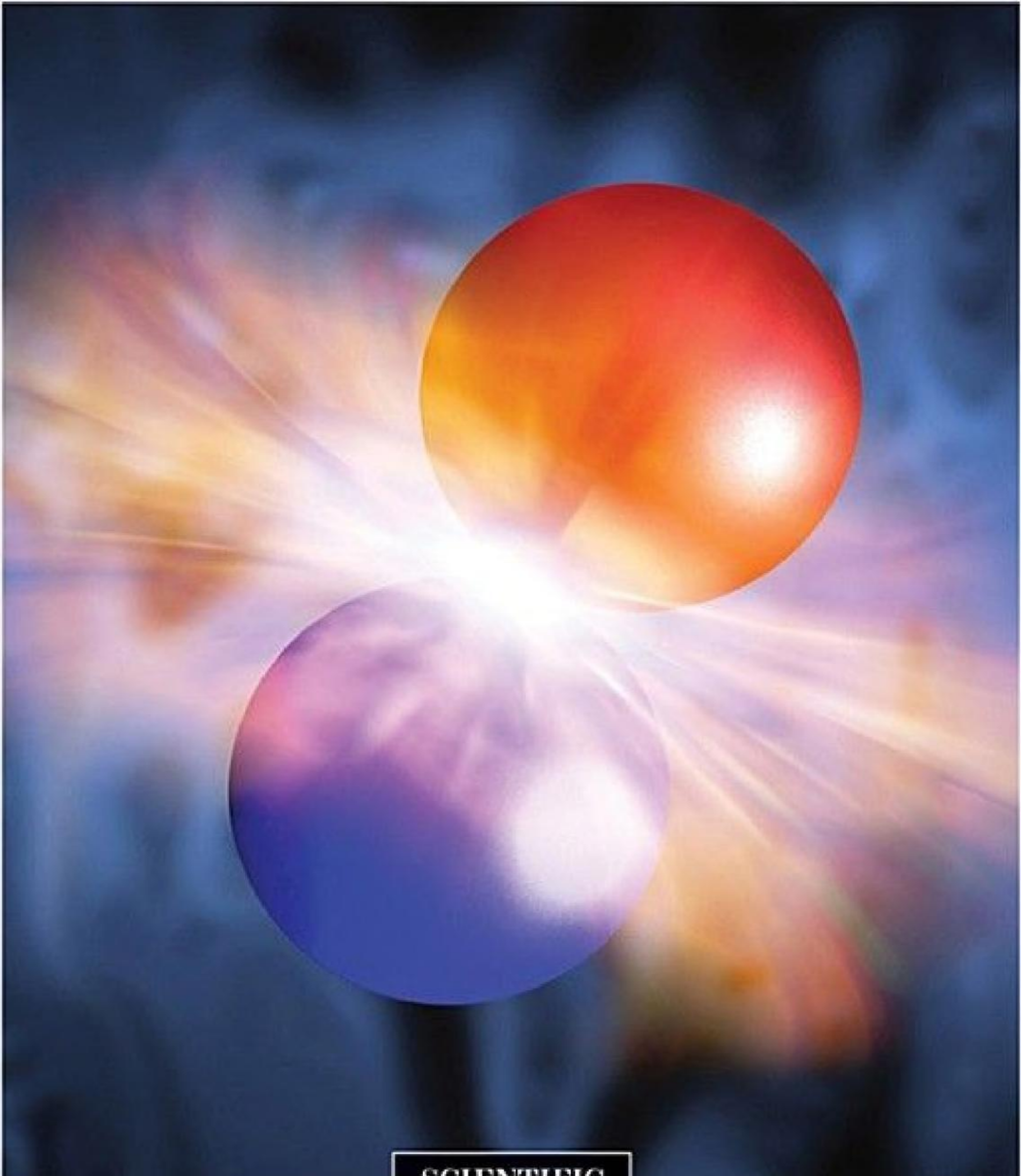
ULTIMATE PHYSICS

From Quarks to the Cosmos



SCIENTIFIC
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Ultimate Physics

From Quarks to the Cosmos

From the Editors of Scientific American

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Letters to the Editor

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THE BROADER OUTLINES OF THE PHYSICAL WORLD, FROM QUARKS to the cosmos, have been apparent for decades. Does this mean physicists are about to tie it all up into a neat package? Not at all. Just when you think you know everything, the universe begins to look its strangest.

The detection of what seems for all the world to be a Higgs boson illustrates this idea beautifully. The Large Hadron Collider at CERN near Geneva has provided fodder for physicists from many nations working on a variety of projects but none more important or as eagerly awaited as the confirmation of the Higgs. Our fly-on-the-wall look at scientists poring over data on small perturbations measured with ultrasensitive instruments shows clearly how answers lead to more questions. The data appear to confirm the Standard Model, the theoretical edifice of particle physics, but also reveal subtle and significant ways in which reality diverges from theory, opening up new vistas for exploration.

Just as physicists thought they had found the smallest building blocks of matter—the tiny quarks and leptons—signs have begun to emerge that there are smaller particles still. Proof of their existence would throw physics into complete disarray, however. Further, scientists have never fully understood the neutrino—a ghostly particle that rains down on the planet but usually passes through us, and all matter, unnoticed. The neutrino is therefore another avenue to new inquiries.

On the largest of scales, scientists feel they are closer than ever before to understanding how the universe began and how it will end. Yet other mysteries are as deep as they ever were. Dark energy, which helps to explain why the universe continues to expand at an accelerating rate, remains an enduring puzzle. Now some scientists are beginning to suspect that dark energy does not exist after all. If they are right, basic notions of the universe going back to Copernicus would need a radical revision.

One of the most compelling intellectual problems of our time remains unsolved: How do we tie together the realms of quantum mechanics and general relativity—the very small and the very large? Such a “theory of everything,” which has played cat and mouse with scientists for decades, may remain forever out of reach, argue physicists Stephen Hawking and Leonard Mlodinow. If that makes you sad, consider that quantum mechanics, an Alice in Wonderland theory that seems to impose severe constraints on what we can know and do, may in fact liberate us by opening a new path to insight. The universe may be finite, but knowledge has not yet been pegged.

--Fred Guterl
Executive Editor

SECTION 1

The Very Small

The Higgs at Last

by Michael Riordan, Guido Tonelli and Sau Lan Wu

LATE ON THE EVENING OF JUNE 14, 2012, GROUPS OF GRADUATE students and postdoctoral researchers working on the Large Hadron Collider began peering into a just opened data cache. This huge machine at CERN, the European laboratory for particle physics near Geneva, had been producing tremendous amounts of data in the months since it awoke from its winter-long slumber. But the more than 6,000 physicists who work on the LHC's two largest experiments were wary of unintentionally adding biases to their analysis. They had agreed to remain completely unaware of the results—performing what are called "blind" analyses—until mid-June, when all would suddenly be revealed in a frenzy of nocturnal activity.

Many of the young scientists worked through that night to untangle the newly freed threads of evidence. Although the LHC is a giant collider feeding multiple experiments, only the two largest ones—ATLAS and CMS—had been tasked with finding the Higgs boson, the long-sought particle that would complete the Standard Model of particle physics, the theoretical description of the subatomic world. Each massive detector records the subatomic debris spewing relentlessly from proton collisions in its midst; a detailed, independent accounting of these remnants can reveal fleeting new phenomena, including perhaps the elusive Higgs boson. Yet the detectors have to sift through the particle tracks and energy deposits while enduring a steady siege of low-energy background particles that threaten to swamp potentially interesting signals. It is like drinking from a fire hose while trying to ferret out a few tiny grains of gold with your teeth.

Fortunately, the scientists knew what they were looking for. After the LHC's disastrous start—an electrical splice between two magnets warmed and melted just nine days after the LHC came online in 2008, triggering a powerful spark that punctured the surrounding vessel, released tons of helium and ripped scores of costly superconducting magnets from their mounts—the collider had been collecting reams of data during 2011, enough to pick up an early hint of a Higgs signal.

After that run ended in October for its scheduled winter shutdown, Fabiola Gianotti, then spokesperson for ATLAS, and one of us (Tonelli), then spokes person for CMS, delivered a special seminar to an overflowing audience in the main CERN auditorium. Both detectors independently found suggestive bumps in the data.

What's more, these telltale hints of a Higgs boson corroborated one another. Both ATLAS and CMS reported several dozen events above the expected background in which two photons came blazing out with combined energies of 125 billion electron volts, or 125 GeV. (GeV is the standard unit of mass and energy in particle physics, about equal to a proton mass.) If proton collisions had created short-lived Higgs bosons, they could have decayed into these photons. Each experiment also found a few surplus events in which four charged leptons (electrons or muons) carried off similar total energies. These could also have been the result of a Higgs. Such a concurrence of signals was unprecedented. It suggested that something real was beginning to appear in the data.

Yet given the stringent norms of particle physics, none of the signals observed in 2011 were strong enough to allow for claims of a “discovery.” Data peaks and bumps like this had often proved ephemeral, mere random fluctuations. And the successful spring 2012 run, which generated more proton collisions in 11 weeks than had come in during all of 2011, could easily have washed out the nascent data peaks, smothering them in background noise.

Of course, the opposite could occur, too. If the bumps were the result of an actual Higgs boson, not just a cruel statistical artifact, all the new data gave researchers a good chance of being able to claim an official discovery—ending this decades-long search and beginning a whole new era in our understanding of matter and the universe.

A THREE-DECADE SEARCH

Never just another particle, the Higgs boson is the cornerstone of a grand intellectual edifice known as the Standard Model, the interwoven set of theories that constitute modern particle physics. This particle’s existence had been suggested in 1964 by Peter W. Higgs of the University of Edinburgh as the result of a subtle mechanism—independently conceived by François Englert and Robert Brout in Brussels plus three theorists in London—that endows elementary particles with mass. The Higgs boson is the physical manifestation of an ethereal fluid (called the Higgs field) that permeates every corner of the cosmos and imbues elementary particles with their distinctive masses. With the discovery of quarks and gluons in the 1970s and the massive, weak-force-bearing *W* and *Z* bosons during the early 1980s, most of the elements of the Standard Model had fallen neatly into place.

Although theorists asserted that the Higgs boson—or something like it—must exist, they could not predict what its mass might be. For this and other reasons, researchers had few clues about where to look for it. An early candidate, weighing in at less than nine times the proton mass, turned up in 1984 at a refurbished, low-energy electron-positron collider in Hamburg, Germany. Yet the evidence withered away after further study.

Most theorists agreed that the Higgs mass should be 10 to 100 times higher. If so, discovering it would require a much larger and more energetic particle collider than even the Fermi National Laboratory's Tevatron, a six-kilometer proton-antiproton collider completed in 1983. That same year CERN began building the billion-dollar Large Electron Positron (LEP) collider, boring a 27-kilometer circular tunnel that crossed the French- Swiss border four times near Geneva. Although LEP had other important physics goals, the Higgs boson was high on its target list.

U.S. particle physicists, encouraged by the Reagan administration to "think big," pushed through grandiose plans for a much larger, multibillion-dollar machine, the Superconducting Super Collider (SSC), in the late 1980s. With a proton-proton collision energy of 40 trillion electron volts (40 TeV, or 40,000 GeV), the SSC was designed to track down the Higgs boson even if it were to come in at a mass near 1,000 GeV.

But after the SSC's projected price tag nearly doubled to $10 billion, Congress voted to kill it in 1993. Dismayed, U.S. Higgs hunters thereafter turned back to Fermilab and CERN to pursue this research. Discoveries and precision measurements made at LEP and the Tevatron soon implied that the Higgs boson should be no more than 200 GeV, which put it potentially within reach of these colliders. In over a decade of searching, however, physicists found no lasting evidence for Higgs-like data bumps.

During the final LEP runs in the summer of 2000, physicists decided to push the collision energy beyond what the machine was designed to handle. That is when hints of a Higgs boson began appearing. In September two of the four LEP experiments reported evidence for a handful of events with a *Z* boson plus another mystery particle that decayed into two bottom quarks—a particle that looked a lot like a 115-GeV Higgs boson. CERN's then director Luciano Maiani granted the machine a six-week stay of execution that autumn, but during that period researchers could unearth only one more candidate event. It was not sufficient. After a heated debate, Maiani decided to shut LEP down and begin its planned conversion into the LHC, a machine designed to find the Higgs boson.

CLOSING IN ON DISCOVERY

The LHC is the most spectacular collection of advanced technology ever assembled. Built inside the original LEP tunnel by hundreds of accelerator physicists and engineers led by project manager Lyndon Evans, it uses little left from that collider. Its principal components include more than 1,200 superconducting dipole magnets—shiny, 15-meter-long cylinders worth nearly $1 million each. Probably the most sophisticated components ever mass-produced, by firms in France, Germany and Italy, they harbor twin beam tubes that are flanked by niobium-titanium magnet coils bathed in liquid helium at 1.9 kelvins, or –271 degrees Celsius. Inside, twin proton beams circulate in both directions at energies up to 7 TeV and velocities approaching light speed.

The beams resemble those of a pulsed laser rather than a flashlight. Each consists of almost 1,400 "bunches," containing up to 150 billion protons apiece—about the number of stars in the Milky Way. Under normal operations, 10 to 30 proton collisions occur during each bunch crossing. That corresponds, however, to around half a billion collisions per second.

Proton collisions are far messier than electron-positron collisions. Theorist Richard Feynman of the California Institute of

Technology once compared the process to smashing garbage cans into garbage cans, which means that lots of junk comes out. Protons are composite objects made of quarks and gluons; in the most interesting events, two gluons collide at energies above 100 GeV—and occasionally up to 1 TeV. Physicists, aided by sophisticated detectors, custom-built electronics and state-of-the art computers, try to sift the few events corresponding to interesting physics from the billions of dull, uninteresting ones.

The ATLAS and CMS experiments cannot observe a Higgs boson directly—it would decay into other particles far too quickly. They look for evidence that it was created inside. Depending on the Higgs boson’s mass, it could decay into lighter particles in a variety of ways. In 2011 attention began to focus on its rare decays into two photons and four charged leptons because these signals would stand out starkly against the tremendous backgrounds that could easily swamp a Higgs signal.

The year’s delay caused by the 2008 magnet disaster gave Fermilab physicists one last shot at making a Higgs discovery. Just before the scheduled Tevatron shutdown in September 2011, the CDF and DZero experiments at the collider reported small excesses of events in which bottom quark pairs appeared at combined energies from 125 to 155 GeV. But as in the LEP closure, the researchers could not convince the lab director to grant them a reprieve, and the Tevatron was soon shut down. (In March 2012 these physicists reported a more detailed analysis that showed a bulge centered at 125 GeV, reinforcing the CERN results.)

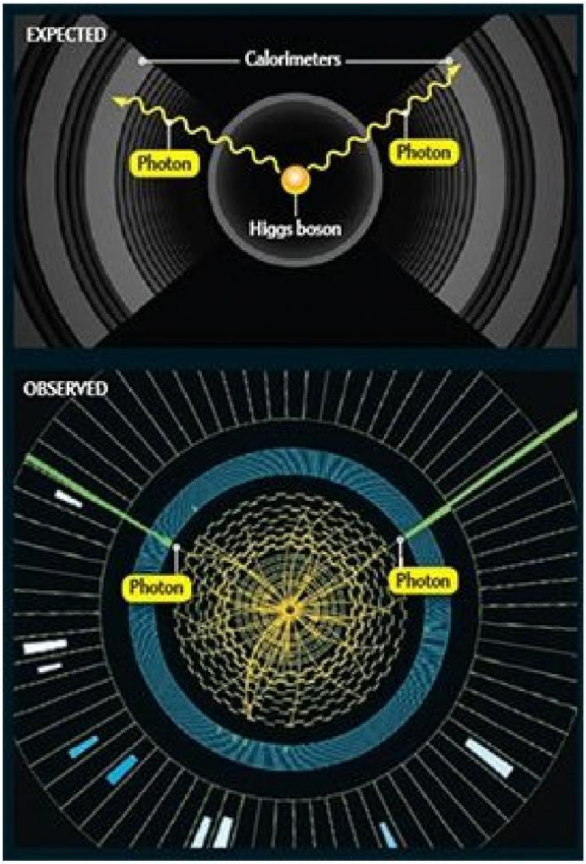
The Delicate, Rare Fingerprints of the Higgs

The Higgs boson is an extremely unstable particle that quickly decays via a number of different processes, or “modes.” Unfortunately, many decay modes are indistinguishable from the thunderous din of ordinary background events that result from

500 million proton-proton collisions every second. The ATLAS and CMS experiments are designed to spot the occasional interesting events that might come from the Higgs decay and throw much of the rest away. The drawings below show four of the most important decay modes that experiments use to search for the Higgs, along with images of actual Higgs-like signals that CMS observed in the 2011 and 2012 runs. (Because the discovery is statistical in nature, no single event can be used as definitive proof.)

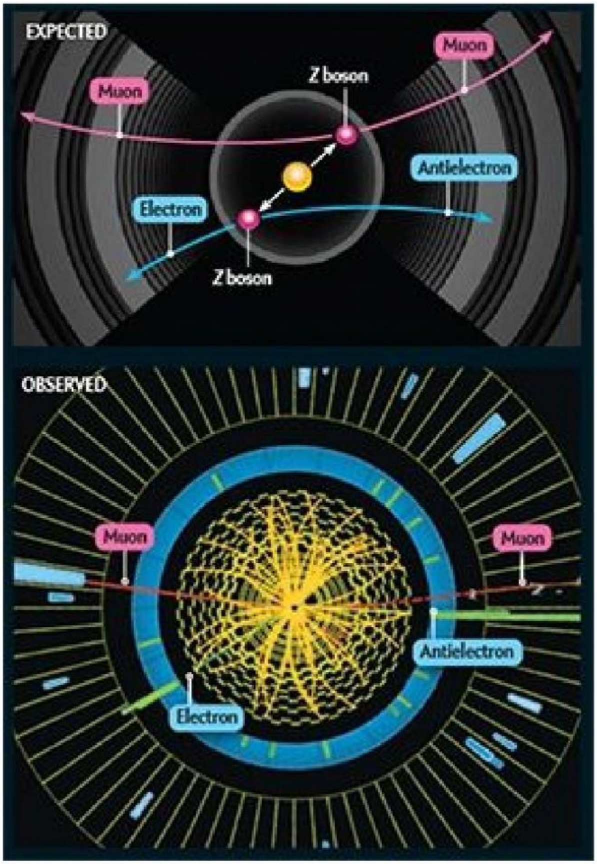
Photons

Each detector includes multiple calorimeters, devices for measuring the energy of particles. The innermost calorimeter is particularly alert for photons. These are absorbed in the calorimeter and create tiny electrical signals. If a Higgs decays into two photons, the detector can measure their total energy at extremely high accuracy, which helps to precisely reconstruct the mass of the newly found particle.



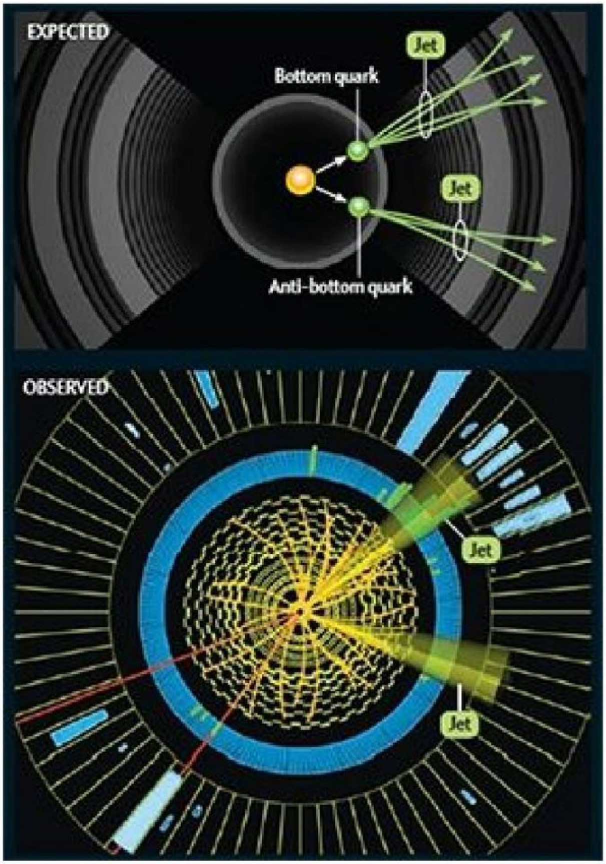
Z Bosons

The Higgs may decay into a pair of *Z* bosons, each of which can decay into an electron paired with an oppositely charged antielectron or two muons. An inner tracker and calorimeter measure the electrons, while muons fly out, leaving footprintlike tracks as they go. High magnetic fields bend the path of electrons and muons during their trip, allowing for a high-resolution measurement of their energy and the original Higgs mass.



Bottom Quarks

The Higgs can also decay to a bottom quark and its antiparticle, each of which decays into a tight “jet” of secondary particles called hadrons (composite particles made of quarks). These hadrons fly through the detector’s inner layers and deposit their energy in the outer calorimeters. Unfortunately, many ordinary collisions also generate jets of hadrons from bottom quarks, which makes it difficult to separate these Higgs events out from the background.



W Bosons

The Higgs can also decay to two *W* bosons, each of which can decay into an electron, antielectron or muon, plus a neutrino or antineutrino. Neutrinos are nearly impossible to detect—they fly out of the detector as if they were never there, taking with them some of the event's energy. Researchers use this missing energy to infer their presence, but the missing energy also prevents them from accurately reconstructing the mass of the original Higgs boson.

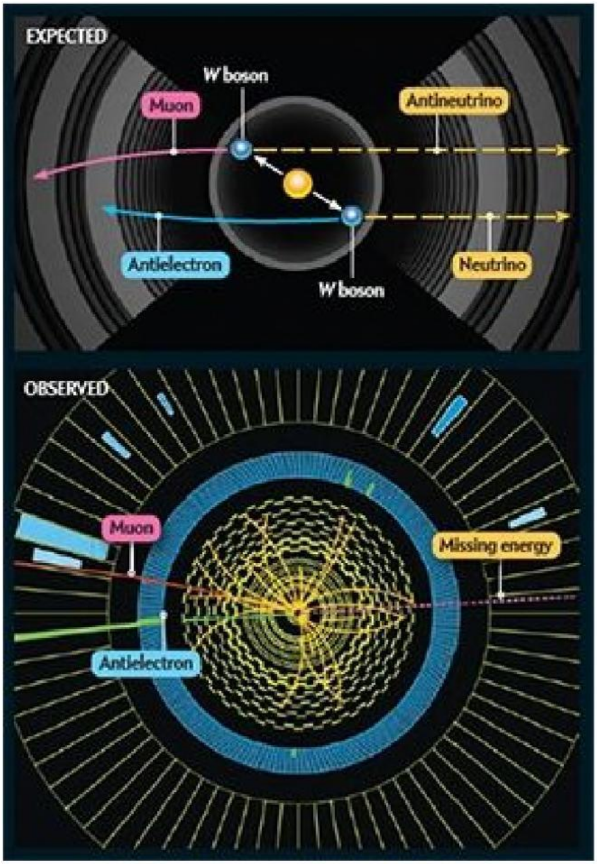


Illustration by George Resteck; Source: Courtesy of CERN (observed signals from CMS detector)

CROSSING THE LINE

By May 2012 the LHC was producing data 15 times faster than the Tevatron had ever achieved, thanks to efforts of physicists and operators led by accelerator director Stephen Myers. This run was a culmination of two decades of work by thousands of ATLAS and CMS physicists who built and now operate the detectors, designed and now manage a computer system that distributes data around the world, created novel hardware and computer software to identify the most interesting collisions, and wrote the algorithms that dig out the most pertinent events from the great morass of data being recorded. They all worked feverishly, anticipating a discovery. So when the researchers opened their data sets in mid-June, they had torrents of events to sift through. After graduate students and postdocs worked through the night, they anxiously prepared to reveal what had turned up.

It was a hot afternoon on June 15, 2012, when CMS physicists began gathering in Room 222 of the CERN filtration plant to hear the young physicists' reports. Soon the room was crowded with hundreds of collaboration members—out of about 3,000 in all—many of them standing or sitting on the floor. Few had slept much the night before. Tension and excitement gripped the room.

The first speaker discussed one possible Higgs decay route, or "channel," into pairs of *W* bosons. A small excess of events appeared in the low-mass region of most interest, but the faint signal generated no great excitement. Then presentations on the rare four-lepton and two-photon decays came one after the other. Now it indeed looked like a Higgs boson was showing up at long last. The signals from the 2012 data were occurring again in the same vicinity—near 125 GeV—that had so tantalized researchers six months earlier. Scientists realized almost immediately that if they were to combine the new data with the 2011 results, chances were good that CMS could claim a Higgs discovery. The crowd cheered at the end of the two key presentations.

Similar revelations occurred in the ATLAS experiment. Spontaneous celebrations broke out in several groups when they first glimpsed the new data. Yet it took more than a week of long workdays and sleepless nights before ATLAS physicists were certain that they had enough good events to conclude that the chances that their results were due to random fluctuations were less than one in three million—corresponding to the stringent "five sigma" standard that particle physicists require before claiming a discovery. At the thrilling moment of recognition, one ATLAS group of about a dozen physicists, meeting in Building 32 on the afternoon of June 25, 2012, erupted in loud clapping and cries of joy, which echoed down the hallway.

By that time word of a discovery had leaked out. Worldwide interest began growing so intense that secrecy was placed at a premium. There were to be no further leaks before the official word was presented, particularly because the exact content of documents under preparation could change. ATLAS members were not supposed to talk about the recent results with CMS physicists, nor vice versa. Individual physicists, however, could not resist discussing the news many had awaited so long. Hushed conversations in the CERN cafeteria and corridors suggested that something big was building up. Pressure to go public swelled.

CERN director Rolf-Dieter Heuer got an early glance at the findings in a June 22, 2012, meeting with Gianotti and Joseph Incandela of the University of California, Santa Barbara, Tonelli's successor as CMS spokesperson. Heuer decided that the evidence was strong enough to make public. He immediately informed the CERN Council (its governing body) to keep them abreast of the fast-moving developments. Heuer then decided to hold a joint seminar at CERN on July 4, 2012, timed to coincide with the opening of the 36th International Conference on High Energy Physics in Melbourne, Australia, followed by a CERN press conference.

The night before the seminar, hundreds of physicists dozed fitfully in the hallways outside the locked main auditorium, desperately hoping to get one of the unreserved seats remaining inside. Myers, Evans and four prior CERN directors who had been heavily involved with the LHC since its conception were seated in the front row. Having just flown to Geneva, Peter Higgs walked in to warm, sustained applause and sat down next to Englert.

Incandela and then Gianotti showed blizzards of slides about the new data and results, mostly covering the 2012 measurements. As in December, graphs of two-photon data revealed striking peaks jutting out at 125 to 126 GeV. And this time around, the experiments had more than a dozen extra events in which a heavy particle had exploded into four charged leptons at 125 GeV. Subtle peaks had begun to form in that channel, too.

That clinched it. Combining this result with the two-photon one, CMS and ATLAS independently concluded that the chances that the apparition was a fluke, due to random fluctuations, were less than one in three million. It had to be real. When the camera panned to Higgs, he could be seen pulling out a handkerchief to wipe his eyes.

“I think we have it,” exulted Heuer, wrapping up the seminar to sustained applause. “We have a discovery,” he went on, guardedly using the word at last. “We have observed a new particle consistent with a Higgs boson.”

A NEW ERA IN PHYSICS?

Few physicists doubt that a heavy new particle has turned up at CERN, but there is still debate about its exact nature. CERN officials initially spoke cautiously on this question, calling it a “Higgs-like” boson, but in March announced that it is indeed a Higgs—though not necessarily the only one. Although physicists have not yet proved beyond a doubt that the new particle has the required property of zero “spin,” preliminary data strongly favor that value. The ATLAS experiment continues to observe more two-photon events than expected , while CMS is reporting results consistent with Standard Model expectations based on a similar amount of data. Could something be amiss here?

Since July 2012 attention has become focused on whether the new particle is indeed “the” Higgs boson as predicted by the

Standard Model. That question can be resolved by determining how the new boson decays into other particles. Results released by ATLAS and CMS since July 2012 show that the Higgs signal has greatly improved, while difficult-to-measure decays into bottom quarks and tau leptons are beginning to appear at about the expected frequency. Meanwhile Fermilab physicists published evidence from the Tevatron for decays of the new particle into bottom quarks. Analyses of the combined LHC and Tevatron data by CERN theorists John Ellis and Tevong You indicated that the new particle, as they put it, “does indeed walk and quack very much like a Higgs boson.”

The new particle’s connection with a pair of high-energy photons has stimulated intrigue. Because the Higgs field imbues elementary particles with mass, it should interact more strongly with heavier particles. Photons have no mass, so the Higgs boson produces them via a mechanism involving other, massive particles. Additional heavy particles (which are required by supersymmetry and other theories) could enhance the process—as may be happening, based on early data. If the tendency holds up, it will strongly suggest physics beyond that described by the Standard Model.

The Higgs discovery marks the end of a long era in particle physics and the beginning of an exciting new phase. After decades in the doldrums, the discipline is energized once again by the heady intercourse of theory and experiment. Questions abound that may find answers from further research on this fascinating particle or its potential partners. Does it play a role in the inflation mechanism considered the force driving the big bang origins of the universe? Does it interact with dark matter particles thought to inhabit the cosmos? And what higher-energy mechanism or process, if any, shields the fragile vacuum from instabilities that may threaten the existence of the universe as we know it?

Although we celebrate the triumph of the Standard Model, such a lightweight Higgs boson should be extremely sensitive to physics lying beyond it. The particle opens up a fabulous new laboratory for further experimentation . Are its properties exactly as predicted? The apparent discrepancies in the early data could be random fluctuations that disappear in months to come. Or perhaps they are offering subtle hints of intriguing new physics.

Five Decades of the Higgs

The 2012 discovery of a Higgs-like particle marks the culmination of a decades-long search. In the years before the Standard Model of particle physics came together, researchers realized that they had no explanation for why particles should have mass. A series of theoretical insights suggested that a new type of field—now called the Higgs field—could slow particles down and give them their inertia. This field should have a particle counterpart, and so the search for the Higgs was on.

August 1964 - THE PAPERS

François Englert and Robert Brout publish the first of three papers proposing a particle and mechanism that will come to be named after Peter W. Higgs, author of the second paper, which is published two weeks later. Gerald Guralnik, Carl Hagen and Tom Kibble publish the third paper in November.

August 1979 - GLUON DISCOVERED

Scientists first observe the gluon, the particle responsible for nuclear forces, at the DESY lab oratory in Hamburg, Germany. Theorists calculate that gluon fusion will create more Higgs bosons than any other process.

January 1983 - W BOSON DISCOVERED

One of the last missing pieces of the Standard Model is uncovered when an experiment at the Super Proton Synchrotron at CERN near Geneva spots *W* bosons for the first time.

July 1989 - NEW COLLIDER COMES ONLINE
In an effort to bag bigger quarry, CERN constructs the Large Electron Positron (LEP) collider inside a circular, 27-kilometer-long tunnel.

September 2000 - LAST PUSH FOR THE HIGGS
Scientists at LEP detect hints of the Higgs boson just as the machine is scheduled to be permanently shut down. Administrators offer a six-week reprieve and push the machine past its design energy but for naught. We now know the weak signal was not the Higgs after all: it was at the wrong mass.

November 2, 2000 - THE END OF AN ERA
The LEP collider closes so that construction may begin on CERN's Large Hadron Collider (LHC), the machine that will eventually find the Higgs.

September 10, 2008 - ALL SYSTEMS GO
The first proton beams shoot around the newly finished LHC.

September 19, 2008 - DISASTER STRIKES
After an electrical splice between two magnets warms and melts, a powerful spark punctures a magnet vessel and releases tons of liquid helium. More than 50 magnets rip from their mounts or are otherwise damaged.

July 4, 2012 - HIGGS-LIKE PARTICLE FOUND
CERN scientists announce that they have discovered a Higgs-like particle at 125 GeV.

Compiled by Marissa Fessenden

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The Inner Life of Quarks

by Don Lincoln

THE UNIVERSE IS A COMPLEX AND INTRICATE PLACE. WE CAN move easily through air and yet not through a wall. The sun transmutes one element to another, bathing our planet in warmth and light. Radio waves have carried a man's voice to Earth from the surface of the moon, whereas gamma rays can inflict fatal damage on our DNA. On the face of it, these disparate phenomena have nothing to do with one another, but physicists have uncovered a handful of principles that fuse into a theory of sublime simplicity to explain all this and much more. This theory is called the Standard Model of particle physics, and it encapsulates the electromagnetic forces that make a wall feel solid, the nuclear forces that govern the sun's power plant, and the diverse family of light waves that both make modern communications possible and threaten our well-being.

The Standard Model is one of the most strikingly successful theories ever devised. In essence, it postulates that two classes of indivisible matter particles exist: quarks and leptons. Quarks of various kinds compose protons and neutrons, and the most familiar lepton is the electron. The right mix of quarks and leptons can make up any atom and, by extension, any of the different types of matter in the universe. These constituents of matter are bound together by four forces—two familiar ones, gravity and electromagnetism, and the less familiar strong and weak nuclear forces. The exchange of one or more particles known as bosons mediates the latter three forces, but all attempts to treat gravity in the microrealm have failed.

The Standard Model leaves other questions unanswered as well, such as: Why do we have four forces and not some other number? And why are there two types of fundamental particles rather than just a single one that handles everything?

These are intriguing problems. Nevertheless, for a long time now a different puzzle has captured my attention and that of many other physicists. The Standard Model views quarks and leptons as indivisible. Astoundingly, though, various clues imply that they are instead built of still smaller components. If quarks and leptons are not fundamental at all, and smaller bits do in fact exist, their presence will force extensive revisions of our theories. Just as nuclear power was inconceivable before Ernest Rutherford discovered the structure of the atom in 1911, unveiling another layer of the subatomic onion will certainly reveal phenomena we cannot yet imagine.

GENERATION GAPS

Resolving this issue requires scientists to smash particles together at extremely high energies. Since the observation of quarks in the 1970s, we have lacked the tools that might allow us to peer inside them. But now the Large Hadron Collider (LHC) at CERN near Geneva—the same machine that recently confirmed the existence of a Higgs boson, the last undocumented particle in the Standard Model—is gaining speed and could be up to the task.

The first hints of structure in quarks and leptons emerged from research into another—still unsolved—poser, related to the numbers of different kinds of quarks and leptons that have been discovered. Protons and neutrons consist of two types of quarks, called the up quark and the down quark. Up quarks have +2/3 the electrical charge of the proton, and down quarks have –1/3 of the proton’s charge. Although only these two types of quarks, plus electrons, suffice to make up the matter of the universe, other quarks have been observed. The strange quark has the same charge as the down quark, but it is heavier. The bottom quark is an even heavier version. Similarly, the charm quark is a heavier cousin of the up quark, with the superheavy top quark rounding out the up quark family. Particle physicists have observed all these quarks, but the four heavier ones decay, in fractions of a second, into the lightest two.

The electron also has heavy, unstable cousins, the muon and the even heavier tau lepton, both of which have the same charge as the electron. And the known menagerie of particles includes three copies of neutrinos, all of which are superlightweight and electrically neutral.

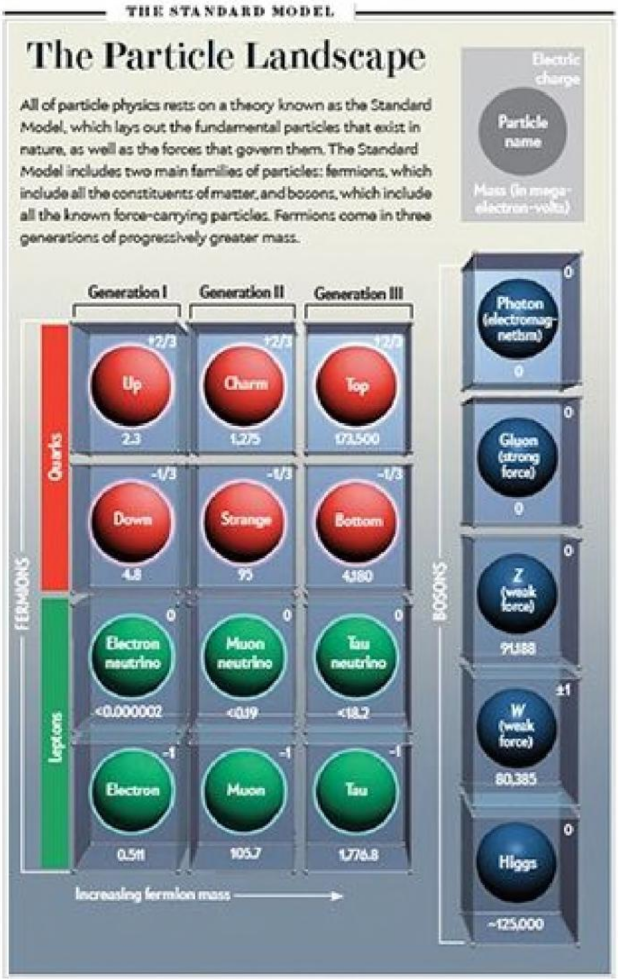
This cornucopia naturally led physicists to ask: Given that the up quark, down quark and electron are the only particles necessary to build a universe, why do they have so many cousins? The question can be encapsulated in Nobel Prize–winning physicist I. I. Rabi's oft-quoted quip when he learned of the discovery of the muon: "Who ordered that?"

One way scientists went about tackling the mystery of populous particle families was to construct a chart delineating the features of all known elementary particles, analogous to the periodic table of chemical elements. The periodic table offered physicists the first hints that the chemical elements might not be fundamental, that systematic patterns in the atom's inner structure might account for similar properties of elements in particular rows and columns.

The table of quarks and leptons has three columns called generations (which is why the mystery of particle multiplicity is now referred to as the generation problem). Generation I, at the far left, includes the up and down quark as well as the electron and electron neutrino—everything needed to explain our familiar universe. Generation II contains the some what more massive versions of the same particles; generation III has the most massive of all.

The Standard Model treats the quarks and leptons as pointlike particles without any internal structure. But the patterns within the table, as within chemistry's periodic table, raise the possibility that the differences in generations stem from the configuration of even smaller building blocks of matter within quarks and leptons.

Another historical precedent, near the dawn of the 20th century, that may have relevance in the search for the quark's underlying structure is the discovery of radioactive decay. Through a process not understood at the time, one element can transmute into another. We now know that by changing the number of protons and neutrons in the nucleus, it is possible to achieve the goal of medieval alchemists and convert lead into gold. The range of possible transmutations is even wider, as nuclear alchemy can even convert a neutron into a proton (or the reverse) by changing the identity of their constituent quarks. This transformation occurs via the weak nuclear force, which can also transmute leptons, although quarks cannot be changed into leptons, or vice versa. Just as the conversion of one element into another reflects the complex inner workings of the atom, so the metamorphosis of the quarks and leptons may provide yet another hint of even finer details within those particles.



THE STANDARD MODEL

The Particle Landscape

All of particle physics rests on a theory known as the Standard Model, which lays out the fundamental particles that exist in nature, as well as the forces that govern them. The Standard Model includes two main families of particles: fermions, which include all the constituents of matter, and bosons, which include all the known force-carrying particles. Fermions come in three generations of progressively greater mass.

Illustration by Malcolm Godwin.

PART AND PARTICLE

Many hypothetical building blocks for quarks and leptons have emerged, each with a different name, but the term "preon" has stuck as a generic descriptor for all of them. In most cases, the same name applies to the constituents of the particles that carry the forces acting on these bits of matter.

As an illustration, consider a straightforward model proposed