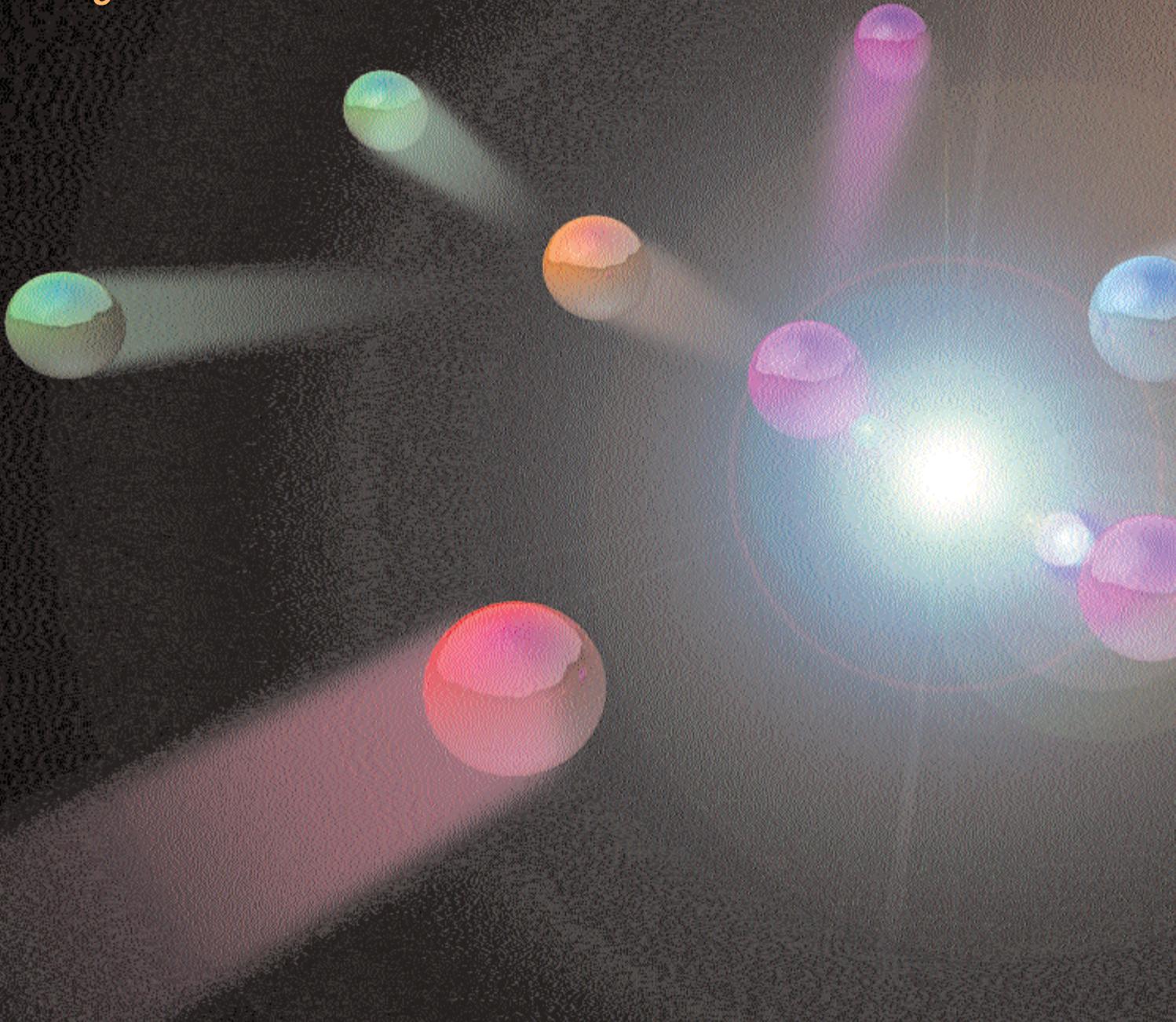
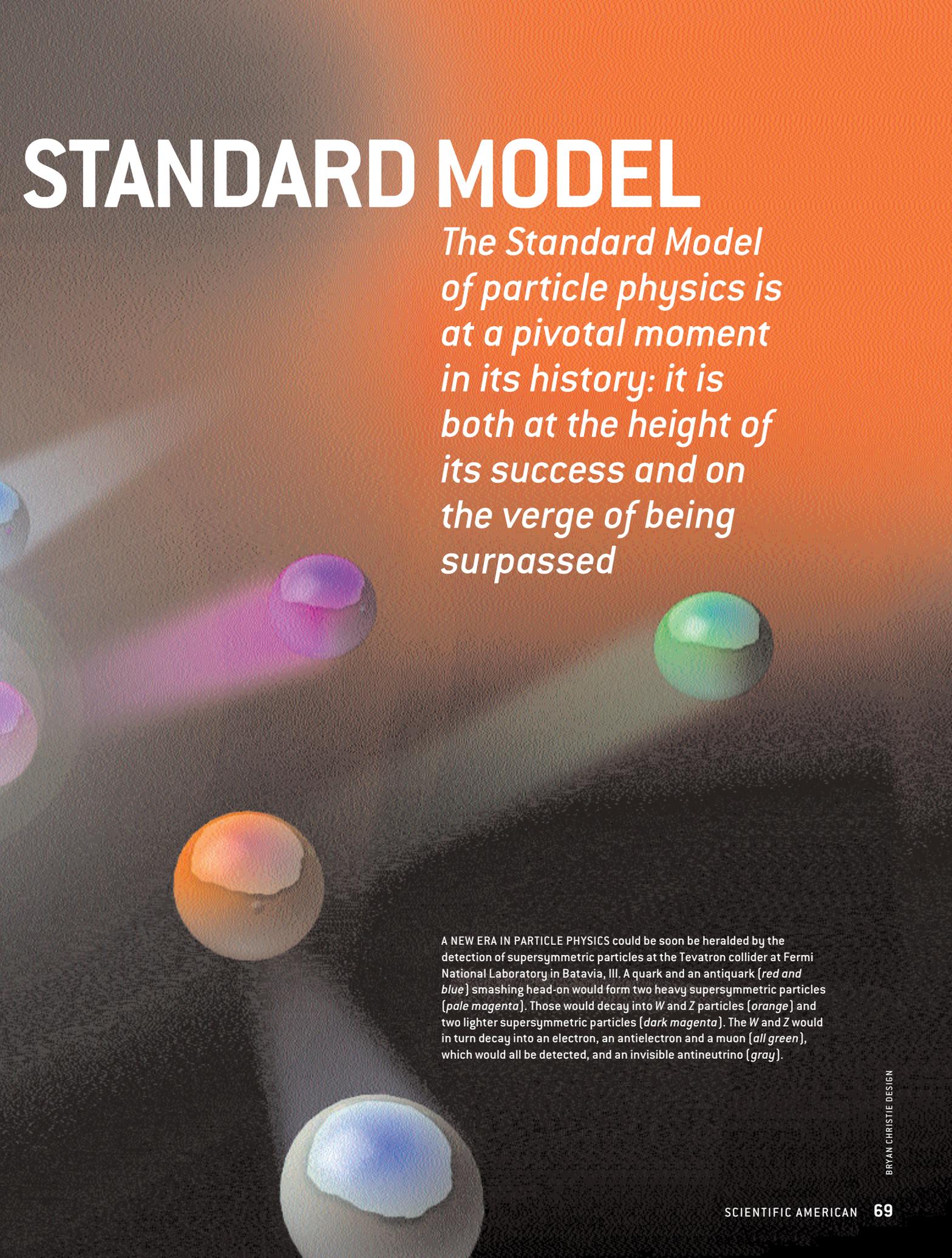


The Dawn of PHYSICS BEYOND THE

By Gordon Kane



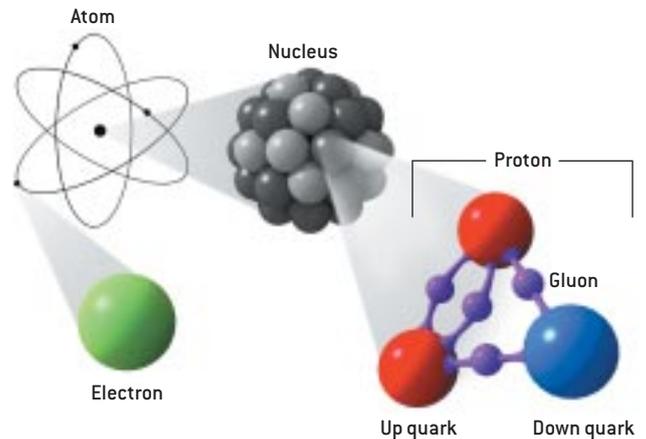
STANDARD MODEL

An abstract visualization of particle physics. The background is a dark, textured gradient. Several glowing, semi-transparent spheres in various colors (purple, green, orange, blue) are scattered across the frame. Some spheres are connected by faint, glowing lines or beams of light, suggesting particle interactions or decay paths. The overall aesthetic is scientific and futuristic.

The Standard Model of particle physics is at a pivotal moment in its history: it is both at the height of its success and on the verge of being surpassed

A NEW ERA IN PARTICLE PHYSICS could be soon be heralded by the detection of supersymmetric particles at the Tevatron collider at Fermi National Laboratory in Batavia, Ill. A quark and an antiquark (*red and blue*) smashing head-on would form two heavy supersymmetric particles (*pale magenta*). Those would decay into *W* and *Z* particles (*orange*) and two lighter supersymmetric particles (*dark magenta*). The *W* and *Z* would in turn decay into an electron, an antielectron and a muon (*all green*), which would all be detected, and an invisible antineutrino (*gray*).

THE STANDARD MODEL



The Particles

ALTHOUGH THE STANDARD MODEL needs to be extended, its particles suffice to describe the everyday world (except for gravity) and almost all data collected by particle physicists.

MATTER PARTICLES (FERMIONS) In the Standard Model, the fundamental particles of ordinary matter are the electron, the up quark (u) and the down quark (d). Triplets of quarks bind together to form protons (uud) and neutrons (udd), which in turn make up atomic nuclei (above). The electron and the up and the down quarks, together with the electron-neutrino, form the first of three groups of particles called generations. Each generation is identical in every respect except for the masses of the particles (grid at right). The values of the neutrino masses in the chart are speculative but chosen to be consistent with observations.

FORCE CARRIERS (BOSONS) The Standard Model describes three of the four known forces: electromagnetism, the weak force (which is involved in the formation of the chemical elements) and the strong force (which holds protons, neutrons and nuclei together). The forces are mediated by force particles: photons for electromagnetism, the W and Z bosons for the weak force, and gluons for the strong force. For gravity, gravitons are postulated, but the Standard Model does not include gravity. The Standard Model unifies the electromagnetic and weak forces—they blend into one “electroweak” force at high energies or, equivalently, at distances smaller than the diameter of protons.

One of the greatest successes of the Standard Model is that the forms of the forces—the detailed structure of the equations describing them—are largely determined by general principles embodied in the theory rather than being chosen in an ad hoc fashion to match a collection of empirical data. For electromagnetism, for example, the validity of relativistic quantum field theory (on which the Standard Model is based) and the existence of the electron imply that the photon must also exist and interact in the way that it does—we finally understand light. Similar arguments predicted the existence and properties, later confirmed, of gluons and the W and Z particles.

Today, centuries after the search began for the fundamental constituents that make up all the complexity and beauty of the everyday world, we have an astonishingly simple answer—it takes just six particles: the electron, the up and the down quarks, the gluon, the photon and the Higgs boson. Eleven additional particles suffice to describe all the esoteric phenomena studied by particle physicists [see box at right]. This is not speculation akin to the ancient Greeks’ four elements of earth, air, water and fire. Rather it is a conclusion embodied in the most sophisticated mathematical theory of nature in history, the Standard Model of particle physics. Despite the word “model” in its name, the Standard Model is a comprehensive theory that specifies what are the basic particles and how they interact. Everything that happens in our world (except for the effects of gravity) results from Standard Model particles interacting according to its rules and equations.

The Standard Model was formulated in the 1970s and tentatively established by experiments in the early 1980s. Nearly three decades of exacting experiments have tested and verified the theory in meticulous detail, confirming all of its predictions. In one respect, this success is rewarding because it confirms that we really understand, at a deeper level than ever before, how nature works. Paradoxically, the success has also been frustrating. Before the advent of the Standard Model, physicists had become used to experiments producing unexpected new particles or other signposts to a new theory almost before the chalk dust had settled on the old one. They have been waiting 30 years for that to happen with the Standard Model.

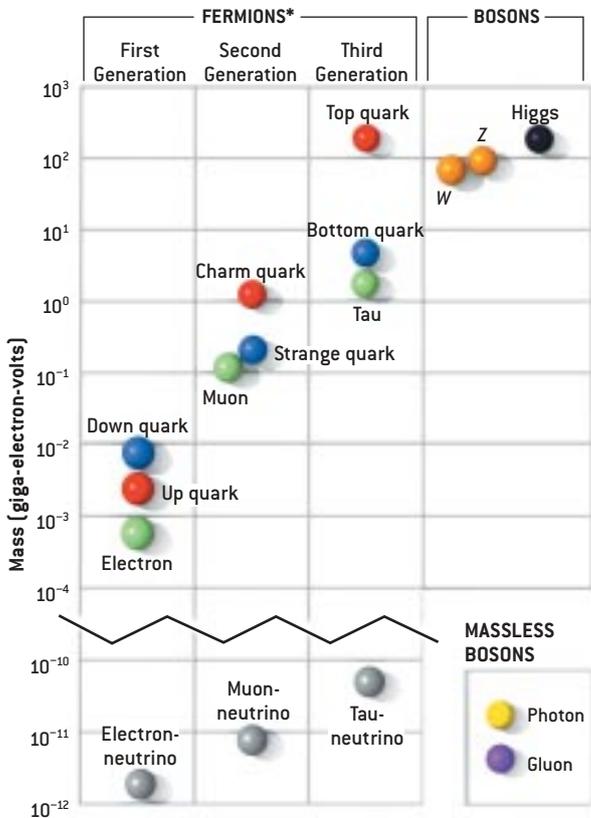
Their wait should soon be over. Experiments that achieve collisions that are higher in energy than ever before or that study cer-

Overview/A New Era

- The Standard Model of particle physics is the most successful theory of nature in history, but increasingly there are signs that it must be extended by adding new particles that play roles in high-energy reactions.
- Major experiments are on the verge of providing direct evidence of these new particles. After 30 years of consolidation, particle physics is entering a new era of discovery. Many profound mysteries could be resolved by post-Standard Model physics.
- One element of the Standard Model—a particle called the Higgs boson—also remains to be observed. The Tevatron collider at Fermilab could detect Higgs bosons within the next few years.

THE SOURCE OF MASS In addition to the particles described above, the Standard Model predicts the existence of the Higgs boson, which has not yet been directly detected by experiment. The Higgs interacts with the other particles in a special manner that gives them mass.

DEEPER LEVELS? Might the Standard Model be superseded by a theory in which quarks and electrons are made up of more fundamental particles? Almost certainly not. Experiments have probed much more deeply than ever before without finding a hint of additional structure. More important, the Standard Model is a consistent theory that makes sense if electrons and quarks are fundamental. There are no loose ends hinting at a deeper underlying structure. Further, all the forces become similar at high energies, particularly if supersymmetry is true [see box on next page]. If electrons and quarks are composite, this unification fails: the forces do not become equal. Relativistic quantum field theory views electrons and quarks as being pointlike—they are structureless. In the future, they might be thought of as tiny strings or membranes (as in string theory), but they will still be electrons and quarks, with all the known Standard Model properties of these objects at low energies.



* FERMIONS ARE SUBDIVIDED INTO QUARKS AND LEPTONS, WITH LEPTONS INCLUDING ELECTRONS, MUONS, TAUS AND THREE FORMS OF NEUTRINO.

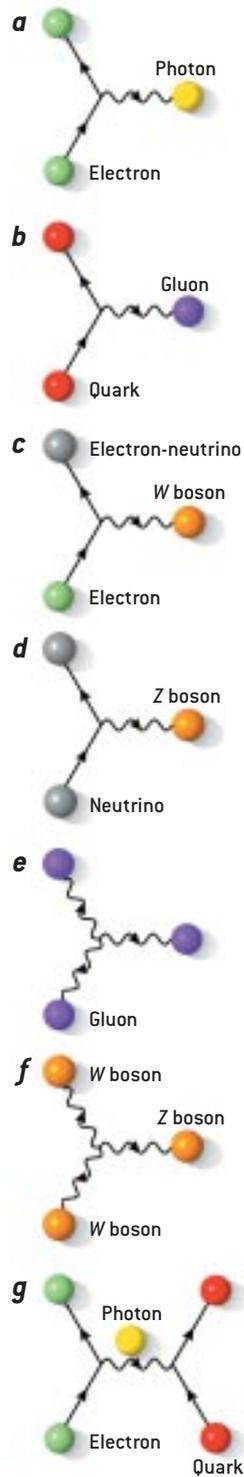
The Rules of the Game

THE STANDARD MODEL describes the fundamental particles and how they interact. For a full understanding of nature, we also need to know what rules to use to calculate the results of the interactions. An example that helps to elucidate this point is Newton's law, $F = ma$. F is any force, m is the mass of any particle, and a is the acceleration of the particle induced by the force. Even if you know the particles and the forces acting on them, you cannot calculate how the particles behave unless you also know the rule $F = ma$. The modern version of the rules is relativistic quantum field theory, which was invented in the first half of the 20th century. In the second half of the 20th century the development of the Standard Model taught researchers about the nature of the particles and forces that were playing by the rules of quantum field theory. The classical concept of a force is also extended by the Standard Model: in addition to pushing and pulling on one another, when particles interact they can change their identity and be created or destroyed.

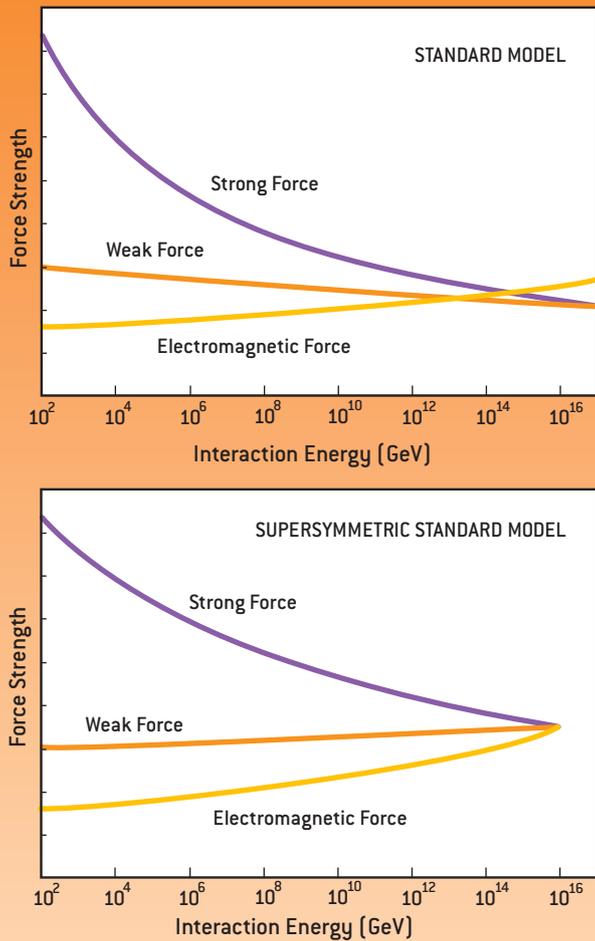
Feynman diagrams (a–g, at right), first devised by physicist Richard P. Feynman, serve as a useful shorthand describing interactions in quantum field theory. The straight lines represent the trajectories of matter particles; the wavy lines represent those of force particles. Electromagnetism is produced by the emission or absorption of photons by any charged particle, such as an electron or a quark. In a, the incoming electron emits a photon and travels off in a new direction. The strong force involves gluons emitted (b) or absorbed by quarks. The weak force involves W and Z particles (c, d), which are emitted or absorbed by both quarks and leptons (electrons, muons, taus and neutrinos). Notice how the W causes the electron to change identity. Gluons (e) and Ws and Zs (f) also self-interact, but photons do not.

Diagrams a through f are called interaction vertices. Forces are produced by combining two or more vertices. For example, the electromagnetic force between an electron and a quark is largely generated by the transfer of a photon (g). Everything that happens in our world, except for gravity, is the result of combinations of these vertices.

—G.K.



Evidence for Supersymmetry



THE MOST WIDELY FAVORED THEORY to supersede the Standard Model is the Minimal Supersymmetric Standard Model. In this model, every known particle species has a superpartner particle that is related to it by supersymmetry. Particles come in two broad classes: bosons (such as the force particles), which can gather en masse in a single state, and fermions (such as quarks and leptons), which avoid having identical states. The superpartner of a fermion is always a boson and vice versa.

Indirect evidence for supersymmetry comes from the extrapolation of interactions to high energies. In the Standard Model, the three forces become similar but not equal in strength (top). The existence of superpartners changes the extrapolation so that the forces all coincide at one energy (bottom)—a clue that they become unified if supersymmetry is true.

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, with a focus on relating theory and experiment and on the implications of supersymmetry for particle physics and cosmology. His hobbies include playing squash, exploring the history of ideas, and seeking to understand why science flourishes in some cultures but not others.

tain key phenomena with greater precision are on the verge of going beyond the Standard Model. These results will not overturn the Standard Model. Instead they will extend it by uncovering particles and forces not described by it. The most important experiment is occurring at the upgraded Tevatron collider at Fermi National Accelerator Laboratory in Batavia, Ill., which began taking data in 2001. It might produce directly the still elusive particles that complete the Standard Model (Higgs bosons) and those predicted by the most compelling extensions of the theory (the so-called superpartners of the known particles).

Significant information is also beginning to come from “B factories,” particle colliders running in California and Japan configured to create billions of b quarks (one of the 11 additional particles) and their antimatter equivalents to study a phenomenon called CP violation. CP (charge-parity) is the symmetry relating matter to antimatter, and CP violation means that antimatter does not exactly mirror matter in its behavior. The amount of CP violation observed so far in particle decays can be accommodated by the Standard Model, but we have reasons to expect much more CP violation than it can produce. Physics that goes beyond the Standard Model can generate additional CP violation.

Physicists are also studying the precise electric and magnetic properties of particles. The Standard Model predicts that electrons and quarks behave as microscopic magnets with a specific strength and that their behavior in an electric field is determined purely by their electric charge. Most extensions of the Standard Model predict a slightly different magnetic strength and electrical behavior. Experiments are beginning to collect data with enough sensitivity to see the tiny effects predicted.

Looking beyond the earth, scientists studying solar neutrinos and cosmic-ray neutrinos, ghostly particles that barely interact at all, have recently established that neutrinos have masses, a result long expected by theorists studying extensions of the Standard Model [see “Solving the Solar Neutrino Problem,” by Arthur B. McDonald, Joshua R. Klein and David L. Wark; *SCIENTIFIC AMERICAN*, April]. The next round of experiments will clarify the form of theory needed to explain the observed neutrino masses.

In addition, experiments are under way to detect mysterious particles that form the cold dark matter of the universe and to examine protons at higher levels of sensitivity to learn whether they decay. Success in either project would be a landmark of post-Standard Model physics.

As all this research proceeds, it is ushering in a new, data-rich era in particle physics. Joining the fray by about 2007 will be the Large Hadron Collider (LHC), a machine 27 kilometers in circumference now under construction at CERN, the European laboratory for particle physics near Geneva [see “The Large Hadron Collider,” by Chris Llewellyn Smith; *SCIENTIFIC AMERICAN*, July 2000]. A 30-kilometer-long linear electron-positron collider that will complement the LHC’s results is in the design stages.

As the first hints of post-Standard Model physics are glimpsed, news reports often make it sound as if the Standard Model has been found to be wrong, as if it were broken and ready to be discarded, but that is not the right way to think about it. Take the example of Maxwell’s equations, written

down in the late 19th century to describe the electromagnetic force. In the early 20th century we learned that at atomic sizes a quantum version of Maxwell's equations is needed. Later the Standard Model included these quantum Maxwell's equations as a subset of its equations. In neither case do we say Maxwell's equations are wrong. They are extended. (And they are still used to design innumerable electronic technologies.)

A Permanent Edifice

SIMILARLY, THE STANDARD MODEL is here to stay. It is a full mathematical theory—a multiply connected and highly stable edifice. It will turn out to be one piece of a larger such edifice, but it cannot be “wrong.” No part of the theory can fail without a collapse of the entire structure. If the theory were wrong, many successful tests would be accidents. It will continue to describe strong, weak and electromagnetic interactions at low energies.

The Standard Model is very well tested. It predicted the existence of the *W* and *Z* bosons, the gluon and two of the heavier quarks (the charm and the top quark). All these particles were subsequently found, with precisely the predicted properties.

A second major test involves the electroweak mixing angle, a parameter that plays a role in unifying the weak and electromagnetic interactions. That mixing angle must have the same value for every electroweak process. If the Standard Model were wrong, the mixing angle could have one value for one process, a different value for another and so on. It is observed to have the same value everywhere, to an accuracy of about 1 percent.

Third, the Large Electron-Positron (LEP) collider at CERN, which ran from 1989 to 2000, looked at about 20 million *Z* bosons. Essentially every one of them decayed in the manner expected by the Standard Model, which predicted the number of instances of each kind of decay as well as details of the energies and directions of the outgoing particles. These tests are but a few of the many that have solidly confirmed the Standard Model.

In its full glory, the Standard Model has 17 particles and about as many free parameters—quantities such as particle masses and strengths of interactions [see box on pages 70 and 71]. These quantities can in principle take any value, and we learn the correct values only by making measurements. Armchair critics sometimes compare the Standard Model's many parameters with the epicycles on epicycles that medieval theorists used to describe planetary orbits. They imagine that the Standard Model has limited predictive power, or that its content is arbitrary, or that it can explain anything by adjusting of some parameter.

The opposite is actually true: once the masses and interaction strengths are measured in any process, they are fixed for the whole theory and for any other experiment, leaving no freedom at all. Moreover, the detailed forms of all the Standard Model's equations are determined by the theory. Every parameter but the Higgs boson mass has been measured. Until we go beyond the Standard Model, the only thing that can change with new results is the precision of our knowledge of the parameters, and as that improves it becomes harder, not easier, for all the experimental data to remain consistent, because

measured quantities must agree to higher levels of precision.

Adding further particles and interactions to extend the Standard Model might seem to introduce a lot more freedom, but this is not necessarily the case. The most widely favored extension is the Minimal Supersymmetric Standard Model (MSSM). Supersymmetry assigns a superpartner particle to every particle species. We know little about the masses of those superpartners, but their interactions are constrained by the supersymmetry. Once the masses are measured, the predictions of the MSSM will be even more tightly constrained than the Standard Model because of the mathematical relations of supersymmetry.

Ten Mysteries

IF THE STANDARD MODEL works so well, why must it be extended? A big hint arises when we pursue the long-standing goal of unifying the forces of nature. In the Standard Model, we can extrapolate the forces and ask how they would behave at much higher energies. For example, what were the forces like in the extremely high temperatures extant soon after the big bang? At low energies the strong force is about 30 times as powerful as the weak force and more than 100 times as powerful as electromagnetism. When we extrapolate, we find that the strengths of these three forces become very similar but are never all exactly the same. If we extend the Standard Model to the MSSM, the forces become essentially identical at a specific high energy [see box on opposite page]. Even better, the gravitational force approaches the same strength at a slightly higher energy, suggesting a connection between the Standard Model forces and gravity. These results seem like strong clues in favor of the MSSM.

Other reasons for extending the Standard Model arise from phenomena it cannot explain or cannot even accommodate:

- 1. All our theories today seem to imply that the universe should contain a tremendous concentration of energy, even in the emptiest regions of space. The gravitational effects of this so-called vacuum energy would have either quickly curled up the universe long ago or expanded it to much greater size. The Standard Model cannot help us understand this puzzle, called the cosmological constant problem.**
- 2. The expansion of the universe was long believed to be slowing down because of the mutual gravitational attraction of all the matter in the universe. We now know that the expansion is accelerating and that whatever causes the acceleration (dubbed “dark energy”) cannot be Standard Model physics.**
- 3. There is very good evidence that in the first fraction of a second of the big bang the universe went through a stage of extremely rapid expansion called inflation. The fields responsible for inflation cannot be Standard Model ones.**
- 4. If the universe began in the big bang as a huge burst of energy, it should have evolved into equal parts matter and antimatter (CP symmetry). But instead the stars and nebulae**

are made of protons, neutrons and electrons and not their antiparticles (their antimatter equivalents). This matter asymmetry cannot be explained by the Standard Model.

5. About a quarter of the universe is invisible cold dark matter that cannot be particles of the Standard Model.

6. In the Standard Model, interactions with the Higgs field (which is associated with the Higgs boson) cause particles to have mass. The Standard Model cannot explain the very special forms that the Higgs interactions must take.

7. Quantum corrections apparently make the calculated Higgs boson mass huge, which in turn would make all particle masses huge. That result cannot be avoided in the Standard Model and thus causes a serious conceptual problem.

8. The Standard Model cannot include gravity, because it does not have the same structure as the other three forces.

9. The values of the masses of the quarks and leptons (such as the electron and neutrinos) cannot be explained by the Standard Model.

10. The Standard Model has three “generations” of particles. The everyday world is made up entirely of first-generation particles, and that generation appears to form a consistent theory on its own. The Standard Model describes all three generations, but it cannot explain why more than one exists.

In expressing these mysteries, when I say the Standard Model *cannot* explain a given phenomenon, I do not mean that the theory has not yet explained it but might do so one day. The Standard Model is a highly constrained theory, and it cannot *ever* explain the phenomena listed above. Possible explanations do exist. One reason the supersymmetric extension is attractive to many physicists is that it can address all but the second and the last three of these mysteries. String theory (in which particles are represented by tiny, one-dimensional entities instead of point objects) addresses the last three [see “The Theory Formerly Known as Strings,” by Michael J. Duff; *SCIENTIFIC AMERICAN*, February 1998]. The phenomena that the Standard Model cannot explain are clues to how it will be extended.

It is not surprising that there are questions that the Standard Model cannot answer—every successful theory in science has increased the number of answered questions but has left some unanswered. And even though improved understanding has led to new questions that could not be formulated earlier, the number of unanswered fundamental questions has continued to decrease.

Some of these 10 mysteries demonstrate another reason why particle physics today is entering a new era. It has become clear that many of the deepest problems in cosmology have their solutions in particle physics, so the fields have merged into “particle cosmology.” Only from cosmological studies could we learn that the universe is matter (and not antimatter) or that the

universe is about a quarter cold dark matter. Any theoretical understanding of these phenomena must explain how they arise as part of the evolution of the universe after the big bang. But cosmology alone cannot tell us what particles make up cold dark matter, or how the matter asymmetry is actually generated, or how inflation originates. Understanding of the largest and the smallest phenomena must come together.

The Higgs

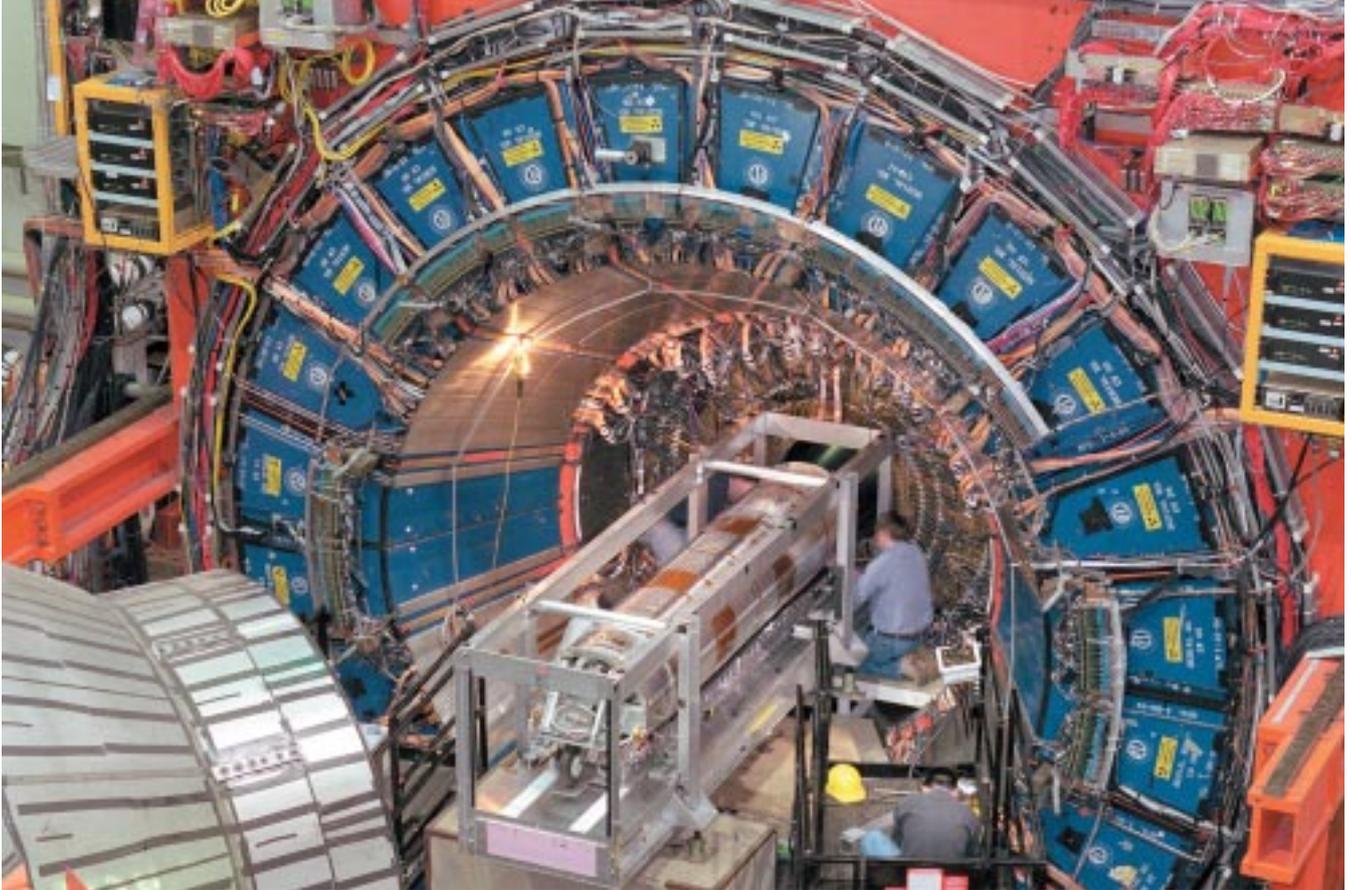
PHYSICISTS ARE TACKLING all these post-Standard Model mysteries, but one essential aspect of the Standard Model also remains to be completed. To give mass to leptons, quarks, and W and Z bosons, the theory relies on the Higgs field, which has not yet been directly detected.

The Higgs is fundamentally unlike any other field. To understand how it is different, consider the electromagnetic field. Electric charges give rise to electromagnetic fields such as those all around us (just turn on a radio to sense them). Electromagnetic fields carry energy. A region of space has its lowest possible energy when the electromagnetic field vanishes throughout it. Zero field is the natural state in the absence of charged particles. Surprisingly, the Standard Model requires that the lowest energy occurs when the Higgs field has a specific nonzero value. Consequently, a nonzero Higgs field permeates the universe, and particles always interact with this field, traveling through it like people wading through water. The interaction gives them their mass, their inertia.

Associated with the Higgs field is the Higgs boson. In the Standard Model, we cannot predict any particle masses from first principles, including the mass of the Higgs boson itself. One can, however, use other measured quantities to calculate some masses, such as those of the W and Z bosons and the top quark. Those predictions are confirmed, giving assurance to the underlying Higgs physics.

Physicists do already know something about the Higgs mass. Experimenters at the LEP collider measured about 20 quantities that are related to one another by the Standard Model. All the parameters needed to calculate predictions for those quantities are already measured—except for the Higgs boson mass. One can therefore work backward from the data and ask which Higgs mass gives the best fit to the 20 quantities. The answer is that the Higgs mass is less than about 200 giga-electron-volts (GeV). (The proton mass is about 0.9 GeV; the top quark 174 GeV.) That there is an answer at all is strong evidence that the Higgs exists. If the Higgs did not exist and the Standard Model were wrong, it would take a remarkable coincidence for the 20 quantities to be related in the right way to be consistent with a specific Higgs mass. Our confidence in this procedure is bolstered because a similar approach accurately predicted the top quark mass before any top quarks had been detected directly.

LEP also conducted a direct search for Higgs particles, but it could search only up to a mass of about 115 GeV. At that very upper limit of LEP’s reach, a small number of events involved particles that behaved as Higgs bosons should. But there were not enough data to be sure a Higgs boson was actually discov-



ered. Together the results suggest the Higgs mass lies between 115 and 200 GeV.

LEP is now dismantled to make way for the construction of the LHC, which is scheduled to begin taking data in four years. In the meantime the search for the Higgs continues at the Tevatron at Fermilab [see illustration above]. If the Tevatron operates at its design intensity and energy and does not lose running time because of technical or funding difficulties, it could confirm the 115-GeV Higgs boson in about two to three years. If the Higgs is heavier, it will take longer for a clear signal to emerge from the background. The Tevatron will produce more than 10,000 Higgs bosons altogether if it runs as planned, and it could test whether the Higgs boson behaves as predicted. The LHC will be a “factory” for Higgs bosons, producing millions of them and allowing extensive studies.

There are also good arguments that some of the lighter superpartner particles predicted by the MSSM have masses small enough so that they could be produced at the Tevatron as well. Direct confirmation of supersymmetry could come in the next few years. The lightest superpartner is a prime candidate to make up the cold dark matter of the universe—it could be directly observed for the first time by the Tevatron. The LHC will produce large numbers of superpartners if they exist, definitively testing whether supersymmetry is part of nature.

Effective Theories

TO FULLY GRASP the relation of the Standard Model to the rest of physics, and its strengths and limitations, it is useful to think in terms of effective theories. An effective theory is a description of an aspect of nature that has inputs that are, in principle at least, calculable using a deeper theory. For example, in nuclear physics one takes the mass, charge and spin of the pro-

ton as inputs. In the Standard Model, one can calculate those quantities, using properties of quarks and gluons as inputs. Nuclear physics is an effective theory of nuclei, whereas the Standard Model is the effective theory of quarks and gluons.

From this point of view, every effective theory is open-ended and equally fundamental—that is, not truly fundamental at all. Will the ladder of effective theories continue? The MSSM solves a number of problems the Standard Model does not solve, but it is also an effective theory because it has inputs as well. Its inputs might be calculable in string theory.

Even from the perspective of effective theories, particle physics may have special status. Particle physics might increase our understanding of nature to the point where the theory can be formulated with no inputs. String theory or one of its cousins might allow the calculation of all inputs—not only the electron mass and such quantities but also the existence of spacetime and the rules of quantum theory. But we are still an effective theory or two away from achieving that goal

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MORE TO EXPLORE

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The Little Book of the Big Bang: A Cosmic Primer. Craig J. Hogan. Copernicus Books, 1998.

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