes in particle physics. The $9 billion machine would be hunting for several discoveries. One is the so-called *supersymmetric particles*, necessary components of the Holy Grail o physics, the yet-to-be-discovered unified theory of all the forces of nature. Another possible discover is *extra space dimensions*, beyond the three we inhabit, which are required by string theory. Thirdly, the LHC experimentalists hope to find the elusive “dark matter” particles that the majority of physicists believe make up more than 80 percent of the matter in the universe. The LHC might even succeed in producing *mini black holes* during its proton–proton collisions, a possibility that, stoked b media reports, initially flared up into worldwide hysteria, with certain individuals attempting to clos down the LHC by litigation.

But most important, the LHC was built for the main purpose of finding the final puzzle piece required to confirm the standard model of particle physics, the so-called *Higgs boson*. Within the almost half-century-old, widely accepted theory describing the subatomic elementary particles and th three subatomic forces (excluding gravity), the mother of all particles was the Higgs. In this standard theory, on which thousands of physicists had worked and contributed to since the mid 1960s, the Higgs particle, or boson, or field, gave all the other elementary particles their masses back near the very beginning of the universe.[1]

Most physicists believe that elementary particle masses come about because of the special relationship the Higgs boson and its field enjoy with the vacuum. This is the physical state of lowest energy existing at all times, including at the beginning of the universe. The modern concept of the vacuum, quantum mechanics tells us, is not simply a void containing nothing; it is a teeming cauldro of particles and antiparticles flashing into existence and immediately annihilating one another. According to the standard model of particle physics, without the Higgs boson, the basic constituents matter—the quarks and leptons—would have no mass.[2] Physicists sometimes liken the Higgs field to a river of flowing molasses or a viscous kind of ether permeating space. When the original, massless elementary particles moved through it at the beginning of the universe, they picked up sticky mass. The idea that we require a Higgs field originated with the physics of low-temperature superconducto —mainly with Russian physicists Lev Landau and Vitaly Lazarevich Ginzburg, and later with the American Nobel laureate Philip Anderson. The Higgs is so important to the standard theory of partic physics that it has been nicknamed the *God particle*.

To date, all the other predictions of the standard model have been validated by experiments. Durin the 1970s, experiments at the Stanford Linear Accelerator (SLAC) verified Murray Gell-Mann's and George Zweig's 1960s-era predictions of quarks. And, in 1983, the so-called *W* and *Z bosons*, the predicted carriers of the weak nuclear force of radioactive decay, were discovered at CERN. Over time, three basic families of quarks and leptons have been detected by colliders, and the carrier of the strong nuclear force, the gluon, was also verified to exist. Today, only the Higgs boson remains to be found. Its detection had to wait until a much larger accelerator could be built to create the incredibly high energies that would be necessary to detect this massive particle, energies equivalent to the temperature at the beginning of the universe, a fraction of a second after the Big Bang.

On July, 4, 2012, two groups associated with the compact muon solenoid (or CMS) and a toroidal LHC apparatus (ATLAS) detectors at the LHC announced the discovery of a new boson at about 125 GeV, that is, at a mass of 125 billion electron volts.[3] This boson appeared to have the properties of th standard-model Higgs boson, but the experimental groups were cautious about identifying it as the Higgs boson. Although the majority of physicists now believe that the new boson is the Higgs boson, we are currently waiting for LHC experimentalists to complete the analysis of the 2012 data and for the accelerator to start up again in 2015 to collect even more data to confirm definitively the identity of the new boson.

The standard theory of particle physics is one of the most successful physics theories of all time. I is on par with James Clerk Maxwell's electromagnetism, Isaac Newton's gravitation, Albert Einstein's general theory of relativity, and the theory of quantum mechanics, which was a cooperativ venture by about a dozen physicists during the early 20th century. Even though the final mechanism that keeps the whole edifice together, the Higgs boson, had not yet been detected in 2008 when I visited CERN, the majority of physicists accepted the theory almost without question, and assumed that the discovery of the Higgs would be inevitable, almost a formality. The Nobel committee, too, had already given out five Nobel Prize(s) in Physics to theorists and experimentalists working on the standard model of particle physics, even though the Higgs had not yet been detected and, therefore, th theory had not been fully proved. Finding the Higgs boson was considered such a certainty in 2008 that a dispute had arisen about who would get the Nobel Prize for predicting it. In 1964, during a three-month period, a total of six physicists published short papers in *Physical Review Letters* promoting a way of giving elementary particles their masses. These physicists were François Englert Robert Brout, Peter Higgs, Carl Hagen, Gerald Guralnik, and Tom Kibble. Because the Stockholm committee can award one prize to no more than three people, if the Higgs was discovered, they would have quite a dilemma deciding among these six physicists. All were eagerly awaiting their Nobel Prizes, and trying to stay alive until the Higgs was found, because the Nobel committee is also constrained by the rule that no prizes can be given posthumously.[4] To complicate matters further, there is a seventh physicist, Philip Anderson at Princeton University, who published a seminal paper in 1963 proposing what is now called the *Higgs mechanism* to give masses to particles. It is worth noting, however, that only the English physicist Peter Higgs had predicted explicitly the existence of an actual particle in his paper.

But what if the standard theory of particle physics was not correct and the particles derived their masses in some other way? Or had their masses right from the beginning, with no intervention necessary by a God particle? What if the Nobel committee had been premature with its awards for th standard model of particle physics? What if the enticing hints of the Higgs boson at 125 GeV either evaporated or turned out to be another new particle entirely? What if the enormous LHC never found the Higgs boson after all?

This was the second reason for my pilgrimage to Geneva in 2008. Along with my research in gravitation and cosmology, I had been working on an alternative theory of particle physics since 199 and there was no Higgs boson in my theory. In the mathematics of my *alternative electroweak theory* all the elementary particles were massless at the beginning; but, except for the massless photon, their masses were then generated not by a single particle with its associated special vacuum features, but b the usual dynamical processes of quantum field theory.[5] That is, the primary observed elementary particles such as the quarks and leptons, and the W and Z bosons conspired—through the quantum field dynamics of self-energies—to produce their own masses. Moreover, my theory did not require the discovery of *any* new particles beyond the already observed ones in the standard model. For example, it did not require any hypothesized particles of supersymmetry, which had, over the years, become a large research industry. My theory seemed to me an economical description of the elementary particles, fields, and forces. I was not the first or only physicist to try to construct an alternative electroweak theory. Attempts to avoid introducing scalar fields and the Higgs mechanism into the standard model had been proposed during the early 1970s by, among others, Roman Jackiw and Kenneth Johnson at the Massachusetts Institute of Technology (MIT).[6]

I called the talk that I gave to the theory division at CERN during that week in April 2008 "Electroweak Model without a Higgs Particle," a provocative title to the theorists and experimentalists who had been working for years, in some cases *decades*, on the standard model of particle physics, on the Higgs mechanism, and on figuring out exactly how the enormous new machi might detect it. Two weeks before my talk, the LHC had had its official opening. Present at the launc was Peter Higgs, retired professor of physics at the University of Edinburgh. During an interview at the LHC opening, a journalist asked Higgs how he felt about having $9 billion spent on finding a particle named after him, and did he think they would find it? Peter replied, "I'm 96 percent certain that they will discover the particle."

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On the day of my talk, Patricia and I parked our rental car outside the visitors' entrance to CERN and made our way across the sprawling research compound to the theory building. I remembered the building well from my days visiting CERN when I was on sabbatical leave at Cambridge University i 1972 and also when I was a visiting fellow at CERN in 1960/1961. As we mounted the scuffed stairs the second-floor administrative office, it struck me that the building had changed little in nearly half century. The halls were dark and dingy, exuding an air of weariness and neglect. I soon discovered th the toilet roll holder in the men's room was broken, just as it had been those many years ago during my last visit. Apparently the $9 billion price tag for the LHC had not included renovations to the theoretical physicists' working quarters.

My talk was scheduled for two o'clock in the large seminar room on the second floor. At five minutes to two, I stood waiting at the front of the hall with the CERN theoretician who had organized the seminar, staring out at the large amphitheater with its rising rows of desks that was completely empty except for my wife sitting in the fourth row. I thought, *My goodness! Maybe no one is going to turn up because of my audacious title*. Then, at three minutes to two, about 50 theorists and experimentalists swarmed into the room and sat down. Five minutes into my talk, I noticed a profess from New York University (NYU), with whom I had had encounters before, walk in and sit at the back. Sure enough, he soon erupted into loud technical protestations about my theory. A verbal duel ensued and, thanks to many years of experience at such seminars, I was able to subdue him sufficiently to continue. There were other interruptions, and I could feel the audience growing increasingly hostile to the idea of a particle physics theory without a Higgs particle. Near the end of my talk, the NYU professor again got excited and explained, as he understood it, that the Higgs particle existed in my theory, but in an altered way. Alvaro de Rújula, a senior theorist at CERN, who was ~~sitting next to him in the back row, could be overheard saying quite loudly, "Moffat does not~~ *hav* a Higgs particle in his theory!" This seemed to flummox our friend and from then on, he kept quiet.

After my talk, Guido Altarelli, a senior physicist in the theory division who is an expert on the electroweak theory and the standard model of particle physics, declared dramatically, "If Moffat is correct, and no new particles are discovered, then that's the end of particle physics! What are we going to do?"

"You can all retire!" I quipped, trying to break the tension in the room with a joke—but no one laughed.

So I pursued Altarelli's point. "What do you mean, Guido, that this will be the end of particle physics?"

Guido, a strongly built, tall Italian, turned to the audience and said, "What I mean is that governments will no longer give us money to build new accelerators and continue our experiments. I that sense, it's the end of particle physics."

"But this is not the way physics works," I said, genuinely astonished. "Not finding the Higgs and, fact, not needing to find any other exotic particles would open up many new questions about the natu of matter. New mysteries would unfold. This kind of situation often leads to a revolution in physics."

I reminded the audience of the famous Michelson–Morley experiment in the United States during the late 19th century that failed to detect the "ether," which virtually every scientist of the day accepted as real. To those scientists, it had seemed obvious that a medium was necessary for electromagnetic waves to propagate. The waves had to be moving through *something*. But Michelson and Morley's ingenious experiment turned up nothing where the ether should have been. Although th physics community of the time was shocked, it was certainly not the end of physics. It heralded a nev beginning, with Einstein's subsequent discovery of special relativity, and Max Planck's discovery of the quantization of energy, which led to quantum physics. A similar boost to the whole enterprise of physics, especially particle physics, would occur if the LHC did not detect the Higgs boson, I concluded.

But neither Altarelli nor the rest of the audience seemed convinced. The questions and comments the end of my talk continued to be skeptical in tone, even hostile.

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I was disappointed by the reception of my alternative electroweak theory at the CERN theory group, but I was not surprised. I knew that even expressing doubts about a prevailing paradigm cause conflict. Physicists are like most other human beings; they become emotionally invested in the truth and beauty of the theoretical structures they have helped to build. To contemplate that those structure might be faulty or incomplete simply pulls the rug out from under their feet. On the other hand, the standard model with the Higgs boson has very attractive features, such as the elegant prediction durir the 1960s of the W and Z bosons by Sheldon Glashow, Steven Weinberg, and, independently, by Abdus Salam. The discovery of the W and Z bosons at CERN in 1983 confirmed this remarkable prediction. Moreover, the inclusion of the Higgs boson into the unified electroweak theory guarantee that one could perform finite calculations of physical quantities in the standard model.

Soon, in a matter of years rather than decades, the answers to the Higgs boson puzzle would be known. The LHC's beams of protons would smash together, spraying subatomic debris into the large and most sophisticated detectors ever built. Physicists would analyze the statistical patterns of those collisions, an immense amount of data. Eventually, after a great many such experiments, CERN woul make its announcement. Either the LHC would have finally discovered the Higgs boson, and therefor proved ~~that the standard model of particle physics was correct in all respects, or the LHC would~~ not have found a Higgs boson, and therefore the standard model would have to be reexamined and changed. If the latter happened, I'd told the skeptical crowd of CERN physicists at the end of my talk I would be standing at the head of the queue called "Other Ideas," offering my alternative electrowea theory without a Higgs boson for serious consideration.

Later in the week, Patricia and I joined one of the last tours of the new accelerator before it was turned on. Once the machine was operating and the protons were chasing around the 27-km circumference of the LHC, then the radiation level would be prohibitive and access to the machine would be severely restricted. We stood on the viewing deck of the enormous ATLAS detector, feeling overwhelmed by its sheer size. The amount of iron used to build just this one detector was equivalent to all the iron in the Eiffel Tower. Colorful cables wound through the complicated electronic parts of the detector, which appeared to us to be about the size of a European cathedral. Together with three other main detectors, ATLAS was the place where the protons would collide and produce a huge amount of particle debris, which would then be analyzed for years by a worldwide grid of computers.

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At this writing, five years later, the LHC has been shut down for two years of maintenance and upgrading to an energy of 13 to 14 TeV. During the past two years, there has been tremendous excitement about what the LHC may have discovered, with many physicists already popping the champagne corks to celebrate the discovery of the Higgs boson. The data accumulated before the LH shutdown have been analyzed and found to be consistent with the standard-model Higgs boson. However, as we will learn in this book, there remain critical experimental issues to determine exactly what the new Higgs-like boson is, which need to be resolved after the machine starts up again in 2015

The fifth-century BC Greek philosopher Leucippus, and his pupil Democritus (460 to 370 BC), presage in broad strokes by more than 2,000 years the standard model of particle physics. They claimed that matter could be broken down to a basic unit. This claim was in contrast to Aristotle (384 to 322 BC), whose ideas, based on Plato's, soon became the establishment view of the day, and who taught that th basic elements of the universe were the earthly elements fire, water, earth, and air, plus the heavenly element, ether. Leucippus and Democritus called their basic unit *atom*, which means "indivisible" or "uncutable" in Greek. By 1964, with the publication of the quark model by Murray Gell-Mann and th independent proposal by George Zweig of *aces*, the ancient Greek idea of a basic unit of matter had finally arrived—and the quarks, along with the leptons, would eventually be heralded as the basic units of all matter.[1]

FINDING THE BUILDING BLOCKS

Particle physics has a long history, reaching back to the 19th century and the discovery of atoms. The reductionist view that matter is constituted of tiny, indivisible units received its first serious validation in 1897, when J. J. Thomson of Cambridge University discovered the electron. Ernest Rutherford's discovery around 1919 of the proton—the positively charged particle at the center of th hydrogen atom, with Thomson's negatively charged electron buzzing around it—introduced another important unit of matter. It was not until 1932, when James Chadwick discovered the neutron with th first particle accelerator, that the dominance of the proton and electron as the only basic units of matter was broken. This was the birth of nuclear physics; the nuclei of more complicated atoms and molecules were discovered to be composed of different numbers of bound protons and neutrons. The radioactive beta decay—or transmutation of matter first discovered by Henri Becquerel in 1896—of some of these nuclei released a further unit of matter, called the *neutrino*, which was a massless, electrically neutral particle. At the time of its discovery, it was believed to have zero mass, and, obeying Einstein's special relativity theory, it moved at the speed of light. The neutrino was first proposed by Wolfgang Pauli in 1931 to explain the observed missing energy in radioactive decays. H surmised that an unseen neutral particle was carrying it off. The neutrino was not confirmed experimentally until 1959, by Fred Reines and Clyde Cowan.

The famous Dirac equation, invented by Paul Dirac in 1928, provided a particle-wave description of the electron in accordance with Einstein's special relativity. However, it had an interesting by-product; it also predicted the existence of antimatter. Carl Anderson's detection in 1932 of the "positron," a positively charged electron, was a triumph for Dirac. Eventually, this discovery led to the understanding that all the basic constituents of matter had antimatter partners. For example, the proton's antiparticle is the antiproton.

As accelerators were developed that collided particles at higher energies, more particles and their antimatter partners were discovered. The muon, a kind of heavy electron, was found by Carl Anderso and Seth Neddermeyer at Caltech in 1936. This was followed by the discovery of the mesons, the particles that were, at that time, considered to be the carriers of the strong force holding atomic nucle together, much as the photon carries the electromagnetic force. In 1935, Japanese physicist Hideki Yukawa had predicted that the protons and neutrons were bound in the atomic nucleus by the exchan of mesons, and after World War II, in 1947, Cecil Powell, César Lattes, and Giuseppe Occhialini of the University of Bristol detected these particles in cosmic rays.

GROUPING THE BUILDING BLOCKS

The electron, proton, neutron, neutrino, antimatter, meson, muon,…! What next? By the mid 1950s, the number of newly discovered particles at accelerators was so large that physicists began referring to them as the *particle zoo*. To make sense of the abundance of particles, physicists began categorizi them, using the ideas from group theory, which had been promoted by Hermann Weyl, John von Neumann, and other mathematicians. Murray Gell-Mann and Yuval Ne’eman played a significant rol in this effort. Gell-Mann was a dominant figure in particle physics during the 1960s and 1970s. He was a professor of physics at Caltech, and won the Nobel Prize in 1969 for his contributions to partic physics and the discovery of quarks.

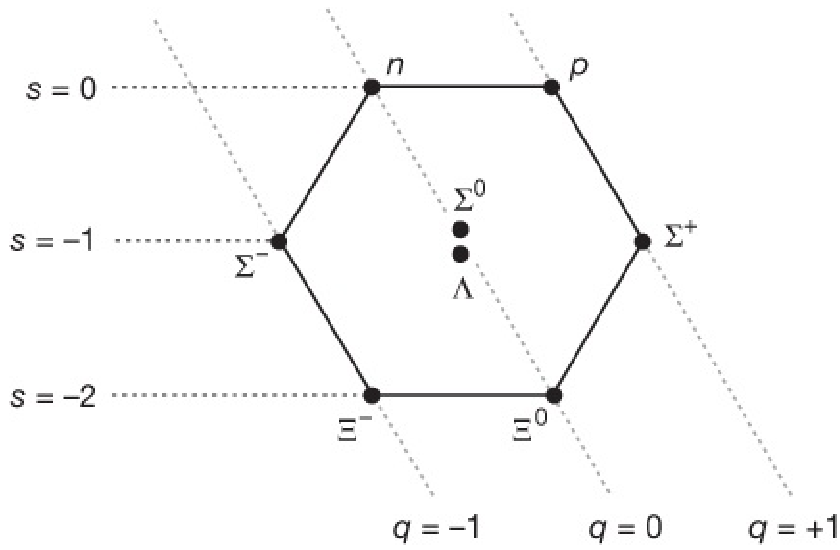

Figure 1.1 Gell-Mann’s Eightfold Way of baryons. Here, *s* stands for the quantum number strangeness, and *q* stands for electric charge.
SOURCE: tikalon.com.

During the early 1960s, before the advent of the quark model, Gell-Mann developed what he calle the *Eightfold Way*, alluding to the Buddhist Noble Eightfold Path of right thought and actions leading to enlightenment. He proposed that what were now called the *baryons* (the proton, neutron, and their cousins with spin ½ and $^3/_2$) fitted into octets (Figure 1.1) and decuplets (Figure 1.2)—namely, patterns of eights and 10s—of the symmetry group from group theory called SU(3).

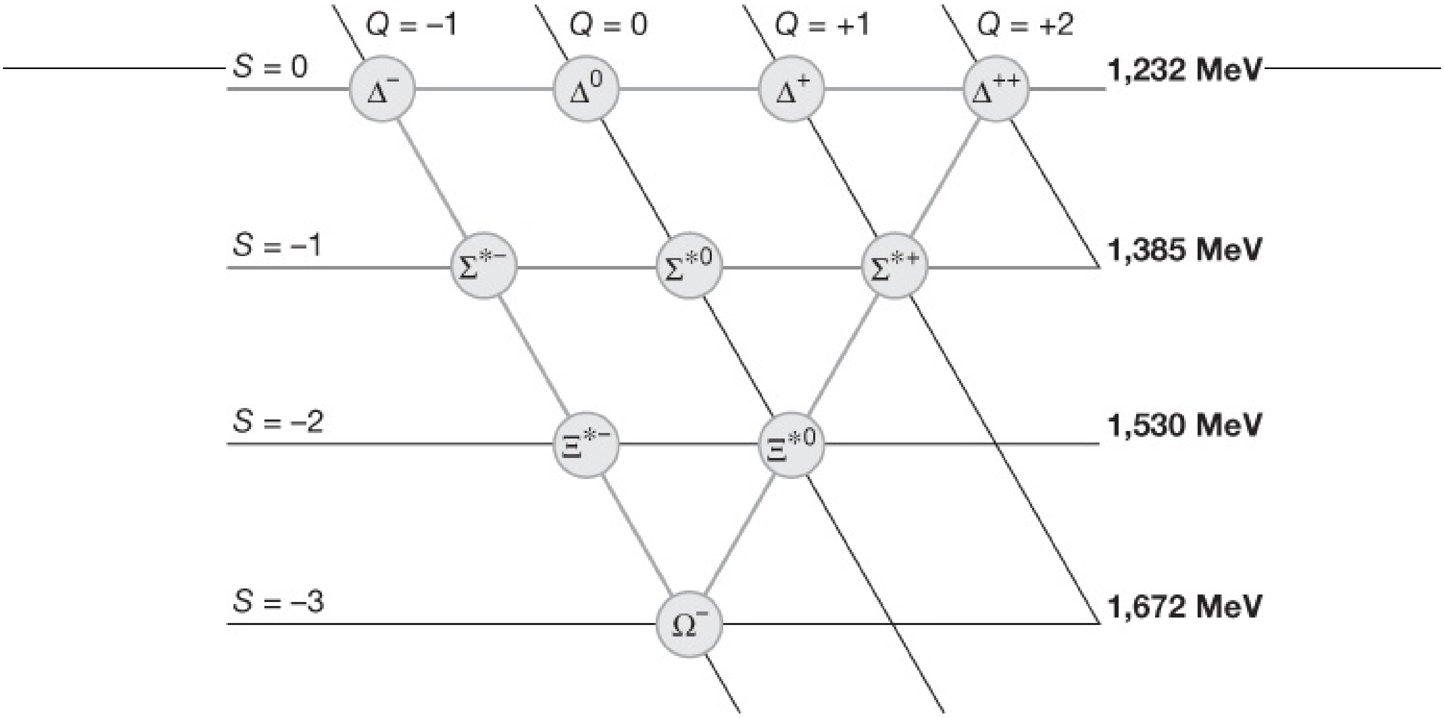

Figure 1.2 Gell-Mann's Eightfold Way decuplet of baryons.
SOURCE: Wikipedia Commons.

One of the baryons in the decuplet was missing. There was nothing in the place where a particle should be at the base of the triangle. Gell-Mann, confident of his patterned scheme, predicted that the missing particle must exist. He called it the Ω^-—the Omega minus, a negatively charged resonance.[2] Gell-Mann's classification scheme was validated in 1964 when a team of physicists from Brookhaven, the University of Rochester, and Syracuse University discovered the Omega minus particle.

Before wading any further into particle physics terminology, some brief explanations are in order. *Spin* is one of several parameters that characterize the different particles. It is an intrinsic quantum number that was discovered during the early development of quantum mechanics by Samuel Goudsmit and George Uhlenbeck in 1925. Spin is a degree of freedom that has meaning only in quantum mechanics. Its classical counterpart is the angular momentum of a body, such as the spinning of a top. However, the quantum mechanical spin does not have a classical interpretation. The spin of a particle is described by being either up or down in direction. Its magnitude can be integer values such as 0, 1, or 2 for bosons, and half-integer values such as ½ and 3⁄2 for fermions. In physical units, the spins of the particles are given in multiples of Planck's constant h; so, for example, the spin of the electron is ½ h.

Some of the other properties that characterize particles are electric charge, mass, and parity (left- or right-handedness). Group theory will be described in more detail in Chapter 3. Suffice it to say here that, of the several mathematical groups that have been applied successfully to particle physics, the group SU(3) is one of the most important groups used by physicists to categorize particles.

In addition to the baryon octet and decuplet categories, there are octets of mesons having spin 0 (Figure 1.3) and spin 1 (Figure 1.4). Most of the particles that fitted into these meson octets, such as the eta meson and the electrically neutral K mesons, were already known in the 1960s or, if not, were soon discovered. Two of these particles were the rho and omega mesons with spin 1, which were thought, at the time, to be important force-carrying particles that bound protons and neutrons together.

A basic feature of the group SU(3) is the triplet. It implies that there could be three fundamental constituents of all the known hadrons, a category that includes baryons and mesons; *hadros* means “heavy” in Greek. Back in 1956, Japanese physicist Shoichi Sakata proposed that three particles are the building blocks of all others: the proton, neutron, and “Lambda (Λ) particle.” Initially, Murray Gell-Mann went along with this idea. The proton and neutron, collectively called *nucleons*, were interpreted in terms of the quantum number called *isospin*, which is a property of the proton- and neutron-like spin. Isospin means that hadrons with similar masses and the same spin but different electric charges were identical as far as the strong interactions within the nucleus were concerned.

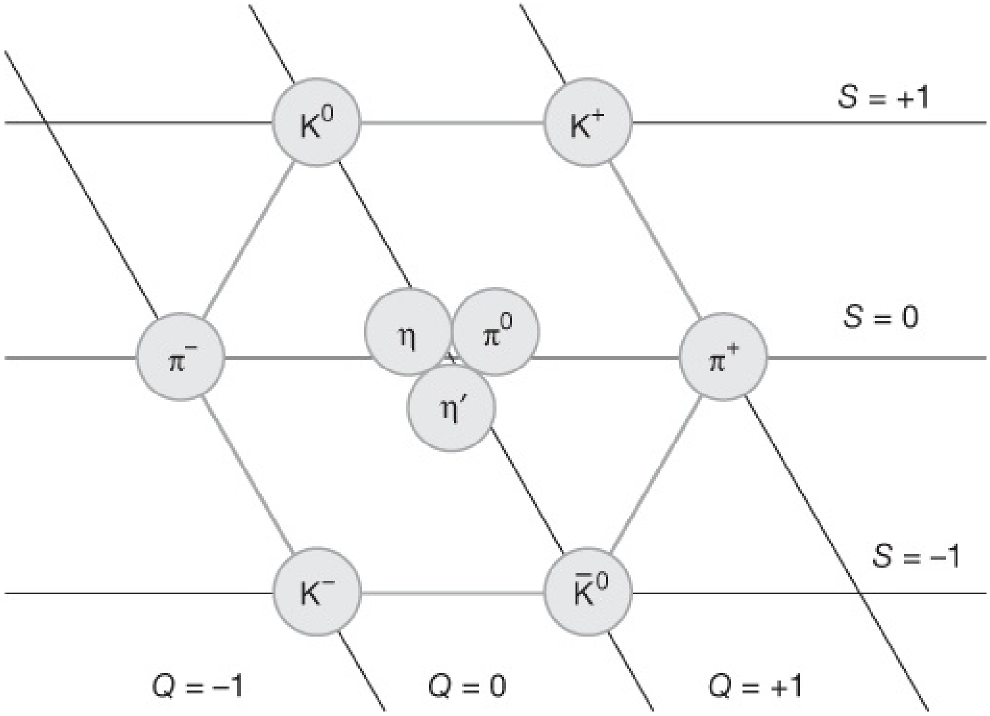

Figure 1.3 Gell-Mann’s Eightfold Way spin-0 pseudoscalar (negative-parity) meson nonet (octet plus a singlet).
SOURCE: Wikipedia Commons.

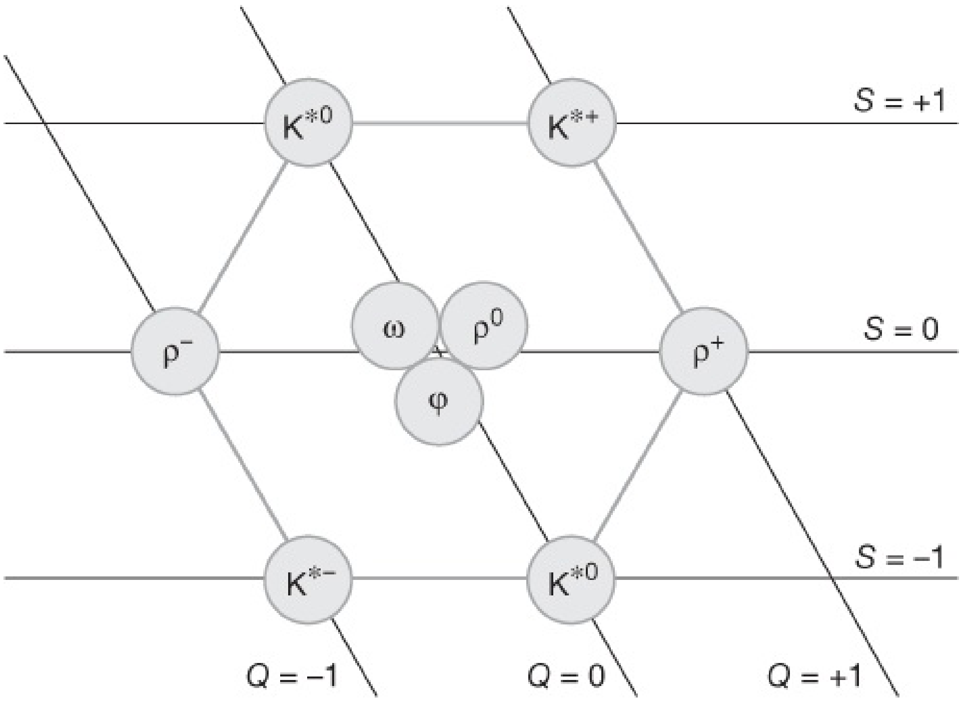

Figure 1.4 Gell-Mann’s Eightfold Way spin-1 pseudoscalar meson nonet (octet plus a singlet).
SOURCE: Wikipedia Commons.

The Lambda particle is an electrically neutral, short-lived particle discovered in 1947. Sakata included the Lambda in the triplet to account for the quantum number "strangeness." Abraham Pais first proposed a quantum number in 1952 to explain that certain particles, such as the Lambda, even though they were produced copiously in particle interactions, decayed slowly, having lifetimes typica of weak radioactive decays. This quantum number was dubbed *strangeness* by Gell-Mann. The idea o the triplet of proton, neutron, and Lambda was that all the other hadrons in the particle zoo were mad up of these three particles bound together. This idea did not fit with the experiments at the time and was abandoned. However, the idea of a stable triplet of basic constituent particles for matter persiste

"THREE QUARKS FOR MUSTER MARK!"

In 1963/1964, Murray Gell-Mann speculated on the basis of a suggestion by Robert Serber, a profess at Columbia University, that there were three basic constituents of all matter, which had not yet been observed. Gell-Mann understood that because these three constituent particles would make up proton and neutrons, which had a unit of positive electric charge and zero charge respectively, the charge of the constituent particles had to be fractional, ⅔ and ⅓, to create a plus-one or zero charge. Because no one had ever observed such fractional electric charges, this seemed an absurd idea. However, Gell Mann continued to pursue the idea and published a letter in *Physics Letters* in 1964 titled, "A Schematic of Baryons and Mesons," proposing that these fractionally charged particles played a mathematically important role in the basic constituents of matter.[3] In his letter, he called the particle *quarks*, taken from James Joyce's *Finnegan's Wake*: "Three quarks for Muster Mark!"

Meanwhile, George Zweig, who was a Caltech graduate visiting CERN as a postdoctoral fellow, proposed independently at about the same time an idea that was very similar to Gell-Mann's quark model. He called his basic constituents of the triplet *aces*. However, he did not publish his paper because senior physicists at CERN considered it to be too speculative. Zweig later recalled:

> The reaction of the theoretical physics community to the ace [quark] model was generally not benign. Getting the CERN report published in the form that I wanted was so difficult that I finally gave up trying. When the physics department of a leading university was considering an appointment for me, their senior theorist, one of the most respected spokesmen for all of theoretical physics, blocked the appointment at a faculty meeting by passionately arguing that the ace model was the work of a "charlatan."[4]

Gell-Mann and Zweig both agreed on the basic attributes of the quark model. There were three species of quarks. The "up" quark (u) and the "down" quark (d) have spin ½ and isospin ½ (called an *isospin doublet*). A third quark, called the *strange quark* (s), has isospin 0 (called an *isospin singlet*) and "strangeness" one. This third quark is needed to explain the existence of baryons carrying a nonzero strangeness number and also mesons like the positively charged K meson, which is compose of an up quark and an antistrange quark; and the neutral K meson, which is composed of a down quar and an antistrange quark. The three quarks—up, down, and strange—each have what is called *baryon number* equal to ⅓, so that the baryon number of the three quarks constituting a proton or neutron adds up to one.

The particle physics community was skeptical about the idea of protons and neutrons being made up of three quarks, and the need for fractional electric charge did not go down well either. Gell-Mann himself was not convinced that his quarks were real. He treated them as a productive way of

visualizing how matter is constituted, and as a mathematical trick to make sense of his Eightfold Wa
model of particles.

During a visit Gell-Mann made to the University of Toronto in 1974, he told me that he had initially submitted his quark paper to *Physical Review Letters* but it was rejected. He told me that he then phoned the theory director at CERN at the time, Leon van Hove, and said that he was planning t submit his quark paper to *Physics Letters B*, where Van Hove was an editor. Van Hove asked him wh a quark was, and he said it was a particle making up the triplet SU(3), which had fractional electric charge and baryon number ⅓. Van Hove was dismissive and didn't think it was a good idea for Gell-Mann to submit the paper for publication. However, Gell-Mann did, and it was accepted and publishe by *Physics Letters B*.

Yet soon, in 1968, the Stanford Linear Accelerator (SLAC) was used to begin experiments to try t detect quarks by bombarding atomic nuclei with electrons. The idea was to use the latest accelerator technology to repeat the Rutherford experiments that had discovered protons inside atomic nuclei. Rutherford had scattered a beam of alpha particles (helium nuclei composed of two protons and two neutrons) off gold leaf, and had found a sufficient number of alpha particles scattering at large angle to conclude that they had hit hard objects—namely, the nuclei of the gold atoms. Similarly, in the SLAC experiment, if the angles of the scattering of electrons hitting the insides of nuclear targets were sufficiently large, this would signal a significant deflection of the electrons by hard, massive objects, and would provide at least indirect proof that quarks existed inside protons and neutrons. Th experiments did indeed produce a distribution of scattering angles that strongly suggested that there were small objects inside protons.

Two kinds of experiments had already been performed in the linear collider to contribute to this conclusion. One was called *elastic proton–electron scattering*. These experiments showed that the proton was not a pointlike object like the electron; it had a diffused structure. This led physicist Robert Hofstadter to experimental investigations of the structure of the proton during the early 1950s for which he won the Nobel Prize for Physics in 1961. Subsequently, a series of experiments of so-called *deep inelastic scattering*, in which scattering electrons and protons produced other particles, d not behave as expected with increasing energy. The data suggested that there were some hard objects inside the proton. These experiments were performed on the 22-GeV, two-mile long linear electron accelerator at SLAC beginning in 1967. This research heralded the new "hard-scattering" era of particle physics, compared with the soft-scattering era that had previously dominated experimental particle physics. *Hard* scattering refers to the hard objects inside protons that were hit by the electro beams whereas *soft* scattering refers to proton–proton collisions in which a plot of the scattering cross-sections displayed a rapid fall-off with increasing energy, indicating that these experiments were not investigating the interior of the protons.

Initially, the Stanford experimentalists were not able to explain these radical deep inelastic scattering results. They knew that something important had been observed, but they were unable to understand the implications fully. At that time, particle physicists had not accepted the reality of fractionally charged quarks inside protons and neutrons. James Bjorken, fondly known as "BJ" by hi colleagues, who was a member of the theory group at SLAC, analyzed the experimental data and discovered a scaling relationship that could constitute proof of the existence of quarks inside the proton.[5] He analyzed the SLAC data in a somewhat esoteric way, using what was called "current algebra sum rules," and found that the electromagnetic structure of the proton scaled with a scaling parameter that consisted of the ratio of the energy loss by electrons radiating off photons and the energy of the new particles produced in the deep inelastic collision.

The experimentalists appreciated that Bjorken had made an important discovery, but a fuller understanding of the experimental results came about only when Richard Feynman visited SLAC in 1968 and invented what he called the "parton model" of strong interactions.[6] The partons were hard objects being hit by the electrons inside the proton, and Feynman was able to explain Bjorken's scaling result using this model. I discuss the parton model in more detail later in this chapter. Eventually, Feynman's partons were identified with Gell-Mann's quarks. Further experiments at SLAC, Brookhaven National Laboratory, and CERN were able to reveal the need for the quarks to have fractional electric charge.

In light of all this experimental evidence, there was a growing impetus for particle physicists to accept that the quarks were real particles and not some fictitious mathematical notion. Gell-Mann wa also eventually convinced that his quarks were real. However, why were the fractionally charged quarks not seen as independent particles experimentally? Why were they only able to be detected indirectly inside the protons and neutrons, when electrons bounced off them? In fact, how *were* they confined inside the protons and neutrons? Answering these questions led to an important turning poi in the development of particle physics, and eventually the quark model and the parton model were subsumed in quantum field theory based on the gauge principle.

The strange physical contradiction between the quarks and gluons of quantum chromodynamics (QCD)[7] and the old particles of nuclear physics, such as protons, neutrons, and electrons, is that the latter particles can be detected directly either by ionization of nuclei producing electrons or by high-energy accelerators. The fact that one cannot detect quarks and gluons directly as free particles outsi the proton was initially considered a failure of the QCD theory. It has not yet been possible to derive theory of quark and gluon confinement from first principles in QCD. That is, it has not been possible to provide a convincing explanation about why the quarks and gluons appear to be trapped within the nucleus and invisible to detection. Instead of obtaining an explanation of confinement from the basic mathematical formulas of QCD, physicists have been forced to come up with a somewhat ad hoc phenomenological explanation added in by hand. However, in the current particle physics communit this problem is simply ignored, and the hidden quarks and gluons are detected indirectly through hadronizing jets appearing as events after the collisions of protons with protons or with antiprotons. These jets consist of streams of hadrons (the particles that contain quarks and gluons), which, when analyzed, tell you which jet is associated with which quark in the detection process. Although the mystery of confinement has been, to some extent, set aside by the theoretical and experimental particle physics community, it still remains a problem that has to be resolved eventually to make QC a convincing theory.

TRYING TO MAKE SENSE OF QUARKS

Along with the mystery of "quark confinement," there was another serious problem in understanding the nature of quarks. The proton and neutron were made of different combinations of three up quarks and down quarks. However, these up and down quarks looked identical as far as the quantum spin ½ i concerned. According to Pauli's exclusion principle, which he discovered during the development of quantum mechanics during the 1920s, three fermions of spin ½ (such as quarks) cannot occupy the same quantum state to make up the proton. Something was wrong. It's like attempting to put three unruly identical triplets into a playpen, but each one refuses to be in the same space with the other two. If you try to put three of these up and down quarks into the same quantum state inside the proto and neutron, this would violate quantum statistics and Pauli's exclusion principle. Theoretical physicist Walter Greenberg proposed a way of solving this conundrum. He changed the nature of the quantum statistics for the quarks, calling the new statistics “parastatistics,” which allowed one to get around the problem with the Pauli exclusion principle for the quarks. To follow through with the analogy of the triplets, Greenberg proposed to put them in a newly constructed playpen in which they were comfortable with one another. By changing the quantum statistics, he managed to get the three quarks in the same quantum state. However, this was a somewhat radical solution to the problem.

Then, Yoichiro Nambu and Moo Young Han proposed yet another radical idea. They invented a new kind of charge associated specifically with quarks in order to bypass the problem of the Pauli exclusion principle. Murray Gell-Mann and Harald Fritzsch proposed that this new charge be called “color charge.” Now, each up and down quark could have one of three “colors”—red, blue, or green. These colors are, of course, not real colors, but are simply used as labels for the new charge. This proposal provided, in effect, three times more quarks for nature to choose from when building particles. The observed hadrons such as baryons and mesons were termed *colorless* or *white*, indicating that their color charges always combined to make the observed hadrons color-neutral.

In collaboration with Swiss physicist Heinrich Leutwyler, Gell-Mann and Fritzsch discovered the mathematical theory underlying the colored quarks. They bound the three colored quarks in the proton by massless force carriers that they called *gluons*, which in turn had their own colors. The mathematical symmetry group describing these colored quarks and gluons was SU(3), but this was a different kind of SU(3) from Gell-Mann’s original Eightfold Way SU(3). The different kinds of quarks and leptons are named by their “flavors.” The three flavors of quarks known during the late 1960s—up, down, and strange—constituted the fundamental triplet of SU(3), whereas the gluon force carriers were represented by the octet of SU(3). In contrast to the colorless photon of electromagnetism, each gluon is a combination of two colors of the three possible colors, to produce eight colored gluons.

In keeping with the fashion among particle physicists of giving fancy titles to particles and theories, Gell-Mann christened the new theory of colored quarks and gluons *quantum chromodynamics*, using the Greek word *chromo*, which means “color.” To accommodate the fact that quarks were always confined and never seen experimentally in high-energy collisions, the hadrons, which are the particles that undergo strong interactions such as protons and neutrons, were colorless and were described as *color singlets* in QCD. In other words, the colored quarks were always combined to produce a colorless hadron. For example, in the mesons, which are composed of a quark and an antiquark, a red quark combines with an anti-red quark to produce a colorless meson. And in the proton, a red, green, and blue quark combine to produce a colorless proton. This means that the hadrons we observe in accelerators do not reveal the colored quarks, which are confined inside them. This, of course, does not explain the dynamics of confinement, and how they came to be that way, but simply indicates the fact that we cannot observe free quarks. The dynamic mechanism of confinement is still a controversial issue in particle physics. (See Figure 1.5 for a summary of the elementary particles of the standard model, and Figure 1.6 for a description of the quark colors.)

FOUR, FIVE, AND SIX QUARKS FOR MUSTER MARK!

James Bjorken and Sheldon Glashow published a paper in 1964 predicting the existence of a fourth quark, which they called the “charm” quark.[8] The four quarks were represented by the fundamental quartet representation of SU(4), which replaced the triplet representation of SU(3). I also came up with the prediction that a fourth quark should exist, and published a paper in *Physical Review* in

1965,[9] with a fractionally charged fourth quark and fractional baryon number. Bjorken and Glashow’ fourth quark had integer charge and baryon number because it was still early days for physicists to accept the idea that quarks were fractionally charged. I called my additional fractionally charged quark simply the “fourth quark,” not nearly as flashy as “charm.”

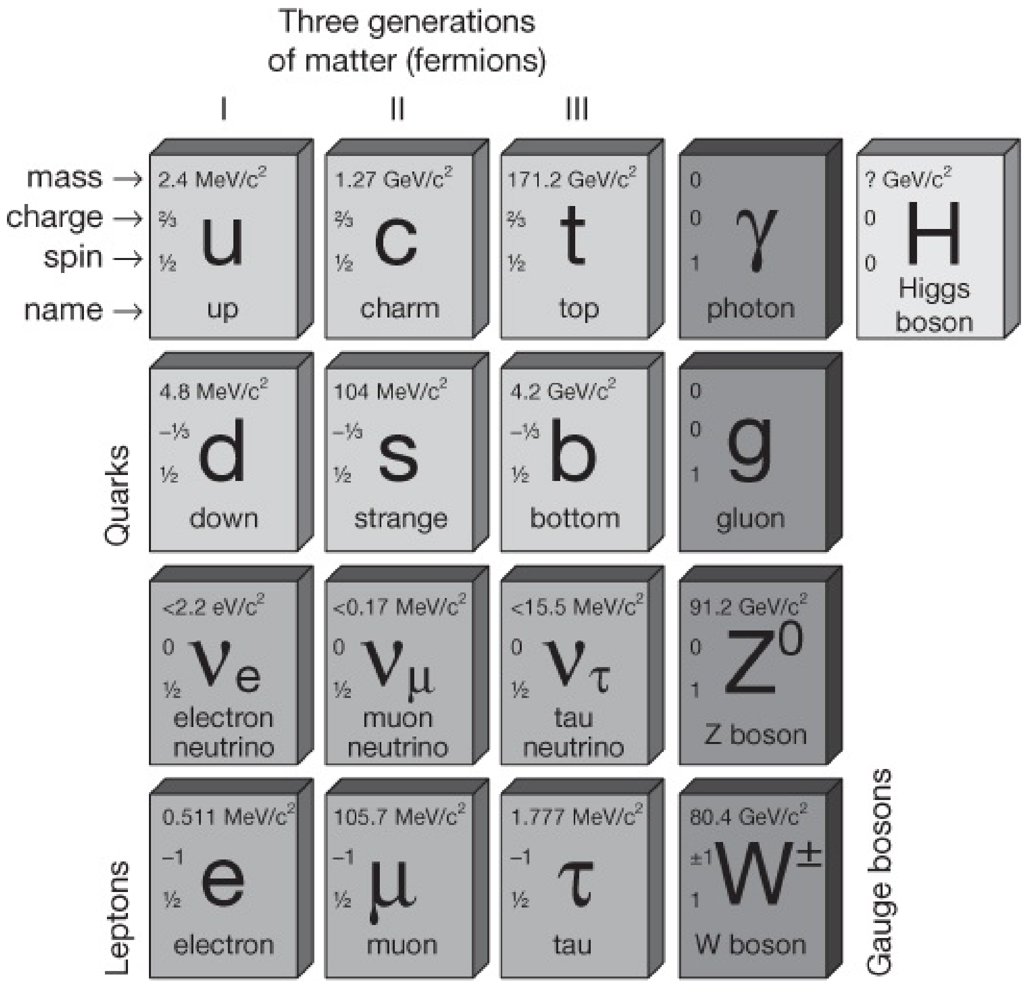

Figure 1.5 The elementary particles of the standard model of particle physics. The quarks and leptons are named by their “flavor,” with six quark flavors and six lepton flavors. The scalar Higgs boson is not a gauge boson, so it is not included in the fourth colum of gauge bosons.

SOURCE: PBS NOVA/Fermilab/Office of Science/US Dept of Energy.

The three quarks—up, down, and strange—constituted three so-called flavors of quarks. The high-energy experiments showed two kinds of currents associated with the weak force to create radioactiv decay. One is an electrically charged current in which quarks are coupled to the charged intermediate vector boson W, and the other is a neutral current that is coupled to the neutral vector boson Z. In weak decays of particles, the charged W boson associated with the charged current can change the charge and flavor of quarks, while the neutral Z boson cannot change the quark charge and flavor. During these neutral Z interactions, no decays of hadrons have been observed that change the quark flavor through the decay.

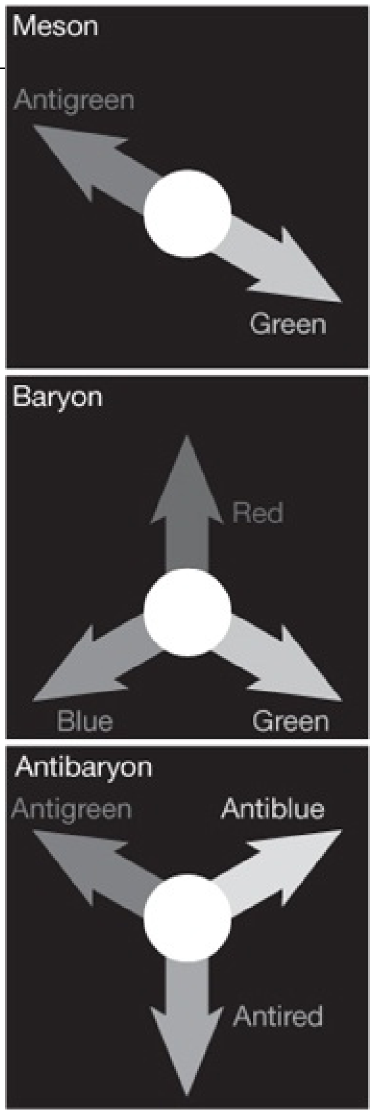

Figure 1.6 The quark color combinations of mesons and baryons.
SOURCE: Wikipedia.

This restriction of neutral current decays in the flavors of quarks is known as the *anomaly problen* In 1970, Sheldon Glashow, John Iliopoulos, and Luciano Maiani used the idea of a fourth quark to solve this anomaly problem in the quark model. They found a way to explain the experimental fact that, in neutral current decays, there was no change of flavor going from the decaying quark to its decay products containing quarks. The *GIM mechanism* (with GIM standing for Glashow, Iliopoulos, and Maiani) explained the lack of flavor-changing neutral currents in weak interactions. This observational fact called for the existence of a fourth quark, which had been predicted in 1964 and 1965.

The quark revolution began to culminate in 1974, when one group at Stanford, headed by Burton Richter, and another at Brookhaven, headed by Samuel Ting, discovered a narrow resonance that was identified immediately as being composed of a charm and an anticharm quark. Ting called the new charm resonance "the J particle," whereas Richter called it "the psi particle," and it eventually becam known as the *J/psi particle*. The narrowness of the new resonance was caused by it being a tightly bound composite of a charm and an anticharm quark, which was later called a *quarkonium system*.

We now had four quarks confirmed experimentally: up, down, strange, and charm. In 1977, Leon Lederman and his collaborators at Fermilab discovered a fifth quark, which was called the *bottom* (o *beauty*) *quark*. It was known theoretically from the properties of QCD that there had to be a sixth quark and, of course, it would be called the *top* (or *truth*) *quark*. Indeed, it was discovered in 1995, also at Fermilab. The names *top* and *bottom* had been introduced by Israeli physicist Haim Harari in 1975, two years before the discovery of the bottom quark, to replicate at higher masses the up and down quarks.

The story of these last two quarks, or the third generation of quarks, is worth telling in more detai In 1973, Japanese physicists Makoto Kobayashi and Toshihide Maskawa had predicted the existence of a third generation or family of quarks to explain the violation of charge conjugation and parity in the decay of K mesons. Charge conjugation is a mathematical transformation of a positively charged particle to a negatively charged one, and vice versa. This transformation turns a particle into its antiparticle. Parity is left–right symmetry in particle physics. This third generation of quarks was required to implement the GIM mechanism. The 1978 discovery by Martin Perl at SLAC of the tau lepton strengthened the need for the introduction of a fifth and sixth quark to implement the GIM mechanism fully, which explained why flavor-changing neutral currents were not detected.

It was not easy to discover these fifth and sixth quarks. Early searches for the top quark at SLAC and at the German accelerator, the Deutsches Elektronen Synchrotron (DESY) in Hamburg, came up with nothing. In 1983, when the super proton synchrotron (SPS) at CERN detected the W and Z bosons, experimentalists at CERN felt that the discovery of the top quark was imminent. A race soon ensued between the Tevatron in the United States, with an energy of 2 TeV, and the SPS collider at CERN to discover the top quark. However the SPS machine reached its energy limit without finding the top quark, which was expected, at the time, to have a mass of about 40 GeV, whereas the energy limit of the SPS was 77 GeV.

At this stage, only the Tevatron accelerator at Fermilab had enough energy to detect the top quark with a mass that was now expected to be greater than 77 GeV. The two detectors, the Collider Detect at Fermilab (CDF) and the D0 detector also at Fermilab, were actually built to discover the top quark Indeed, in 1992, the two groups associated with these two detectors saw the first hint of a top quark. I was a tempting clue that the top quark discovery was imminent. By 1995, there were enough events t establish the existence of the top quark at an energy of about 175 GeV.

We now have six quarks discovered in the lineup of elementary particles. In the standard model, however, there also had to be six leptons to match them. Indeed, new leptons were discovered eventually. In addition to the electron and the muon, there was the tau and also a neutrino associated with each of these leptons: the electron neutrino, the muon neutrino, and the tau neutrino. These quarks and leptons are the basic building blocks of the standard model (Figure 1.5).

THE FORCES OR INTERACTIONS IN NATURE

There are four basic forces in nature that have been confirmed experimentally: strong, electromagnetic, weak, and gravity. The weakest force is gravity. Isaac Newton published in his *Principia* in 1687 the first universal gravity theory based on his mechanics. Newton hypothesized tha the inverse square law of gravity held true everywhere in the universe. The strength of this gravitational force was proportional to Newton's gravitational constant, and his calculations agreed with the observed 28-day period of the moon with remarkable accuracy. In 1916, Einstein published his seminal paper on generalizing his special theory of relativity to include gravity and named it the "general theory of relativity."[10] He postulated that gravity was not a "force" between two masses, as had been under Newton, but was a warping of spacetime geometry by matter. A key prediction of his new theory was accounting for an unusual feature of the planet Mercury's orbit. The perihelion, or