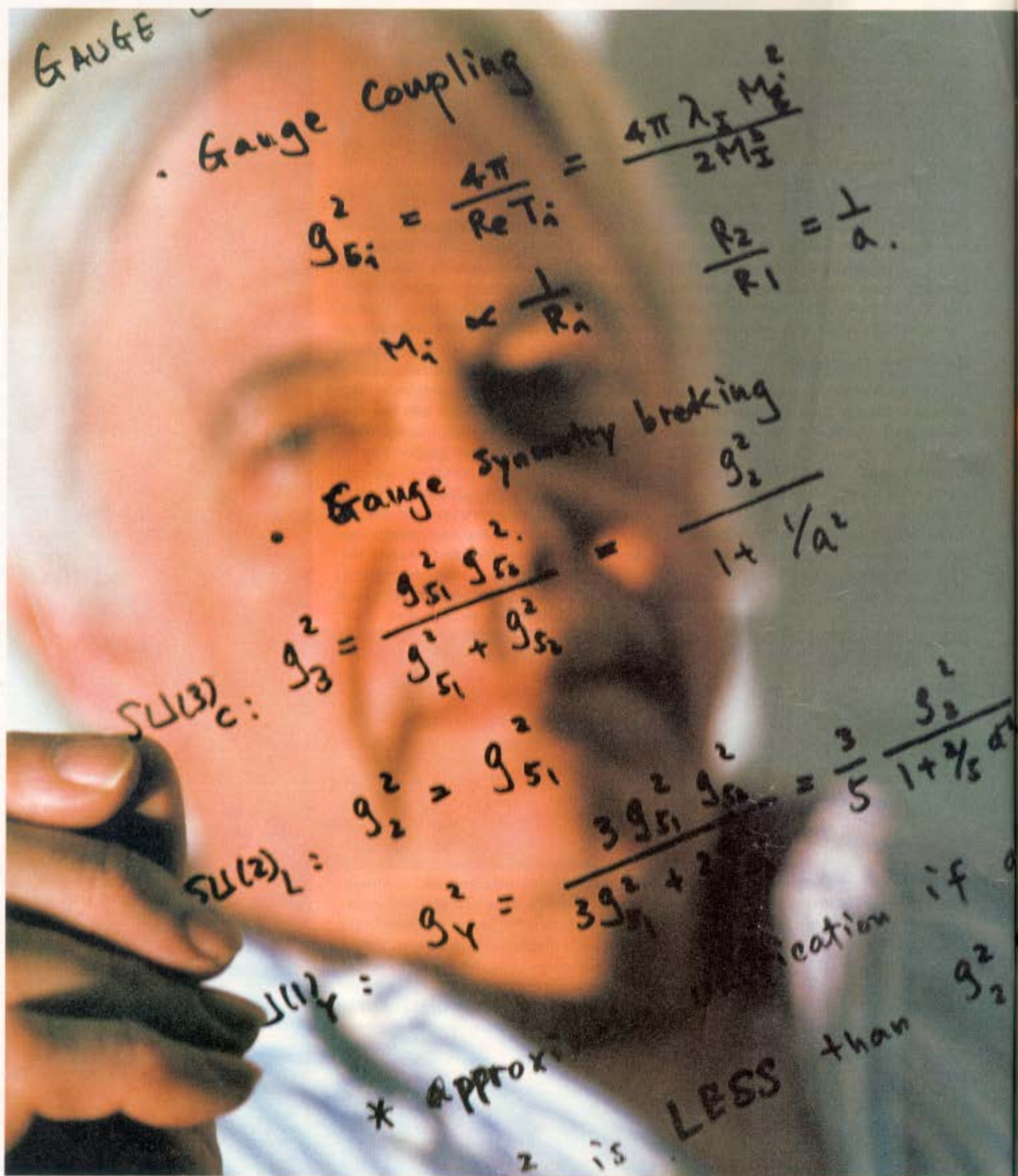
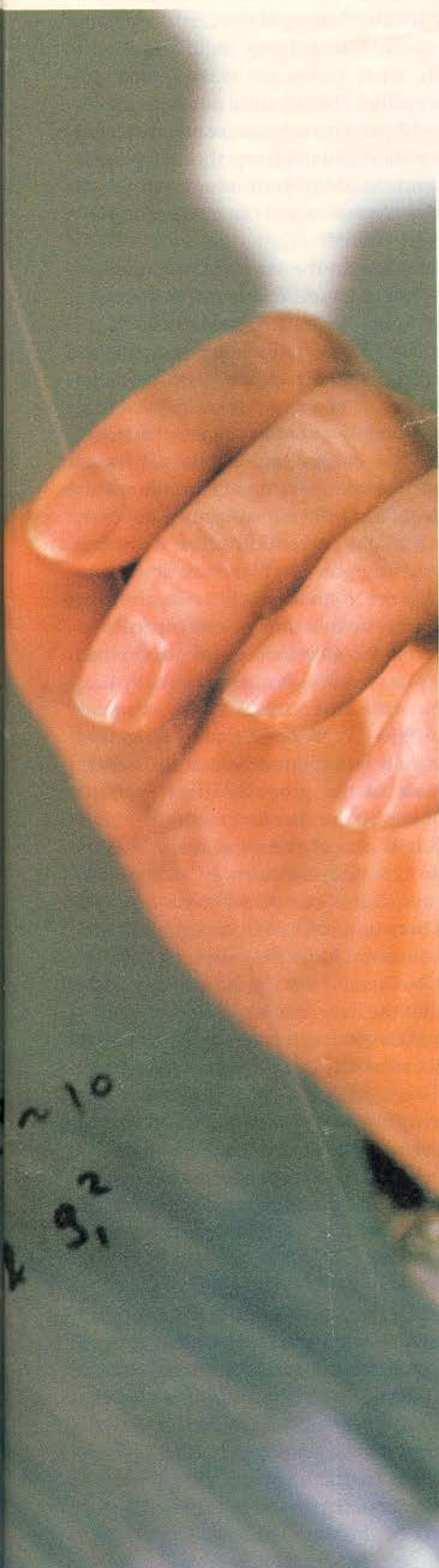


HUNTING THE HIGGS





It's the missing piece of the particle physics puzzle, and it could tell us a great deal about the Universe we live in. Leading theoretical physicists Gordon Kane (left) and Edward Witten (above) explain why they're convinced that the Higgs particle is just waiting to be discovered

PREHISTORIC humans long knew about electromagnetism, or at least some of its manifestations. Lodestones, rocks that exert natural magnetic forces, were known in ancient times. Likewise, it was known that fur sometimes makes sparks when it is rubbed and that lightning at times lights up the sky. And of course photons—or the light waves that they comprise, a form of electromagnetic radiation—are detected all the time by the human eye.

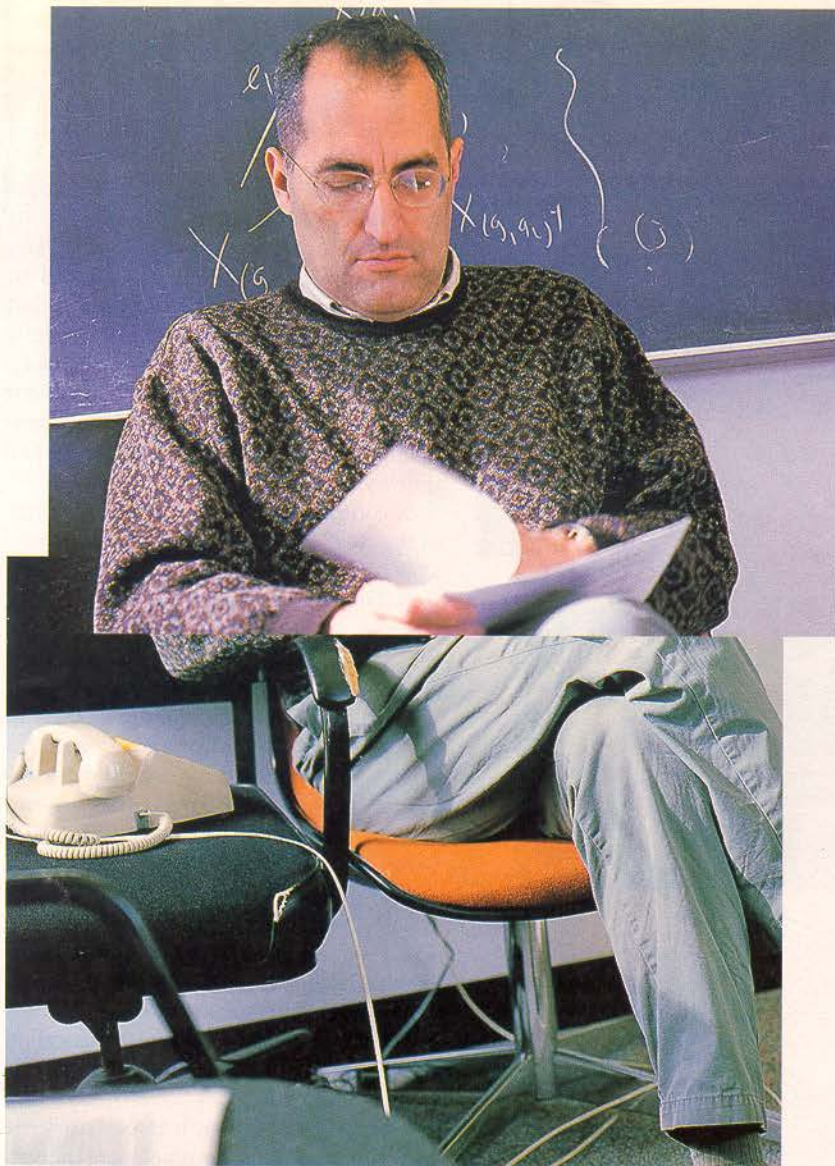
By contrast, to discover even the existence of the weak interactions, which are responsible for certain forms of radioactive decay, took late 19th-century science. Studying them in detail required the technology of the latter part of the 20th century.

Yet when theoretical understanding of the weak interactions finally dawned in about 1970 with the rise of the standard model of particle physics, it became clear that electromagnetism and weak interactions are two sides of the same coin. In the very early Universe, just after the big bang, they were equally powerful and prominent. The difference between them arose spontaneously when the Universe expanded and cooled.

What does this mean, in plain language? For an analogy, think about the Earth. The North Pole is cold, while central Africa, on the equator, is hot. This is not because there is an inherent difference between the North Pole and Africa. Rather, it results from the Earth's motion. The Earth's climate is determined by the way it revolves around the Sun, and rotates on its axis; because of this motion, the North Pole is frigid and the equator basks in sunshine.

To pursue the analogy, we might think of the North Pole as being analogous to the basic particles that transmit the weak interactions while the equator is similar to the photon, which is the basic unit or quantum of light. In the standard model of particle physics, nature is built out of elementary building blocks, such as electrons and quarks. Forces between particles are transmitted by other particles, such as photons, the carrier of electromagnetic forces, and W and Z particles, the basic particles that transmit the weak interactions.

Humans have lived on the equator for as long as they have existed, and have always known about light. By contrast, the North Pole and the effects of the W and Z particles were out of reach for most of human history. The North Pole was only reached by



explorers early in the 20th century; discovering the W and Z particles required a sophisticated particle accelerator that was built at the European Laboratory for Particle Physics (CERN) near Geneva in the early 1980s.

While the motion of the Earth singles out the North Pole as being frigid and hard to reach, what makes the weak interactions inaccessible? The technical answer is that the W and Z particles are massive and travel only a very short distance, too short to perceive without modern technology, while the photon is massless and can travel a long way. But why is this?

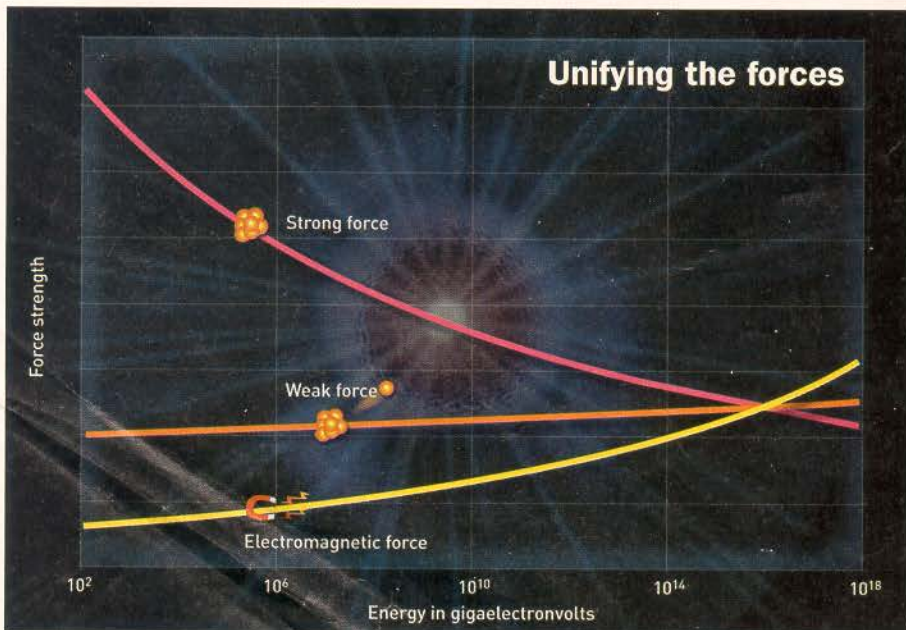
According to the standard model of particle physics, the difference comes because of something called the Higgs particle, named after Peter Higgs, one of the originators of the underlying ideas. The Higgs particle is the quantum of a new field called the Higgs field, which was zero in the very early Universe, but turned on as the expanding Universe cooled—just as the motion of the Earth emerged when it condensed out of the dust and gas surrounding the early Sun. Which way the Earth moves determines which is the North Pole. Which way the Higgs field turns on determines which particles—the W and Z—are inaccessible, and which one—the photon—is obvious in daily life.

The weak interactions really are weak, while light is obvious all around us, so there must really be something in nature that plays the role of the proposed Higgs particle. According to the standard model, the Higgs particle is one of the elementary building blocks of nature, like electrons and photons, and in fact it is one of the most important ones because of its role in determining what the real world looks like: allowing us to see light but not to see the W and Z particles without the help of modern science.

More elaborate alternatives to the standard model have also been proposed, in which the Higgs particle is made by combining other entities that are even more elementary, roughly as the proton is made out of quarks. In these theories, several hypothetical new particles and forces are postulated to do the job that the Higgs particle does in the standard model.

Is the standard model picture of the Higgs particle correct, or will one of the more elaborate theories win out? We won't know until experiment decides this question.

But, probably in common with most particle physicists, we would bet that the standard model picture of a simple Higgs particle is basically correct. There are three main reasons for this. First, almost all other aspects of the standard model, apart from the Higgs particle, have been spectacularly



confirmed by experiment, while competing theories have repeatedly run into trouble. Second, the standard model Higgs approach works for all the particles, while other approaches typically fail for some. Third, unlike its rivals, the standard model has offered an effective starting point for unified field theories, and string theories, that seek to probe deeper into nature.

These theories are attractive but unproven. Our hope is that, along with discovering the Higgs particle, experimental physicists will in the coming years begin exploring this deeper level.

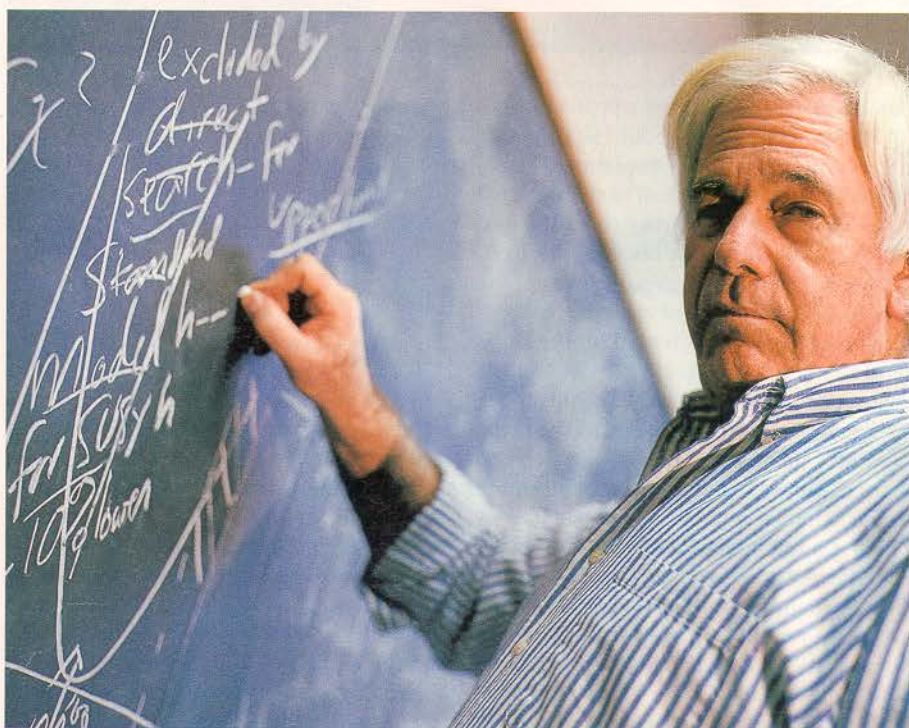
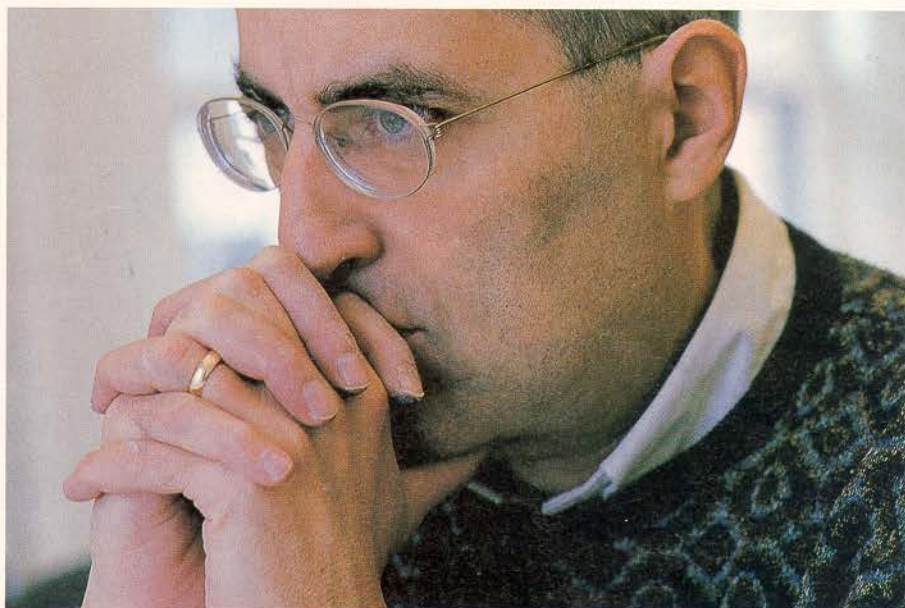
The standard model is tested most directly by accelerating particles to very high energies, letting them collide, and comparing the results to the model's predictions. Such experiments have been done in a variety of laboratories in Europe (CERN, and DESY in Hamburg), the US (especially SLAC in California and Fermilab near Chicago), and Japan (the KEK laboratory).

One reason for confidence in the standard model is its correct prediction of the existence and mass and other properties of some previously unknown particles: the W and Z particles, the top quark, and the tau neutrino. Also, numerous standard model predictions for details of elementary particle reactions have been tested successfully. For example, tens of millions of Z particles have been produced and studied, especially at the Large Electron Positron (LEP) accelerator at CERN. They behaved in accord with the standard model to a very high degree.

Sometimes, before a particle is actually discovered, its existence and the energy required to produce it can be inferred from the theory plus other experiments. This is possible because the standard model is a mathematical theory that describes many things at once, so one can predict the outcome of some experiments once other experiments have already been done.

For example, in building the proton collider that discovered the W and Z particles, CERN knew just what energy was needed. The masses of the W and Z particles had been inferred using the standard model theory plus experiments already performed. By Einstein's formula $E = mc^2$, the mass of a particle determines the energy required to produce it. In building an accelerator, it is a great advantage to know exactly what energy is needed, since the cost increases rapidly with the energy.

The discovery of the heaviest known elementary particle, the top quark, provides a more recent example of predicting the mass of a new particle from experiments at lower energy. Found by Fermilab six years ago, it weighs about 175 gigaelectronvolts. By

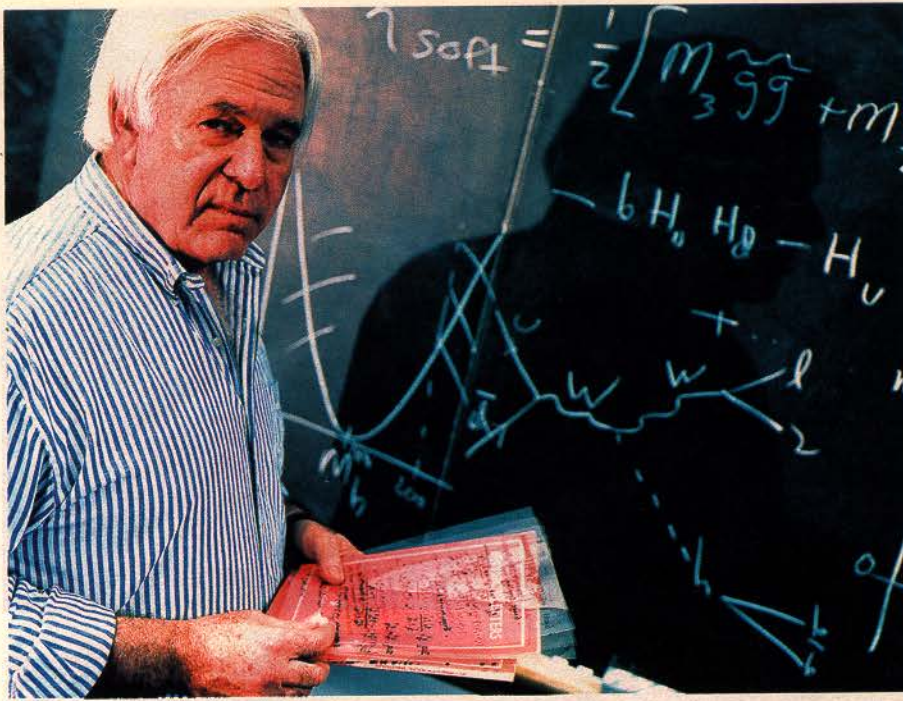


comparison, the proton mass is about 1 GeV, and the W and Z weigh about 80 and 90 GeV respectively.

Experimental physicists searched for the top quark for almost 20 years before finding it. The standard model said that there had to be a top quark, but its mass could not be predicted on theoretical grounds alone, and there were also competing theories without top quarks. Just like the Higgs particle today, until the top quark was actually observed, its existence was very likely but not a sure thing. When experimenters first searched for the top quark, they hoped it would weigh only 10 or 20 GeV and be discovered

quickly. Accelerators kept raising the energy, looking for top quarks, and not finding them. Finally, the tests of the standard model became so precise that one could infer that the top quark must weigh around 170 GeV. Fermilab finally reached the energy and sensitivity that was needed to find such a heavy top quark, and it was duly found.

Just as the top quark mass could not be predicted from theory alone, neither can the Higgs mass. Can we deduce the mass of the Higgs particle from theory plus experiments already done? Up to a point, the answer is yes. From the standard model tests, one can infer with extremely high confidence that



the Higgs particle weighs less than about 200 GeV, and less than about 160 GeV with high confidence. Direct experiments have swept through roughly half of the expected range of masses. When they cover the rest, we (and probably most but not all of our colleagues) expect a Higgs particle to appear.

How far has experiment currently reached? The best experimental bound on the Higgs particle mass is that it is at least 113.5 GeV, assuming the validity of the standard model.

This measurement was made by the extraordinarily successful LEP collider, which also carried out many of the most accurate standard model tests. When the final stage of LEP was built, it was expected to search for Higgs particles up to an energy of about 105 GeV. By straining everything to the limit, LEP engineers were able to operate the machine beyond its design, making it possible to search for the Higgs up to 113.5 GeV.

Famously, in the closing stage of the LEP programme, a hint was found of a discovery of the Higgs particle with a mass of very nearly 115 GeV. Unfortunately, LEP did not quite have the energy and intensity to establish this conclusively or rule it out. So we will have to await future experiments.

Thus the motivation for proving the existence of Higgs particles is as strong or stronger than ever, and there is very good indirect evidence, and a hint of direct evidence, that they do in fact exist. Just as direct observation of the top quark remained elusive until facilities with sufficient energy and intensity were available, so it is now for Higgs particles.

Where will the next results come from? At

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present, the highest energies in the world are attained at the Tevatron collider at Fermilab, which recently resumed operation after an upgrade to provide more intense particle beams. If it performs as planned, it will be able to discover Higgs particles up to about 180 GeV within several years, and hopefully confirm or exclude by 2004 the hint from LEP.

Beyond the Tevatron, the next big step in energy will come with the commissioning of the Large Hadron Collider (LHC) at CERN, scheduled for 2006. It is expected to have roughly seven times the energy of the Tevatron and considerably more intense particle beams. The LHC will cover the whole range of Higgs particle masses up to 200 GeV and far beyond, and should find the Higgs particle, or whatever does the job that it is supposed to do, whether it's the standard model theory of the Higgs particle that proves to be correct or one of its competitors.

Finding and studying the Higgs particle and exploring the standard model at yet higher energies makes an exciting mission. And the properties of the Higgs particle will point to new developments. There is a good chance that the LHC, and possibly the Tevatron, will

actually do much more than we have so far suggested. To explain why, we must explain the third reason for surmising that the standard model theory of the Higgs particle will prevail: it seems to offer the best starting point for unifying the forces of nature.

The standard model describes three of the forces of nature: electromagnetism, the weak interactions and the nuclear force. It omits only gravity. With the help of the Higgs particle, the standard model describes the electromagnetic and weak interactions as two sides of the same coin.

Can we go further and build a unified field theory of all three standard model forces? A beautiful strategy for doing so was proposed almost 30 years ago in the "grand unified theory" of Howard Georgi and Sheldon Glashow, which drew on earlier work by Jogesh Pati and Abdus Salam. The precise measurements performed since then have given an important hint that such a unification is indeed present in nature. In fact, as explained in the Figure on p 30, the strengths of the three standard model forces are just right to make grand unification work.

But there is a catch: grand unification only makes sense if the standard model concept of the Higgs particle is right. So either this is so, or the beautiful relationship between three coupling strengths shown in the Figure is an accident, a sort of cruel trick played by nature on unwary physicists.

And that is not the only catch. For grand unification to work, one also needs to assume supersymmetry. To explain supersymmetry properly is a subject for another article. But in brief, supersymmetry is an enrichment of Einstein's theory of special relativity to include quantum variables in the structure of space-time. It relates the quarks and electrons to the particles that transmit the forces. It predicts new particles, partners for the particles we already know, that should be discovered at the Tevatron and LHC and future facilities such as a linear electron collider. It offers a window to grand unification and beyond that to the even more ambitious string theory, which may unify gravity along with the other forces. Supersymmetry affects the details of searches for Higgs particles but not the general idea.

If supersymmetry is discovered, it will put physics on a new level. It will enable experimenters to make many important and exciting measurements and give a boost to the whole idea of grand unification and deeper insights beyond that. □

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