THE COMING REVOLUTIONS IN PARTICLE PHYSICS

The current Standard Model of particle physics begins to unravel when probed much beyond the range of current particle accelerators. So no matter what the Large Hadron Collider finds, it is going to take physics into new territory **By Chris Quigg**

KEY CONCEPTS

- The Large Hadron Collider (LHC) is certain to find *something* new and provocative as it presses into unexplored territory.
- The Standard Model of particle physics requires a particle known as the Higgs boson, or a stand-in to play its role, at energies probed by the LHC. The Higgs, in turn, poses deep questions of its own, whose answers should be found in the same energy range.
- These phenomena revolve around the question of symmetry. Symmetries underlie the interactions of the Standard Model but are not always reflected in the operation of the model. Understanding why not is a key question.

—The Editors

When physicists are forced to give a single-word answer to the question of why we are building the Large Hadron Collider (LHC), we usually reply "Higgs." The Higgs particle—the last remaining undiscovered piece of our current theory of matter—is the marquee attraction. But the full story is much more interesting. The new collider provides the greatest leap in capability of any instrument in the history of particle physics. We do not know what it will find, but the discoveries we make and the new puzzles we encounter are certain to change the face of particle physics and to echo through neighboring sciences.

In this new world, we expect to learn what distinguishes two of the forces of nature—electromagnetism and the weak interactions—with broad implications for our conception of the everyday world. We will gain a new understanding of simple and profound questions: Why are there atoms? Why chemistry? What makes stable structures possible?

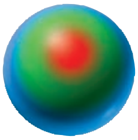
The search for the Higgs particle is a pivotal step, but only the first step. Beyond it lie phenomena that may clarify why gravity is so much weaker than the other forces of nature and that could reveal what the unknown dark matter that fills the universe is. Even deeper lies the prospect of insights into the different forms of matter, the unity of outwardly distinct particle categories and the nature of spacetime. The questions in play all seem linked to one another and to the knot of problems that motivated the prediction of the Higgs particle to begin with. The LHC will help us refine these questions and will set us on the road to answering them.

The Matter at Hand

What physicists call the "Standard Model" of particle physics, to indicate that it is still a work in progress, can explain much about the known world. The main elements of the Standard Model fell into place during the heady days of the 1970s and 1980s, when waves of landmark experimental discoveries engaged emerging theoretical ideas in productive conversation. Many particle physicists look on the past 15 years as an era of consolidation in contrast to the ferment of earlier decades. Yet even as the Standard Model has gained ever more experimental support, a growing list of phenomena lies outside its purview, and new theoretical ideas have expanded our conception of what a richer and more comprehensive worldview might look like. Taken together, the continuing progress in experiment and theory point to a very lively decade ahead. Perhaps we will look back and see that revolution had been brewing all along.

Our current conception of matter comprises two main particle categories, quarks and leptons, together with three of the four known fundamental forces, electromagnetism and the strong and weak interactions [*see box on page 48*]. Gravity is, for the moment, left to the side. Quarks, which make up protons and neutrons, generate and feel all three forces. Leptons, the best known of which is the electron, are immune to the strong force. What distinguishes these two categories is a property akin to electric charge, called color. (This name is metaphorical; it has nothing to do with ordinary colors.) Quarks have color, and leptons do not.

The guiding principle of the Standard Model



STUDYING THE WORLD with a resolution a billion times finer than atomic scales, particle physicists seek a deeper understanding of the everyday world and of the evolution of the universe.

is that its equations are symmetrical. Just as a sphere looks the same whatever your viewing angle is, the equations remain unchanged even when you change the perspective from which they are defined. Moreover, they remain unchanged even when the perspective shifts by different amounts at different points in space and time.

Ensuring the symmetry of a geometric object places very tight constraints on its shape. A sphere with a bump no longer looks the same from every angle. Likewise, the symmetry of the equations places very tight constraints on them. These symmetries beget forces that are carried by special particles called bosons [see "Gauge Theories of the Forces between Elementary Particles," by Gerard 't Hooft; SCIENTIFIC AMERICAN, June 1980, and "Elementary Particles and Forces," by Chris Quigg; SCIENTIFIC AMERICAN, April 1985].

In this way, the Standard Model inverts Louis Sullivan's architectural dictum: instead of "form follows function," function follows form. That is, the form of the theory, expressed in the symmetry of the equations that define it, dictates the function—the interactions among particles—that the theory describes. For instance, the strong nuclear force follows from the requirement that the equations describing quarks must be the same no matter how one chooses to define quark colors (and even if this convention is set independently at each point in space and time). The strong force is carried by eight particles known as gluons. The other two forces, electromagnetism and the weak nuclear force, fall under the rubric of the "electroweak" forces and are based on a different symmetry. The electroweak forces are carried by a quartet of particles: the photon, Z boson, W^+ boson and W^- boson.

Breaking the Mirror

The theory of the electroweak forces was formulated by Sheldon Glashow, Steven Weinberg and Abdus Salam, who won the 1979 Nobel Prize in Physics for their efforts. The weak force, which is involved in radioactive beta decay, does not act on all the quarks and leptons. Each of these particles comes in mirror-image varieties, termed left-handed and right-handed, and the beta-decay

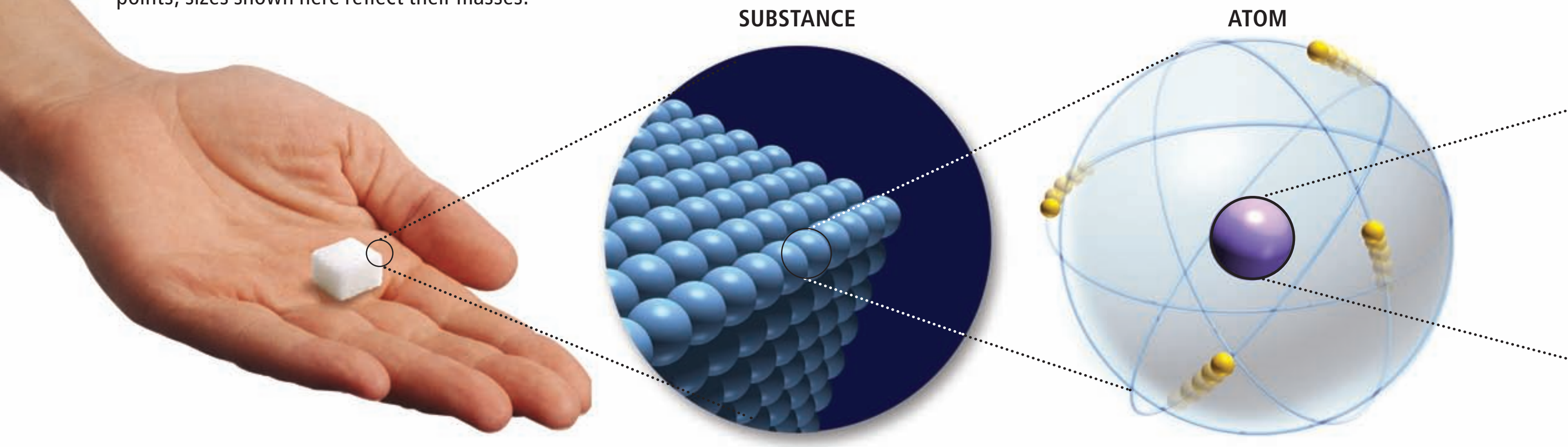
KENN BROWN (*Vitruvian man*); COURTESY OF CHRIS QUIGG (*Quigg*)

[THE AUTHOR]

Chris Quigg is a senior scientist at Fermi National Accelerator Laboratory, where for 10 years he led the theoretical physics department. He is the author of a celebrated textbook on the so-called gauge theories that underlie the Standard Model, as well as the former editor of the *Annual Review of Nuclear and Particle Science.* Quigg's research on electroweak symmetry breaking and supercollider physics highlighted the importance of the terascale. He is a frequent visitor to CERN. When not blazing the trail to the deepest workings of nature, he can be found hiking on one of France's *Sentiers de Grande Randonnée.*

What Really Matters

If you look deep inside a lump of matter, it is made up of only a few types of elementary particles, drawn from a palette of a dozen flavors. The Standard Model treats the particles as geometrical points; sizes shown here reflect their masses.



PARTICLES OF MATTER

QUARKS

These particles make up protons, neutrons and a veritable zoo of lesser-known particles. They have never been observed in isolation.

UP — u

Electric charge: $+^{2}/_{3}$
Mass: 2 MeV
Constituent of ordinary matter; two up quarks, plus a down, make up a proton.

CHARM — c

Electric charge: $+^{2}/_{3}$
Mass: 1.25 GeV
Unstable heavier cousin of the up; constituent of the J/ψ particle, which helped physicists develop the Standard Model.

TOP — t

Electric charge: $+^{2}/_{3}$
Mass: 171 GeV
Heaviest known particle, comparable in mass to an atom of osmium. Very short-lived.

DOWN — d

Electric charge: $-^{1}/_{3}$
Mass: 5 MeV
Constituent of ordinary matter; two down quarks, plus an up, compose a neutron.

STRANGE — s

Electric charge: $-^{1}/_{3}$
Mass: 95 MeV
Unstable heavier cousin of the down; constituent of the much studied kaon particle.

BOTTOM — b

Electric charge: $-^{1}/_{3}$
Mass: 4.2 GeV
Unstable and still heavier copy of the down; constituent of the much studied B-meson particle.

LEPTONS

These particles are immune to the strong force and are observed as isolated individuals. Each neutrino shown here is actually a mixture of neutrino species, each of which has a definite mass of no more than a few eV.

ELECTRON NEUTRINO — ν_e

Electric charge: 0
Immune to both electromagnetism and the strong force, it barely interacts at all but is essential to radioactivity.

MUON NEUTRINO — ν_μ

Electric charge: 0
Appears in weak reactions involving the muon.

TAU NEUTRINO — ν_τ

Electric charge: 0
Appears in weak reactions involving the tau lepton.

ELECTRON — e

Electric charge: –1
Mass: 0.511 MeV
The lightest charged particle, familiar as the carrier of electric currents and the particles orbiting atomic nuclei.

MUON — μ

Electric charge: –1
Mass: 106 MeV
A heavier version of the electron, with a lifetime of 2.2 microseconds; discovered as a component of cosmic-ray showers.

TAU — τ

Electric charge: –1
Mass: 1.78 GeV
Another unstable and still heavier version of the electron, with a lifetime of 0.3 picosecond.

PARTICLES OF FORCE

BOSONS

At the quantum level, each force of nature is transmitted by a dedicated particle or set of particles.

PHOTON — γ

Electric charge: 0
Mass: 0
Carrier of electromagnetism, the quantum of light acts on electrically charged particles. It acts over unlimited distances.

Z BOSON — Z

Electric charge: 0
Mass: 91 GeV
Mediator of weak reactions that do not change the identity of particles. Its range is only about 10^{-18} meter.

W^+/W^- BOSONS — W

Electric charge: +1 or –1
Mass: 80.4 GeV
Mediators of weak reactions that change particle flavor and charge. Their range is only about 10^{-18} meter.

GLUONS — g

Electric charge: 0
Mass: 0
Eight species of gluons carry the strong interaction, acting on quarks and on other gluons. They do not feel electromagnetic or weak interactions.

HIGGS (not yet observed) — H

Electric charge: 0
Mass: Expected below 1 TeV, most likely between 114 and 192 GeV.
Believed to endow *W* and *Z* bosons, quarks and leptons with mass.

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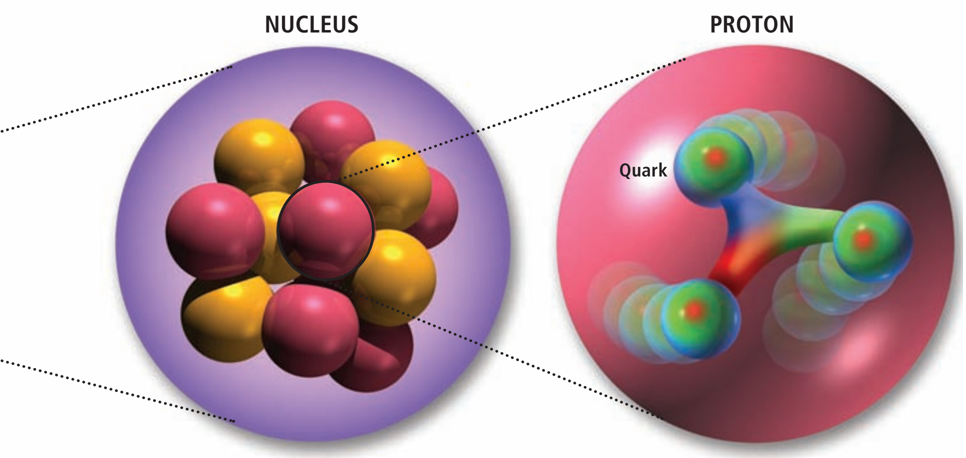
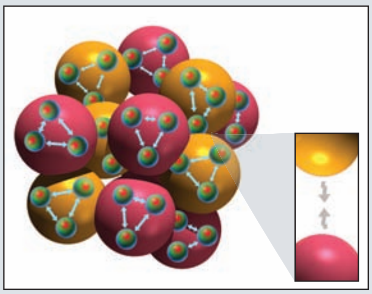


HOW THE FORCES ACT

An interaction among several colliding particles can change their energy, momentum or type. An interaction can even cause a single particle in isolation to decay spontaneously.

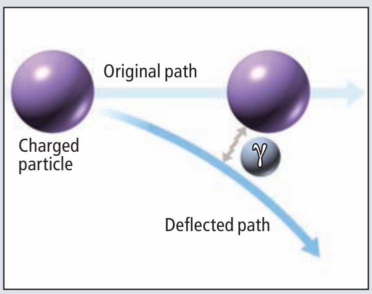
STRONG INTERACTION

The strong force acts on quarks and gluons. It binds them together to form protons, neutrons and more. Indirectly, it also binds protons and neutrons into atomic nuclei.



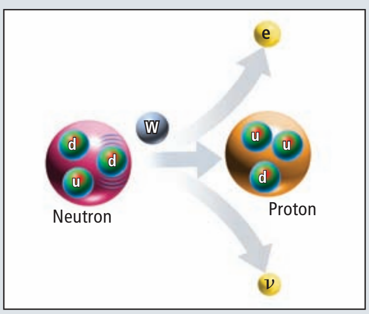
ELECTROMAGNETIC INTERACTION

The electromagnetic interaction acts on charged particles, leaving the particles unchanged. It causes like-charged particles to repel.



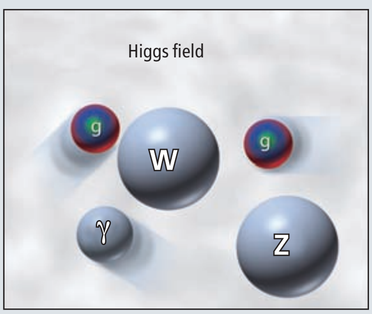
WEAK INTERACTION

The weak interaction acts on quarks and leptons. Its best-known effect is to transmute a down quark into an up quark, which in turn causes a neutron to become a proton plus an electron and a neutrino.



HIGGS INTERACTION

The Higgs field (*gray background*) is thought to fill space like a fluid, impeding the W and Z bosons and thereby limiting the range of weak interactions. The Higgs also interacts with quarks and leptons, endowing them with mass.



force acts only on the left-handed ones—a striking fact still unexplained 50 years after its discovery. The family symmetry among the left-handed particles helps to define the electroweak theory.

In the initial stages of its construction, the theory had two essential shortcomings. First, it foresaw four long-range force particles—referred to as gauge bosons—whereas nature has but one: the photon. The other three have a short range, less than about 10^{-17} meter, less than 1 percent of the proton's radius. According to Heisenberg's uncertainty principle, this limited range implies that the force particles must have a mass approaching 100 billion electron volts (GeV). The second shortcoming is that the family symmetry does not permit masses for the quarks and leptons, yet these particles do have mass.

The way out of this unsatisfactory situation is to recognize that a symmetry of the laws of nature need not be reflected in the outcome of those laws. Physicists say that the symmetry is "broken." The needed theoretical apparatus was worked out in the mid-1960s by physicists Peter Higgs, Robert Brout, François Englert and others. The inspiration came from a seemingly unrelated phenomenon: superconductivity, in which certain materials carry electric current with zero resistance at low temperatures. Although the laws of electromagnetism themselves are symmetrical, the behavior of electromagnetism within the superconducting material is not. A photon gains mass within a superconductor, thereby limiting the intrusion of magnetic fields into the material.

As it turns out, this phenomenon is a perfect prototype for the electroweak theory. If space is filled with a type of "superconductor" that affects the weak interaction rather than electromagnetism, it gives mass to the W and Z bosons and limits the range of the weak interactions. This superconductor consists of particles called Higgs bosons. The quarks and leptons also acquire their mass through their interactions with the Higgs boson [see "The Higgs Boson," by Martinus Veltman; SCIENTIFIC AMERICAN, November 1986]. By obtaining mass in this way, instead of possessing it intrinsically, these particles remain consistent with the symmetry requirements of the weak force.

The modern electroweak theory (with the Higgs) accounts very precisely for a broad range of experimental results. Indeed, the paradigm of quark and lepton constituents interacting by means of gauge bosons completely revised our conception of matter and pointed to the possibility that the strong, weak and electromagnet-

[WHY THE HIGGS?]

BREAKING SYMMETRY

A central question of the Standard Model is why the electroweak forces are asymmetrical: electromagnetism is long-ranged, whereas the weak nuclear force is short-ranged. Physicists think these forces are actually symmetrical, but their symmetry is hidden, or "broken."

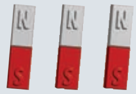
MAGNETIC SPATIAL SYMMETRY

A simple analogy is an infinite grid of magnetic filings. The symmetry in this case is the equivalence of all directions in space.

The symmetry is evident at high temperatures. Heat jostles the filings every which way.

Symmetry

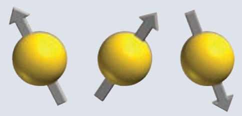
When the temperature drops, the filings lock one another in place. Although their alignment may seem more orderly, it is less symmetrical, because it singles out one randomly chosen direction over the others.



Broken symmetry

ELECTROWEAK SYMMETRY

This symmetry is more abstract. It means the freedom to decide which leptons are electrons and which are neutrinos or how to label up and down quarks.



In the symmetrical case, the lepton-naming convention (*represented by an arrow*) is set independently at each point in space. What one person calls an electron, another might call some mixture of electron and neutrino, and it would make no difference to their predictions.

In the broken symmetry, the convention is fixed everywhere. What one person calls an electron, all do. The Higgs field brings about this symmetry breaking.

Electroweak symmetry makes all the electroweak force particles massless.

Broken symmetry gives masses to the *W* and *Z* bosons, thereby restricting their range.

ic interactions meld into one when the particles are given very high energies. The electroweak theory is a stunning conceptual achievement, but it is still incomplete. It shows how the quarks and leptons might acquire masses but does not predict what those masses should be. The electroweak theory is similarly indefinite in regard to the mass of the Higgs boson itself: the existence of the particle is essential, but the theory does not predict its mass. Many of the outstanding problems of particle physics and cosmology are linked to the question of exactly how the electroweak symmetry is broken.

Where the Standard Model Tells Its Tale

Encouraged by a string of promising observations in the 1970s, theorists began to take the Standard Model seriously enough to begin to probe its limits. Toward the end of 1976 Benjamin W. Lee of Fermi National Accelerator Laboratory in Batavia, Ill., Harry B. Thacker, now at the University of Virginia, and I devised a thought experiment to investigate how the electroweak forces would behave at very high energies. We imagined collisions among pairs of *W*, *Z* and Higgs bosons. The exercise might seem slightly fanciful because, at the time of our work, not one of these particles had been observed. But physicists have an obligation to

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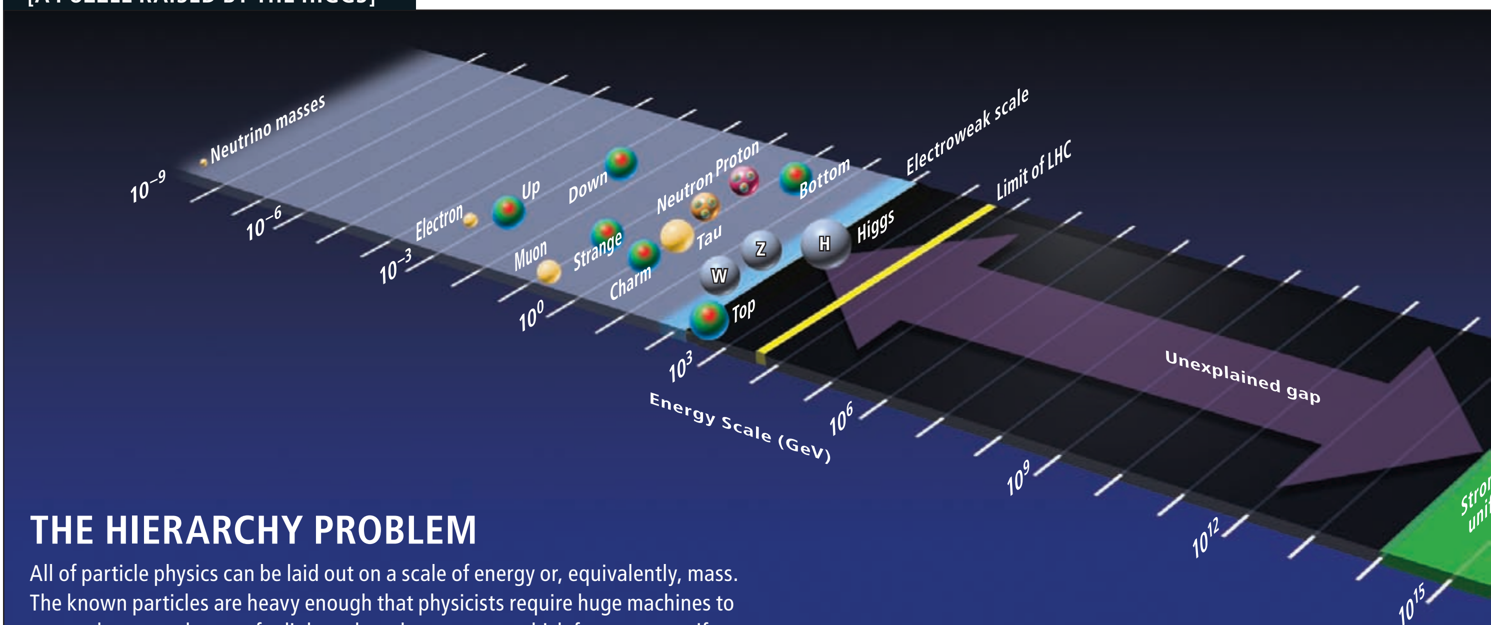
[A PUZZLE RAISED BY THE HIGGS]



THE HIERARCHY PROBLEM

All of particle physics can be laid out on a scale of energy or, equivalently, mass. The known particles are heavy enough that physicists require huge machines to create them, yet they are far lighter than the energy at which forces may unify or gravity may come into play. What enforces the separation? No one yet knows. This puzzle is especially acute for the Higgs. Extremely high-energy processes tend to pull its mass far above 1 TeV. What holds it down?

test any theory by considering its implications as if all its elements were real.

What we noticed was a subtle interplay among the forces generated by these particles. Extended to very high energies, our calculations made sense only if the mass of the Higgs boson were not too large—the equivalent of less than one trillion electron volts, or 1 TeV. If the Higgs is lighter than 1 TeV, weak interactions remain feeble and the theory works reliably at all energies. If the Higgs is heavier than 1 TeV, the weak interactions strengthen near that energy scale and all manner of exotic particle processes ensue. Finding a condition of this kind is interesting because the electroweak theory does not directly predict the Higgs mass. This mass threshold means, among other things, that something new—either a Higgs boson or other novel phenomena—is to be found when the LHC turns the thought experiment into a real one.

Experiments may already have observed the behind-the-scenes influence of the Higgs. This effect is another consequence of the uncertainty principle, which implies that particles such as the Higgs can exist for moments too fleeting to be observed directly but long enough to leave a subtle mark on particle processes. The Large Electron Positron collider at CERN, the previous inhabitant of the tunnel now used by the LHC, detected the work of such an unseen hand.

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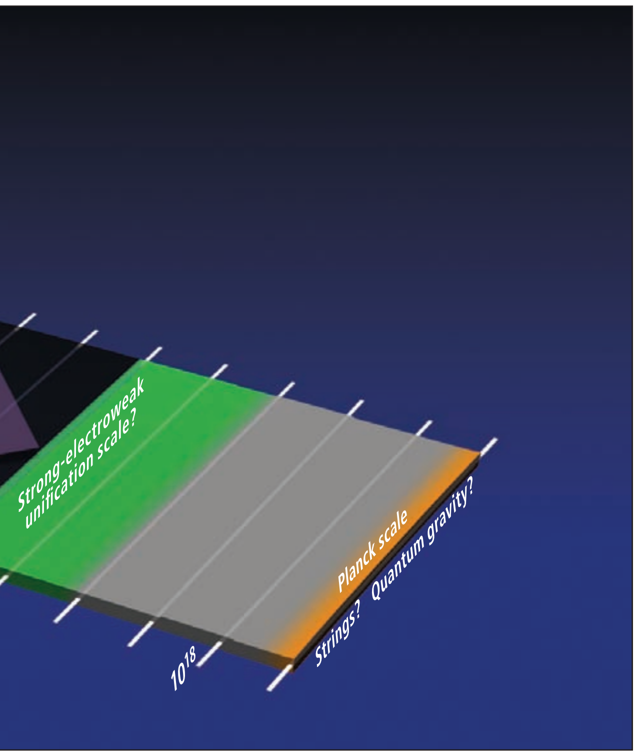


Comparison of precise measurements with theory strongly hints that the Higgs exists and has a mass less than about 192 GeV.

For the Higgs to weigh less than 1 TeV, as required, poses an interesting riddle. In quantum theory, quantities such as mass are not set once and for all but are modified by quantum effects. Just as the Higgs can exert a behind-the-scenes influence on other particles, other particles can do the same to the Higgs. Those particles come in a range of energies, and their net effect depends on where precisely the Standard Model gives way to a deeper theory. If the model holds all the way to 10^{15} GeV, where the strong and electroweak interactions appear to unify, particles with truly titanic energies act on the Higgs and give it a comparably high mass. Why, then, does the Higgs appear to have a mass of no more than 1 TeV?

This tension is known as the hierarchy problem. One resolution would be a precarious balance of additions and subtractions of large numbers, standing for the contending contributions of different particles. Physicists have learned to be suspicious of immensely precise cancellations that are not mandated by deeper principles. Accordingly, in common with many of my colleagues, I think it highly likely that both the Higgs boson and other new phenomena will be found with the LHC.

Supertechnifragilisticexpialidocious

Theorists have explored many ways in which new phenomena could resolve the hierarchy problem. A leading contender known as supersymmetry supposes that every particle has an as yet unseen superpartner that differs in spin [see "Is Nature Supersymmetric?" by H. E. Haber and G. L. Kane; Scientific American, June 1986]. If nature were exactly supersymmetric, the masses of particles and superpartners would be identical, and their influences on the Higgs would cancel each other out exactly. In that case, though, physicists would have seen the superpartners by now. We have not, so if supersymmetry exists, it must be a broken symmetry. The net influence on the Higgs could still be acceptably small if superpartner masses were less than about 1 TeV, which would put them within the LHC's reach.

Another option, called technicolor, supposes that the Higgs boson is not truly a fundamental particle but is built out of as yet unobserved constituents. (The term "technicolor" alludes to a generalization of the color charge that de-

[SOLVING THE HIGGS PUZZLE]

WANTED: NEW PHYSICS

Whatever keeps the Higgs mass near the 1-TeV scale must come from beyond the Standard Model. Theorists have advanced many possible solutions. The Large Hadron Collider will decide. Here are three promising lines:

SUPERSYMMETRY

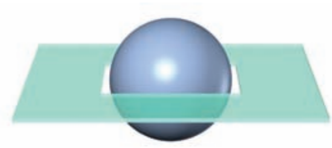
What tends to elevate the Higgs mass is its interaction with so-called virtual particles—copies of quarks, leptons and other particles that temporarily materialize around the Higgs. But if each particle species is paired with a superpartner, the two will offset each other, holding down the Higgs mass.

TECHNICOLOR

Perhaps the Higgs is not a truly elementary particle but a bundle of more fundamental constituents, much as the proton is a mini galaxy of quarks and gluons. Then the Higgs mass would derive mostly from the energy of its constituents and would not be so sensitive to high-energy processes that add to its mass.

EXTRA DIMENSIONS

If space has dimensions beyond the familiar three, particles might interact differently at high energies, and the conjectured unification energy might not be as high as physicists now think. The hierarchy problem would be recast or even eliminated.



[A HIGGS-LESS WORLD]

Hidden Symmetry That Shapes Our World

If there were no Higgs mechanism, what a different world it would be! Elementary particles of matter such as quarks and electrons would have no mass. Yet that does not mean the universe would contain no mass. An underappreciated insight from the Standard Model is that particles such as the proton and neutron represent matter of a novel kind. The mass of a proton, in contrast to macroscopic matter, is only a few percent of its constituent masses. (In fact, quarks account for not more than 2 percent of the proton's mass.) Most of the mass arises through the original form of Albert Einstein's famous equation, $m = E/c^2$, from the energy stored up in confining the quarks in a tiny volume. In identifying the energy of quark confinement as the origin of proton and neutron mass, we explain nearly all the visible mass of the universe, because luminous matter is made mostly of protons and neutrons in stars.

Quark masses do account for an important detail of the real world: that the neutron is slightly more massive than the proton. One might expect the proton to be the more massive one, because its electric charge contributes to its intrinsic energy—a source of self-energy the neutron lacks. But quark masses tip the balance the other way. In the no-Higgs zone, the proton would outweigh the neutron. Radioactive beta decay would be turned on its head. In our world, a neutron sprung from a nucleus decays into a proton, electron and antineutrino in about 15 minutes, on average. If quark masses were to vanish, a free proton would decay into a neutron, positron and neutrino. Consequently, hydrogen atoms could not exist. The lightest "nucleus" would be one neutron rather than one proton.

In the Standard Model, the Higgs mechanism differentiates electromagnetism from the weak force. In the absence of the Higgs, the strong force among quarks and gluons would induce the distinction. As the strong interaction confined the colored quarks into colorless objects like the proton, it would also act to distinguish the weak and electromagnetic interactions, giving small masses to the *W* and *Z* bosons while leaving the photon massless. This manifestation of the strong force would not give any appreciable mass to the electron or the quarks. If it, rather than the Higgs, operated, beta decay would operate millions of times faster than in our world.

Some light nuclei would be produced in the early no-Higgs universe and survive, but they would not form atoms we would recognize. An atom's radius is inversely proportional to the electron's mass, so if the electron has zero mass, atoms—less than a nanometer across in our world—would be infinitely big. Even if other effects gave electrons a tiny mass, atoms would be macroscopic. A world without compact atoms would be a world without chemistry and without stable composite structures like our solids and liquids. —*C.Q.*

WITHOUT THE HIGGS, atoms could be several inches across or bigger.

A DECADE OF DISCOVERY

Many people think of the past decade in particle physics as an era of consolidation, but in fact it has been a vibrant time, setting the stage for revolutions to come.

A NEW LAW OF NATURE
Experiments have tested the electroweak theory, a key element of the Standard Model, over a staggering range of distances, from the subnuclear to the galactic.

NEUTRINO MASS
Particle detectors have established that neutrinos can morph from one type to another. These elusive particles must have mass, which the Standard Model does not naturally explain.

TOP QUARK
Fermilab experiments discovered the top quark in collisions of protons and their antimatter counterpart, antiprotons. The top stands out because its mass is some 40 times that of its partner, the bottom quark.

AN IMPERFECT MIRROR
KEK (the Japanese high-energy physics laboratory) and the Stanford Linear Accelerator Center detected differences between the decays of B mesons and of their antiparticles. Such subtle asymmetries bear on why the universe contains so little antimatter.

NOVEL FORMS OF MATTER AND ENERGY
A remarkable concordance of astronomical observations indicates that we live in an approximately flat universe dominated by dark matter and an unidentified form of dark energy that drives cosmic acceleration.

fines the strong force.) If so, the Higgs is not fundamental. Collisions at energies around 1 TeV (the energy associated with the force that binds together the Higgs) would allow us to look within it and thus reveal its composite nature. Like supersymmetry, technicolor implies that the LHC will set free a veritable menagerie of exotic particles.

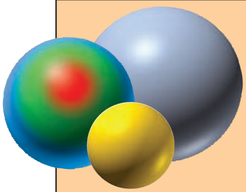
A third, highly provocative idea is that the hierarchy problem will go away on closer examination, because space has additional dimensions beyond the three that we move around in. Extra dimensions might modify how the forces vary in strength with energy and eventually meld together. Then the melding—and the onset of new physics—might not happen at 10^{12} TeV but at a much lower energy related to the size of the extra dimensions, perhaps only a few TeV. If so, the LHC could offer a peek into those extra dimensions [see "The Universe's Unseen Dimensions," by Nima Arkani-Hamed, Savas Dimopoulos and Georgi Dvali; SCIENTIFIC AMERICAN, August 2000].

One more piece of evidence points to new phenomena on the TeV scale. The dark matter that makes up the bulk of the material content

PAT LACROIX *Getty Images*

[WHAT TO EXPECT]

FIVE GOALS FOR THE LHC

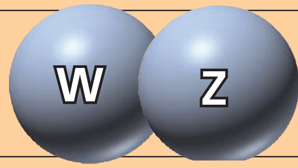


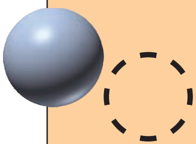
REDISCOVER THE STANDARD MODEL

The first goal of the collider is not to probe the new but to confirm the old. The machine will produce familiar particles in prodigious numbers (several top quarks per second, for example) and scrutinize them with increasing refinement. Not only does this test the machine and its instruments, it sets precise benchmarks for determining whether new phenomena are indeed new.

DETERMINE WHAT BREAKS THE ELECTROWEAK SYMMETRY

The collider will seek the Higgs boson (or what stands in its place) and determine its properties. Does the Higgs provide mass not only to the *W* and *Z* particles but also to the quarks and leptons?





SEARCH FOR NEW FORCES OF NATURE

New force particles would decay into known particles such as electrons and their antimatter counterparts, positrons. Such forces would indicate new symmetries of nature and might guide physicists toward a unified understanding of all the interactions.

PRODUCE DARK MATTER CANDIDATES

By observing neutral, stable particles created in high-energy collisions, the collider could help solve one of astronomy's greatest puzzles and test researchers' understanding of the history of the universe.

ABOVE ALL, EXPLORE!

The collider will examine its immense new domain for evidence of hidden spacetime dimensions, new strong interactions, supersymmetry and the totally unexpected. Physicists will have to be attentive to connections among today's great questions and alert to new questions the collider will open up.

of the universe appears to be a novel type of particle [see "The Search for Dark Matter," by David B. Cline; Scientific American, March 2003]. If this particle interacts with the strength of the weak force, then the big bang would have produced it in the requisite numbers as long as its mass lies between approximately 100 GeV and 1 TeV. Whatever resolves the hierarchy problem will probably suggest a candidate for the dark matter particle.

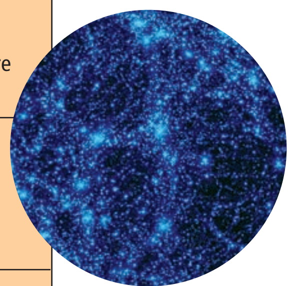
Revolutions on the Horizon

Opening the TeV scale to exploration means entering a new world of experimental physics. Making a thorough exploration of this world—where we will come to terms with electroweak symmetry breaking, the hierarchy problem and dark matter—is the top priority for accelerator experiments. The goals are well motivated and matched by our experimental tools, with the LHC succeeding the current workhorse, Fermilab's Tevatron collider. The answers will not only be satisfying for particle physics, they will deepen our understanding of the everyday world.

But these expectations, high as they are, are still not the end of the story. The LHC could well find clues to the full unification of forces or indications that the particle masses follow a rational pattern [see "A Unified Physics by 2050?" by Steven Weinberg; Scientific American, December 1999]. Any proposed interpretation of new particles will have consequences for rare decays of the particles we already know. It is very likely that lifting the electroweak veil will bring these problems into clearer relief, change the way we think about them and inspire future experimental thrusts.

Cecil Powell won the 1950 Nobel Prize in Physics for discovering particles called pions—proposed in 1935 by physicist Hideki Yukawa to account for nuclear forces—by exposing highly sensitive photographic emulsions to cosmic rays on a high mountain. He later reminisced: "When [the emulsions] were recovered and developed in Bristol, it was immediately apparent that a whole new world had been revealed.... It was as if, suddenly, we had broken into a walled orchard, where protected trees had flourished and all kinds of exotic fruits had ripened in great profusion." That is just how I imagine our first look at the TeV scale. ■

Dark matter simulation



SLIM FILMS (illustration); ANDREY KRAVTSOV (dark matter)

MORE TO EXPLORE

LHC Physics: The First One–Two Year(s). F. Gianotti and M. Mangano in *Proceedings of the 2nd Italian Workshop on the Physics of Atlas and CMS,* pages 3–26. Edited by G. Carlino and P. Paolucci. Frascati Physics Series, Vol. 38; 2005. Preprint available at **www.arxiv.org/abs/hep-ph/0504221**

Particles and the Standard Model. Chris Quigg in *The New Physics for the Twenty-First Century.* Edited by Gordon Fraser. Cambridge University Press, 2006.

Chris Quigg's Web site (with links to slides and video of his public talks): **http://lutece.fnal.gov**

The LHC Project: **http://lhc.web.cern.ch/lhc**

ATLAS Experiment at the LHC: **www.atlasexperiment.org**

Compact Muon Solenoid Experiment at the LHC: **http://cms.cern.ch**

Collider Detector at Fermilab: **www-cdf.fnal.gov**

DØ Experiment: **www-d0.fnal.gov**