



MALE AFRICAN ELEPHANT (about 6,000 kilograms) and the smallest species of ant (0.01 milligram) differ in mass by more than 11 orders of magnitude—roughly the same span as the top quark and the neutrino. Why the particle masses should differ by such a large amount remains a mystery.

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Most people think they know what mass is, but they understand only part of the story. For instance, an elephant is clearly bulkier and weighs more than an ant. Even in the absence of gravity, the elephant would have greater mass—it would be harder to push and set in motion. Obviously the elephant is more massive because it is made of many more atoms than the ant is, but what determines the masses of the individual atoms? What about the elementary particles that make up the atoms—what determines their masses? Indeed, why do they even have mass?

We see that the problem of mass has two independent aspects. First, we need to learn how mass arises at all. It turns out mass results from at least three different mechanisms, which I will describe below. A key player in physicists' tentative theories about mass is a new kind of field that permeates all of reality, called the Higgs field. Elementary particle masses are thought to come about from the interaction with the

Higgs field. If the Higgs field exists, theory demands that it have an associated particle, the Higgs boson. Using particle accelerators, scientists are now hunting for the Higgs.

The second aspect is that scientists want to know why different species of elementary particles have their specific quantities of mass. Their intrinsic masses span at least 11 orders of magnitude, but we do not yet know why that should be so [see illustration on page 36]. For comparison, an elephant and the smallest of ants differ by about 11 orders of magnitude of mass.

What Is Mass?

ISAAC NEWTON presented the earliest scientific defini-

tion of mass in 1687 in his landmark *Principia*: “The quantity of matter is the measure of the same, arising from its density and bulk conjointly.” That very basic definition was good enough for Newton and other scientists for more than 200 years. They understood that science should proceed first by describing how things work and later by understanding why. In recent years, however, the *why* of mass has become a research topic in physics. Understanding the meaning and origins of mass will complete and extend the Standard Model of particle physics, the well-established theory that describes the known elementary particles and their interactions. It will also resolve mysteries such as dark matter, which makes up about 25 percent of the universe.

The foundation of our modern understanding of mass is far more intricate than Newton's definition and is based on the Standard Model. At the heart of the Standard

The Mysteries of

MASS

Physicists are hunting for an elusive particle that would reveal the presence of a new kind of field that permeates all of reality. Finding that Higgs field will give us a more complete understanding about how the universe works

By Gordon Kane

BRYAN CHRISTIE DESIGN

Model is a mathematical function called a Lagrangian, which represents how the various particles interact. From that function, by following rules known as relativistic quantum theory, physicists can calculate the behavior of the elementary particles, including how they come together to form compound particles, such as protons. For both the elementary particles and the compound ones, we can then calculate how they will respond to forces, and for a force F , we can write Newton's equation $F = ma$, which relates the force, the mass and the resulting acceleration. The Lagrangian tells us what to use for m here, and that is what is meant by the mass of the particle.

constituents' rest mass and also their kinetic energy of motion and potential energy of interactions contribute to the particle's total mass. Energy and mass are related, as described by Einstein's famous equation, $E = mc^2$ (energy equals mass times the speed of light squared).

An example of energy contributing to mass occurs in the most familiar kind of matter in the universe—the protons and neutrons that make up atomic nuclei in stars, planets, people and all that we see. These particles amount to 4 to 5 percent of the mass-energy of the universe [see box on page 37]. The Standard Model tells us that protons and neutrons are composed of elementary particles

The Higgs Mechanism

UNLIKE PROTONS and neutrons, truly elementary particles—such as quarks and electrons—are not made up of smaller pieces. The explanation of how they acquire their rest masses gets to the very heart of the problem of the origin of mass. As I noted above, the account proposed by contemporary theoretical physics is that fundamental particle masses arise from interactions with the Higgs field. But why is the Higgs field present throughout the universe? Why isn't its strength essentially zero on cosmic scales, like the electromagnetic field? What is the Higgs field?

The Higgs field is a quantum field.



Why is the Higgs field present throughout the universe? What is the Higgs field?

But mass, as we ordinarily understand it, shows up in more than just $F = ma$. For example, Einstein's special relativity theory predicts that massless particles in a vacuum travel at the speed of light and that particles with mass travel more slowly, in a way that can be calculated if we know their mass. The laws of gravity predict that gravity acts on mass and energy as well, in a precise manner. The quantity m deduced from the Lagrangian for each particle behaves correctly in all those ways, just as we expect for a given mass.

Fundamental particles have an intrinsic mass known as their rest mass (those with zero rest mass are called massless). For a compound particle, the

called quarks that are bound together by massless particles called gluons. Although the constituents are whirling around inside each proton, from outside we see a proton as a coherent object with an intrinsic mass, which is given by adding up the masses and energies of its constituents.

The Standard Model lets us calculate that nearly all the mass of protons and neutrons is from the kinetic energy of their constituent quarks and gluons (the remainder is from the quarks' rest mass). Thus, about 4 to 5 percent of the entire universe—almost all the familiar matter around us—comes from the energy of motion of quarks and gluons in protons and neutrons.

That may sound mysterious, but the fact is that all elementary particles arise as quanta of a corresponding quantum field. The electromagnetic field is also a quantum field (its corresponding elementary particle is the photon). So in this respect, the Higgs field is no more enigmatic than electrons and light. The Higgs field does, however, differ from all other quantum fields in three crucial ways.

The first difference is somewhat technical. All fields have a property called spin, an intrinsic quantity of angular momentum that is carried by each of their particles. Particles such as electrons have spin $\frac{1}{2}$ and most particles associated with a force, such as the photon, have spin 1. The Higgs boson (the particle of the Higgs field) has spin 0. Having 0 spin enables the Higgs field to appear in the Lagrangian in different ways than the other particles do, which in turn allows—and leads to—its other two distinguishing features.

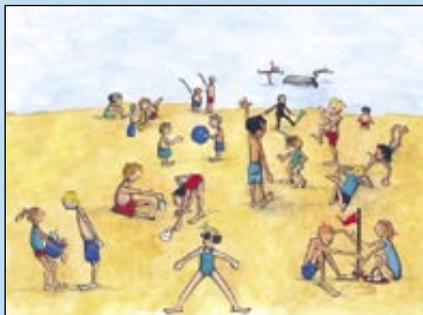
The second unique property of the Higgs field explains how and why it has nonzero strength throughout the universe. Any system, including a universe, will tumble into its lowest energy state, like a ball bouncing down to the bottom of a valley. For the familiar fields, such as the electromagnetic fields that give us

Overview/Higgs Physics

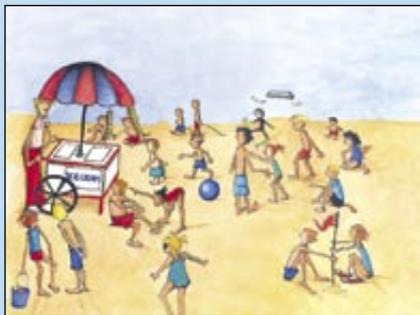
- Mass is a seemingly everyday property of matter, but it is actually mysterious to scientists in many ways. How do elementary particles acquire mass in the first place, and why do they have the specific masses that they do?
- The answers to those questions will help theorists complete and extend the Standard Model of particle physics, which describes the physics that governs the universe. The extended Standard Model may also help solve the puzzle of the invisible dark matter that accounts for about 25 percent of the cosmos.
- Theories say that elementary particles acquire mass by interacting with a quantum field that permeates all of reality. Experiments at particle accelerators may soon detect direct evidence of this so-called Higgs field.

PROPERTIES OF THE ELUSIVE HIGGS

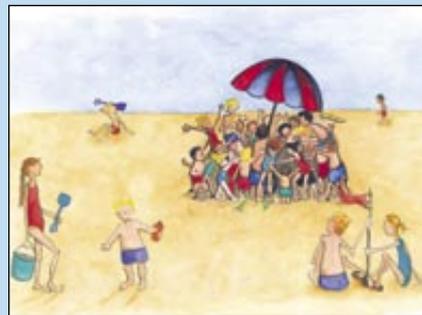
HOW THE HIGGS FIELD GENERATES MASS



“Empty” space, which is filled with the Higgs field, is like a beach full of children.



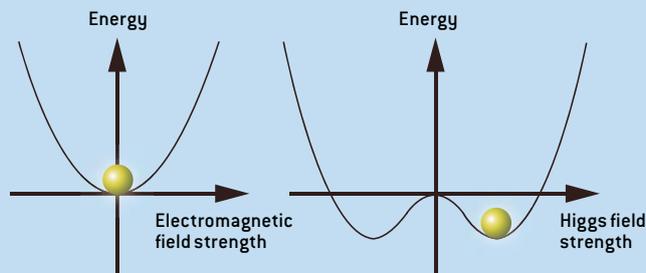
A particle crossing that region of space is like an ice cream vendor arriving ...



... and interacting with kids who slow him down—as if he acquires “mass.”

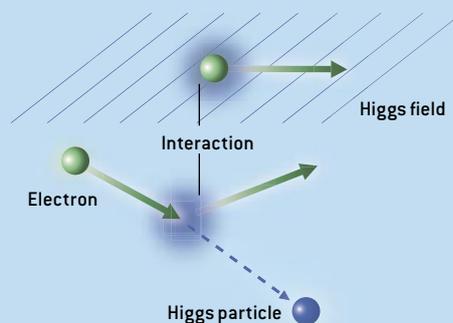
PERMEATING REALITY

A typical field, such as the electromagnetic field, has its lowest energy at zero field strength (*left*). The universe is akin to a ball that rolled around and came to rest at the bottom of the valley—that is, it has settled at a field strength of zero. The Higgs, in contrast, has its minimum energy at a nonzero field strength, and the “ball” comes to rest at a nonzero value (*right*). Thus, the universe, in its natural lowest energy state, is permeated by that nonzero value of the Higgs field.



CAUSING TWO PHENOMENA

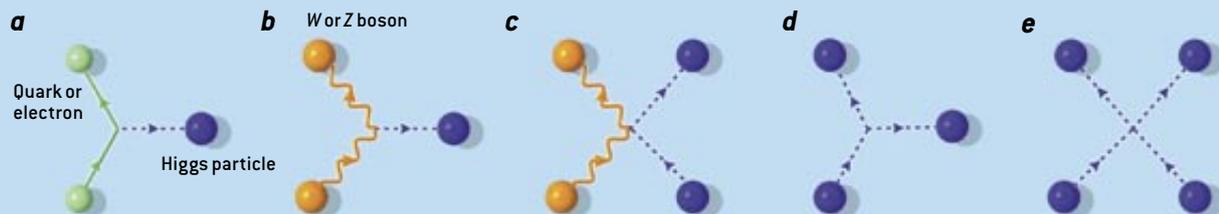
Two completely different phenomena—the acquisition of mass by a particle (*top*) and the production of a Higgs boson (*bottom*)—are caused by exactly the same interaction. This fact will be of great use in testing the Higgs theory by experiments.

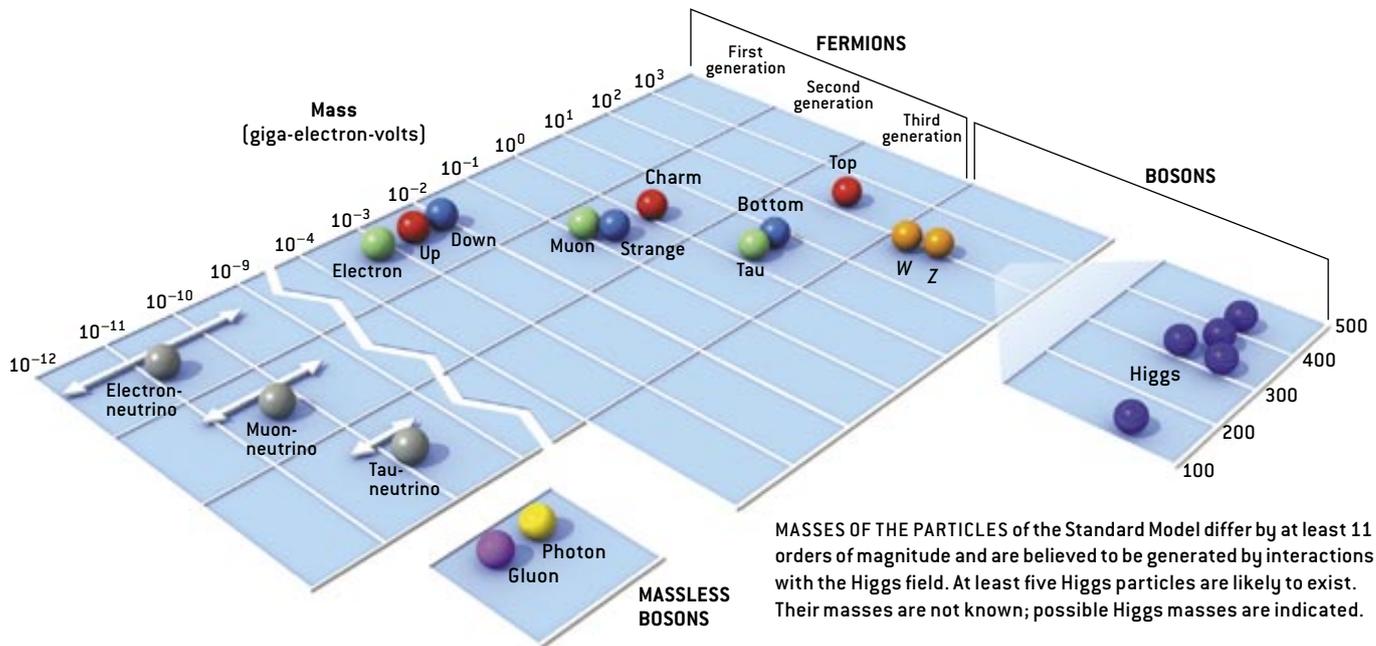


INTERACTING WITH OTHER PARTICLES

Force diagrams called Feynman diagrams represent how the Higgs particle interacts with other particles. Diagram (*a*) represents a particle such as a quark or an electron emitting (*shown*) or absorbing a Higgs particle. Diagram (*b*) shows the corresponding process for a *W* or *Z* boson. The *W* and *Z* can also interact simultaneously with two Higgs, as shown in (*c*), which also represents a *W* or *Z* scattering (roughly speaking,

colliding with) a Higgs particle. The interactions represented by diagrams (*a*) through (*c*) are also responsible for generating particles' masses. The Higgs also interacts with itself, as represented by diagrams (*d*) and (*e*). More complicated processes can be built up by joining together copies of these elementary diagrams. Interactions depicted in (*d*) and (*e*) are responsible for the shape of the energy graph (*above left*).





radio broadcasts, the lowest energy state is the one in which the fields have zero value (that is, the fields vanish)—if any nonzero field is introduced, the energy stored in the fields increases the net energy of the system. But for the Higgs field, the energy of the universe is lower if the field is not zero but instead has a constant nonzero value. In terms of the valley metaphor, for ordinary fields the valley floor is at the location of zero field; for the Higgs, the valley has a hillock at its center (at zero field) and the lowest point of the valley forms a circle around the hillock [see box on preceding page]. The universe, like a ball, comes to rest somewhere on this circular trench, which corresponds to a nonzero value of the field. That is, in its natural, lowest energy state, the universe is permeated throughout by a *nonzero* Higgs field.

The final distinguishing characteristic of the Higgs field is the form of its interactions with the other particles. Particles that interact with the Higgs field behave as if they have mass, proportional to the strength of the field times the strength of the interaction. The masses arise from the terms in the Lagrangian that have the particles interacting with the Higgs field.

Our understanding of all this is not yet complete, however, and we are not sure how many kinds of Higgs fields there are. Although the Standard Model requires only one Higgs field to generate all the elementary particle masses, physicists know that the Standard Model must be superseded by a more complete

theory. Leading contenders are extensions of the Standard Model known as Supersymmetric Standard Models (SSMs). In these models, each Standard Model particle has a so-called superpartner (as yet undetected) with closely related properties [see “The Dawn of Physics beyond the Standard Model,” by Gordon Kane, on page 4]. With the Supersymmetric Standard Model, at least two different kinds of Higgs fields are needed. Interactions with those two fields give mass to the Standard Model particles. They also give some (but not all) mass to the superpartners. The two Higgs fields give rise to five species of Higgs boson: three that are electrically neutral and two that are charged. The masses of particles called neutrinos, which are tiny compared with other particle masses, could arise rather indirectly from these interactions or from yet a third kind of Higgs field.

Theorists have several reasons for expecting the SSM picture of the Higgs interaction to be correct. First, without the Higgs mechanism, the *W* and *Z* bosons that mediate the weak force would be massless, just like the photon (which they are related to), and the weak interaction would be as strong as the electromagnetic one. Theory holds that the Higgs mechanism confers mass to the *W* and *Z* in a very special manner. Predictions of that approach (such as the ratio of the *W* and *Z* masses) have been confirmed experimentally.

Second, essentially all other aspects of the Standard Model have been well

tested, and with such a detailed, interlocking theory it is difficult to change one part (such as the Higgs) without affecting the rest. For example, the analysis of precision measurements of *W* and *Z* boson properties led to the accurate prediction of the top quark mass before the top quark had been directly produced. Changing the Higgs mechanism would spoil that and other successful predictions.

Third, the Standard Model Higgs mechanism works very well for giving mass to *all* the Standard Model particles, *W* and *Z* bosons, as well as quarks and leptons; the alternative proposals usually do not. Next, unlike the other theories, the SSM provides a framework to unify our understanding of the forces of nature. Finally, the SSM can explain why the energy “valley” for the universe has the shape needed by the Higgs mechanism. In the basic Standard Model the shape of the valley has to be put in as a postulate, but in the SSM that shape can be derived mathematically.

Testing the Theory

NATURALLY, PHYSICISTS want to carry out direct tests of the idea that mass arises from the interactions with the different Higgs fields. We can test three key features. First, we can look for the signature particles called Higgs bosons. These quanta must exist, or else the explanation is not right. Physicists are currently looking for Higgs bosons at the Tevatron Collider at Fermi National Accelerator Laboratory in Batavia, Ill.

A Cosmic Stocktaking

Second, once they are detected we can observe how Higgs bosons interact with other particles. The very same terms in the Lagrangian that determine the masses of the particles also fix the properties of such interactions. So we can conduct experiments to test quantitatively the presence of interaction terms of that type. The strength of the interaction and the amount of particle mass are uniquely connected.

Third, different sets of Higgs fields, as occur in the Standard Model or in the various SSMs, imply different sets of Higgs bosons with various properties, so tests can distinguish these alternatives, too. All that we need to carry out the tests are appropriate particle colliders—ones that have sufficient energy to produce the different Higgs bosons, sufficient intensity to make enough of them and very good detectors to analyze what is produced.

A practical problem with performing such tests is that we do not yet understand the theories well enough to calculate what masses the Higgs bosons themselves should have, which makes searching for them more difficult because one must examine a range of masses. A combination of theoretical reasoning and data from experiments guides us about roughly what masses to expect.

The Large Electron-Positron Collider (LEP) at CERN, the European laboratory for particle physics near Geneva, operated over a mass range that had a significant chance of including a Higgs boson. It did not find one—although there was tantalizing evidence for one just at the limits of the collider's energy and intensity—before it was shut down in 2000 to make room for constructing a newer facility, CERN's Large Hadron Collider (LHC). The Higgs must therefore be heavier than about 120 proton masses. Nevertheless, LEP did produce indirect evidence that a Higgs boson exists: experimenters at LEP made a number of precise measurements, which can be combined with similar measurements from the Tevatron and the collider at the Stanford Linear Accelerator Center. The entire set of data agrees well with theory only

The theory of the Higgs field explains how elementary particles, the smallest building blocks of the universe, acquire their mass. But the Higgs mechanism is not the only source of mass-energy in the universe ("mass-energy" refers to both mass and energy, which are related by Einstein's $E = mc^2$).

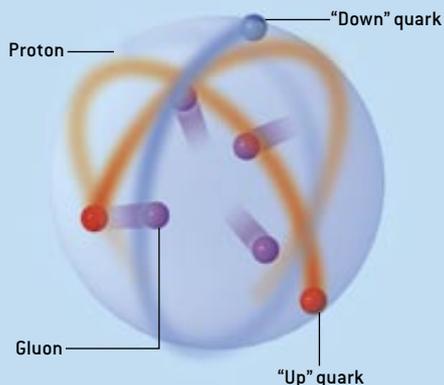
About 70 percent of the mass-energy of the universe is in the form of so-called dark energy, which is not directly associated with particles. The chief sign of the existence of dark energy is that the universe's expansion is accelerating. The precise nature of dark energy is one of the most profound open questions in physics [see "A Cosmic Conundrum," by Lawrence M. Krauss and Michael S. Turner, on page 66].

The remaining 30 percent of the universe's mass-energy comes from matter, particles with mass. The most familiar kinds of matter are protons, neutrons and electrons, which make up stars, planets, people and all that we see. These particles provide about one sixth of the matter of the universe, or 4 to 5 percent of the entire universe. As is explained in the main text, most of this mass arises from the energy of motion of quarks and gluons whirling around inside protons and neutrons.

A smaller contribution to the universe's matter comes from particles called neutrinos, which come in three

varieties. Neutrinos have mass but surprisingly little. The absolute masses of neutrinos are not yet measured, but the existing data put an upper limit on them—less than half a percent of the universe.

Almost all the rest of the matter—around 25 percent of the universe's total mass-energy—is matter we do not see, called dark matter. We deduce its existence from its gravitational effects on what we do see. We do not yet know what this dark matter actually is, but there are good candidates, and experiments are under way to test different ideas [see "The Search for Dark Matter," by David B. Cline; SCIENTIFIC AMERICAN, March 2003]. The dark matter should be composed of massive particles because it forms galaxy-size

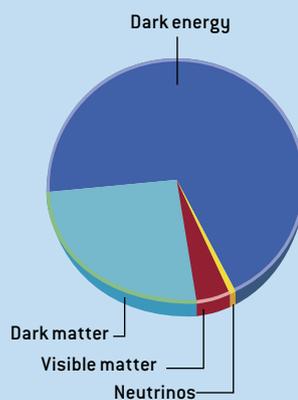


MOST VISIBLE MASS is locked up in protons and neutrons. Each of these consists of quarks and gluons flying around. Almost all of the proton's or neutron's mass is from the energy of motion of the quarks and gluons.

clumps under the effects of the gravitational force. A variety of arguments have let us conclude that the dark matter cannot be composed of any of the normal Standard Model particles.

The leading candidate particle for dark matter is the lightest superpartner (LSP), which is discussed in greater detail in the main text. The lightest superpartner occurs in extensions of the Standard Model called Supersymmetric Standard Models. The mass of the LSP is thought to be about 100 proton masses. That the LSP was a good candidate for the dark matter was recognized by theorists before cosmologists knew that a new form of fundamental matter was needed to explain dark matter. —G.K.

THE UNIVERSE



MASS-ENERGY of the universe mainly comes in four broad types: mysterious dark energy that causes the universe's expansion to accelerate; invisible dark matter that we can detect by its gravitational effects; visible matter; and neutrinos.

if certain interactions of particles with the lightest Higgs boson are included and only if the lightest Higgs boson is not heavier than about 200 proton masses. That provides researchers with an upper limit for the mass of the Higgs boson, which helps to focus the search.

For the next few years, the only collider that could produce direct evidence for Higgs bosons will be the Tevatron. Its energy is sufficient to discover a Higgs boson in the range of masses implied by the indirect LEP evidence, *if* it can consistently achieve the beam intensity it was expected to have, which so far has not been possible. In 2007 the LHC, which is seven times more energetic and is designed to have far more intensity

particle of the SSM is the lightest superpartner (LSP). Among the superpartners of the known Standard Model particles predicted by the SSM, the LSP is the one with the lowest mass. Most superpartners decay promptly to lower-mass superpartners, a chain of decays that ends with the LSP, which is stable because it has no lighter particle that it can decay into. (When a superpartner decays, at least one of the decay products should be another superpartner; it should not decay entirely into Standard Model particles.) Superpartner particles would have been created early in the big bang but then promptly decayed into LSPs. The LSP is the leading candidate particle for dark matter.

Neutrino masses may also arise from interactions with additional Higgs or Higgs-like fields, in a very interesting way. Neutrinos were originally assumed to be massless, but since 1979 theorists have predicted that they have small masses, and over the past decade or so several impressive experiments have confirmed the predictions [see “Solving the Solar Neutrino Problem,” by Arthur B. McDonald, Joshua R. Klein and David L. Wark, on page 22]. The neutrino masses are less than a millionth the size of the next smallest mass, the electron mass. Because neutrinos are electrically neutral, the theoretical description of their masses is more subtle than for charged particles. Several processes contribute to



The LEP collider saw tantalizing evidence for the Higgs particle.

than the Tevatron, is scheduled to begin taking data. It will be a factory for Higgs bosons (meaning it will produce many of the particles a day). Assuming the LHC functions as planned, gathering the relevant data and learning how to interpret it should take one to two years. Carrying out the complete tests that show in detail that the interactions with Higgs fields are providing the mass will require a new electron-positron collider in addition to the LHC (which collides protons) and the Tevatron (which collides protons and antiprotons).

Dark Matter

WHAT IS DISCOVERED about Higgs bosons will not only test whether the Higgs mechanism is indeed providing mass, it will also point the way to how the Standard Model can be extended to solve problems such as the origin of dark matter.

With regard to dark matter, a key

The Higgs bosons may also directly affect the amount of dark matter in the universe. We know that the amount of LSPs today should be less than the amount shortly after the big bang, because some would have collided and annihilated into quarks and leptons and photons, and the annihilation rate may be dominated by LSPs interacting with Higgs bosons.

As mentioned earlier, the two basic SSM Higgs fields give mass to the Standard Model particles and *some* mass to the superpartners, such as the LSP. The superpartners acquire more mass via additional interactions, which may be with still further Higgs fields or with fields similar to the Higgs. We have theoretical models of how these processes can happen, but until we have data on the superpartners themselves we will not know how they work in detail. Such data are expected from the LHC or perhaps even from the Tevatron.

the mass of each neutrino species, and for technical reasons the actual mass value emerges from solving an equation rather than just adding the terms.

Thus, we have understood the three ways that mass arises: The main form of mass we are familiar with—that of protons and neutrons and therefore of atoms—comes from the motion of quarks bound into protons and neutrons. The proton mass would be about what it is even without the Higgs field. The masses of the quarks themselves, however, and also the mass of the electron, are entirely caused by the Higgs field. Those masses would vanish without the Higgs. Last, but certainly not least, most of the amount of superpartner masses, and therefore the mass of the dark matter particle (if it is indeed the lightest superpartner), comes from additional interactions beyond the basic Higgs one.

Finally, we consider an issue known as the family problem. Over the past half a century physicists have shown that the world we see, from people to flowers to stars, is constructed from just six particles: three matter particles (up quarks, down quarks and electrons), two force quanta (photons and gluons), and Higgs bosons—a remarkable and surprisingly

THE AUTHOR

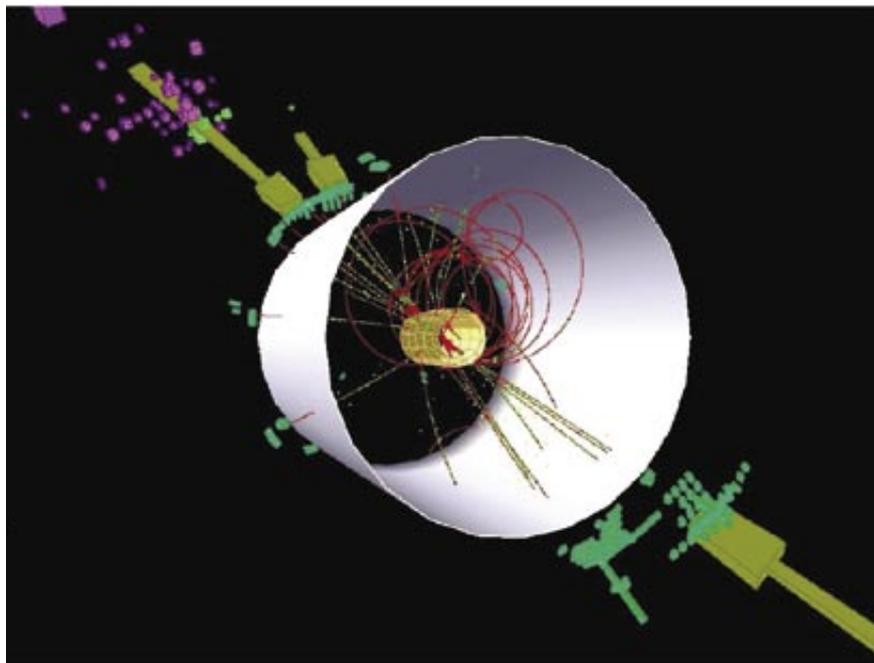
GORDON KANE, a particle theorist, is Victor Weisskopf Collegiate Professor of Physics at the University of Michigan at Ann Arbor. His work explores ways to test and extend the Standard Model of particle physics. In particular, he studies Higgs physics and the Standard Model's supersymmetric extension and cosmology, with a focus on relating theory and experiment. Recently he has emphasized integrating these topics with string theory and studying the implications for collider experiments.

simple description. Yet there are four more quarks, two more particles similar to the electron, and three neutrinos. All are very short-lived or barely interact with the other six particles. They can be classified into three families: up, down, electron-neutrino, electron; charm, strange, muon-neutrino, muon; and top, bottom, tau-neutrino, tau. The particles in each family have interactions identical to those of the particles in other families. They differ only in that those in the second family are heavier than those in the first, and those in the third family are heavier still. Because these masses arise from interactions with the Higgs field, the particles must have different interactions with the Higgs field.

Hence, the family problem has two parts: Why are there three families when it seems only one is needed to describe the world we see? Why do the families differ in mass and have the masses they do? Perhaps it is not obvious why physicists are astonished that nature contains three almost identical families even if one would do. It is because we want to fully understand the laws of nature and the basic particles and forces. We expect that every aspect of the basic laws is a necessary one. The goal is to have a theory in which all the particles and their mass ratios emerge inevitably, without making ad hoc assumptions about the values of the masses and without adjusting parameters. If having three families is essential, then it is a clue whose significance is currently not understood.

Tying It All Together

THE STANDARD MODEL and the SSM can accommodate the observed family structure, but they cannot explain it. This is a strong statement. It is not that the SSM has not *yet* explained the family structure but that it *cannot*. For me, the most exciting aspect of string theory is not only that it may provide us with a quantum theory of all the forces but also that it may tell us what the elementary particles are and why there are three families. String theory seems able to address the question of why the interactions with the Higgs field differ among



A HIGGS PARTICLE might have been created when a high-energy positron and electron collided in the L3 detector of the Large Electron-Positron Collider at CERN. The lines represent particle tracks. The green and purple blobs and gold histograms depict amounts of energy deposited in layers of the detector by particles flying away from the reaction. Only by combining many such events can physicists conclude whether Higgs particles were present in some of the reactions or if all the data were produced by other reactions that happened to mimic the Higgs signal.

the families. In string theory, repeated families can occur, and they are not identical. Their differences are described by properties that do not affect the strong, weak, electromagnetic or gravitational forces but that do affect the interactions with Higgs fields, which fits with our having three families with different masses. Although string theorists have not yet fully solved the problem of having three families, the theory seems to have the right structure to provide a solution. String theory allows many different family structures, and so far no one knows why nature picks the one we observe rather than some other [see “The String Theory Landscape,” by Raphael Bousso and Joseph Polchinski, on page 40]. Data on the quark and lepton masses and on their superpartner masses

may provide major clues to teach us about string theory.

One can now understand why it took so long historically to begin to understand mass. Without the Standard Model of particle physics and the development of quantum field theory to describe particles and their interactions, physicists could not even formulate the right questions. Whereas the origins and values of mass are not yet fully understood, it is likely that the framework needed to understand them is in place. Mass could not have been comprehended before theories such as the Standard Model and its supersymmetric extension and string theory existed. Whether they indeed provide the complete answer is not yet clear, but mass is now a routine research topic in particle physics. SA

MORE TO EXPLORE

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An excellent collection of particle physics Web sites is listed at particleadventure.org/particleadventure/other/othersites.html

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