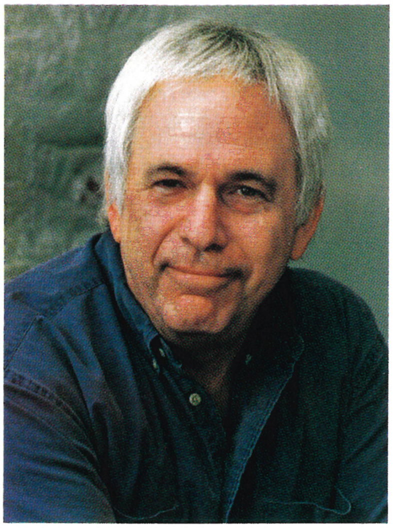

GORDON KANE received his PhD from the University of Illinois in 1963. Since then, he has spent most of his career on the faculty of the University of Michigan.

In addition to many research papers, he has written *The Particle Garden* (Addison-Wesley Helix, 1995), a general book on particle physics, and *Modern Elementary Particle Physics* (Addison-Wesley, 1988), a presentation of the Standard Model of particle physics for physicists in any area; and he recently edited two volumes for World Scientific Publishing (currently in press), *Perspectives on Higgs Physics II* and *Perspectives on Supersymmetry*.

His main hobby is understanding the history of ideas, and the effects of science and society on each other; he enjoys occasionally teaching a course in which these areas are integrated with physics to undergraduate students, both nonscience and science majors.

He says that, since he began working mainly on supersymmetry and Higgs physics nearly two decades ago, he has been living in the future; thus, this article came naturally for him. He hopes reality catches up soon.

EXPERIMENTAL EVIDENCE FOR MORE DIMENSIONS REPORTED

Gordon L. Kane
May 2011

The worldview of physicists working on unification theories has been changing rapidly recently. That change culminated in March, at the 46th annual Recontres de Moriond conference in Les Arcs, France, with the announcement of some startling data from CERN's Large Hadron Collider (LHC).

More than two hundred years ago, Charles Augustin Coulomb showed that the electrical force had the same form as the gravitational force. Since then, physicists have been fascinated with the possibility of somehow unifying the various forces of nature that they observe. Nearly a century ago, in the 1920s, Oskar Klein (then an assistant professor of physics at the University of Michigan) showed that a single theory in five dimensions—one of time plus four of space—could combine electromagnetism and gravitation if one of the space dimensions was "compactified," meaning that the size of the universe in that dimension was small compared to the smallest distances probed by experiments. Earlier, the mathematician Theodor Kaluza had examined a five-dimensional theory, but Klein was the first to seriously regard the extra dimensions as being physical. Usually, such theories are called Kaluza–Klein (KK) theories. (Following Hideki Yukawa's work in 1935 on the nuclear force, Klein tried unifying all of the forces using the extra-dimension approach. In a remarkable paper published in the proceedings of a 1938 conference on new theories in physics, held in Kazimierz, Poland, he essentially anticipated the modern $SU(2) \times U(1)$ electroweak gauge theory. Because the work was well ahead of its time, and because of World War II, Klein's insight went largely unnoticed. See L. O'Raifeartaigh, *The Dawning of Gauge Theory*, Princeton University Press, 1977.)

The fields of the higher-dimensional theory were the gravitational tensor field, the electromagnetic vector potential field and a scalar field. Of course, the theories of electricity and magnetism were unified without extra dimensions by Maxwell, and the successful unifications of the electromagnetic and weak forces into the electroweak force in the 1970s, and of the electroweak force and the strong force—fully accepted in 2000 after the discovery at Fermilab of the needed supersymmetric partners—also did not suggest the existence of extra dimensions. Instead, the implication was that such unifications should occur at very small distances, near the Planck scale, in our everyday four-dimensional world.

New physics from the LHC

The ten events that were reported in March—roughly two years after the LHC finally achieved its design luminosity, and after the data analysis needed to understand the complicated detectors was complete—are being interpreted as evidence for additional compactified dimensions. Five of the events have very energetic pairs of hadronic jets. Within experimental resolution, the effective mass of each pair is 950 GeV. Three other events each have a charged lepton pair (two e^+e^-, one $\mu^+\mu^-$) with the same effective mass. The remaining two events, one with two jets and one with an electron and a positron, have an effective mass of about 1900 GeV. For such energetic events, little background is expected, much less than one event for both the quark and leptonic channels.

That such events should occur at all is not expected in the Standard Model of particle physics. Nor can they be interpreted as heavy superpartners, because they don't have the characteristic missing energy carried away by the lightest superpartner that escapes the detector. Thus, there has to be some new physics.

So far, three possibilities have been proposed. First, the events could be interpreted as being due to a Z' state, analogous to the Z boson, from a fundamental $U(1)'$ symmetry different from that of the Standard Model. Such Z' states would fit well into unified theories and thus are well motivated. Second, resonances at high mass like those reported could also, in general, signal the onset of strong interactions, giving states analogous to the ρ and ω of low-energy pion scattering. Finally, the events could imply the existence of one or two compactified spatial dimensions, with a diameter of about 10–18 m. This third, less conventional interpretation, is being favored by theorists over either of the other two. In the days of Kaluza and Klein, the smallest experimental distances were the size of atoms and, until now, probes were able to reach down to about a thousand times smaller than the size of the proton. The additional factor of seven provided by the LHC made all the difference.

Several items argue against the strong-interaction interpretation. The width of the state at 950 GeV is consistent with the experimental resolution of the detectors, presently about 20 GeV. A strongly interacting state should have a considerably larger width, 10–20% of its mass, while Z' states or KK states (for the particles predicted by the Kaluza–Klein–like theories as described below) should have a width of order 1% of their mass, consistent with what was reported. A strongly interacting state also is unlikely to have leptonic widths as large as hadronic ones, contrary to what was reported. The evidence against the Z' interpretation is less compelling because of the limited data: the presence of the second state at twice the mass of the first is unlikely for a Z'. To understand why the evidence favors the KK states, we have to describe the predictions of such theories.

Lilliputian landscapes

Originally, Kaluza–Klein theories arose as imaginative ways to unify gravity and electromagnetism. Today, a consistent quantum theory of gravity is embedded in superstring theory, which requires ten dimensions. In superstring theories, particles are vibrations of the basic string, and there is an infinite sequence of such vibrations analogous to the harmonics of a vibrating violin string. The spectrum of vibrations is often referred to as an infinite tower. In addition, the states in the higher-dimensional theory give rise to a tower of states when the theory is recast into four dimensions.

Physical systems that actually occur in the world are described by solutions to the basic equations of physics. Solving the equations requires determining the ground state of the system, often called the vacuum. Finding the correct vacuum is still an unsolved problem for superstring theories.

It is commonly assumed that the superstring theory describes a real multidimensional world having a size measured in the Planck scale unit, about $R \cong 10^{-35}$ m; in the vacuum state, one time and three space dimensions have expanded to the size we observe. Each resulting tower of particles includes a massless state and its excitations, whose masses are set by the size of the compact dimensions, which would naturally be $R^{-1} \cong 10^{19}$ GeV (in units where $\hbar = c = 1$). The observed Standard Model particles and their superpartners are the massless states, which then get a "small" mass from the breaking of the electroweak symmetry and supersymmetry. But there is no compelling reason why all dimensions should be either the size of the Planck scale or the size of the universe—it could happen that dimensions on the order of the weak scale arose in determining the ground state. Then the associated particles would have masses of about 1.

Indeed, in the early 1990s Ignatius Antoniadis (at the Ecole Polytechnique near Paris) argued that the occurrence of TeV particles happened naturally in string theories. He and his collaborators showed that explicit solutions could be written in which the supersymmetric structure both kept the theory finite and retained the successful descriptions of experimental results, such as the well-known unification of the Standard Model gauge couplings. The quarks and leptons in such a theory were to be identified with states that had no KK excitations, while the gauge bosons (the photon, the Z and the W) had a tower of excitations of mass $m_n \cong n/R$. Thus, there should be a photon, a Z and a $W^\pm$ (γ^*, Z^*, W^*), all of mass about 1/R (apart from electroweak and supersymmetric corrections of order 10–20%), another set (γ^{**}, Z^{**}, W^{**}) of mass about 2/R and so on. The interactions of these excitations with quarks, leptons and gauge bosons were fixed by the theory. All the massive states are unstable, with lifetimes of about 10^{-25} s, and decay into quarks or leptons. Although work on this approach did not become a mainstream activity because the existing unifications did not seem to require such a mechanism, it was pursued by Antoniadis, with Mariano Quiros (at the Instituto de Estructura de la Materia in Madrid) and their collaborators. Their calculated production cross sections and decay widths of the excitations are consistent with what has now been reported from the LHC.

> Although anticipated by a few theorists nearly 20 years ago, the ten new events really came as a surprise to everyone

The second state in particular, with a mass about twice that of the first state, is a strong indication that KK excitations are being observed. Not only the production cross sections and decay widths (of order 1% of the mass), but also the relative branching ratios into quark jets and leptons, are consistent with expectations. As implied by the observed cross sections, these states have full-strength gauge theory couplings and behave like point-like objects, just as the Z and W do. In the electroweak theory, the Z and γ are linear combinations of the two symmetry eigenstates, B (the U(1) gauge boson) and W^0 (the SU(2) gauge boson). Similarly, the excitations can be linear combinations of the symmetry eigenstates so their couplings to the quarks and leptons can shift, and will have to be determined by more data. Getting the data will be mainly a matter of accumulation for both detectors, since neither the energy nor the luminosity of the LHC can be increased much. Both of the large international collaborations responsible for

ATLAS and CMS expect their resolution to improve, as they come to a better understanding of their detectors.

Everyone likes a surprise

If these data are confirmed as the LHC continues to run, the implications for our understanding of the primary laws of nature are enormous. Because we do not yet understand how supersymmetry is broken or how to determine the vacuum of superstring theory, many testable predictions of superstrings are encouraging but not compelling. Such predictions include the masses of particles and their superpartners and decay branching ratios (including rare ones such as proton decay). If the theorists know how the vacuum treats the dimensional structure of the theory, they may be able to recognize how to get such a vacuum. More data might give them just the information they need to complete the new theoretical understanding. The supersymmetry of the KK theory is broken by the presence of different scales, leading to some excitations at the TeV scale while leaving others at the Planck scale. The new insight may then lead to an understanding of how the supersymmetry is broken in general. Once dozens of events are in hand, and data from production cross sections and different decay channels are combined to untangle γ^*, Z^* and W^* states and their couplings, the theory should be greatly clarified. Moreover, in the work of Antoniadis and his collaborators, the KK states decay into neither W and Z bosons nor into superpartners. Generalizations of that work, however, do allow such decays; it will be very interesting to see what happens as more data come in. It may be that such events have already occurred but were not recognized because of their complicated signatures.

As more data from the LHC are analyzed, it will also help in another direction, enabling researchers to determine the masses of the heavier superpartners and supersymmetric Higgs bosons. The masses of superpartners arise mainly from the effects of broken supersymmetry, and thus also help fix the mysterious origin of supersymmetry breaking. If the results of the data analysis remain consistent with the spectral tower pattern expected from the KK approach, the general confidence in the correctness of the whole picture will be amply justified.

The US–Japanese electron–positron collider, which had its first collisions last year and is currently achieving its design luminosity, eventually could play an essential role in helping untangle the underlying physics because of its large beam polarization—different polarization states provide additional information about the quantum numbers of the KK excitations. The linear collider is not quite energetic enough to produce the KK states, but its planned upgrade will put the states within reach.

These exciting discoveries are welcomed by the ATLAS and CMS experimenters for yet another reason. Although anticipated by a few theorists nearly 20 years ago, the ten new events really came as a surprise to everyone. That has not happened for nearly four decades in collider particle physics, where many of the fundamental discoveries—including the Higgs boson—that established the Standard Model and supersymmetry, were long-anticipated from predictions. For the first time in a long time, experiment is a little ahead of theory. ■