See? Within the ATLAS particle detector, a particle collision appears to produce a Higgs boson that decays into two pairs of electrons (red and blue).

not include gravity.) The forces are conveyed by particles of their own, known collectively as "gauge bosons."

The whole kit and caboodle is encoded mathematically in one master function called the Lagrangian, which describes everything physicists know about how particles and their force fields behave (see sidebar, p. 1288). Here's the most important point in the whole theory: The standard model Lagrangian possesses three different mathematical symmetries called "local gauge symmetries," which predict the existence of the three forces in the theory: weak, strong, and electromagnetic. For example, the simplest local gauge symmetry generates the quantum field for the photon, the gauge boson that conveys the electromagnetic force.

The connection between local gauge symmetries and forces is so strong that it defines the standard model, says Fermilab's Quigg. "I don't know that it's a miracle, but it's a wonderful thing," he says. To construct the standard model, theorists had to find the Lagrangian with the right gauge symmetries to explain the observed forces.

In the early 1960s, however, physicists were just beginning to appreciate the importance of gauge symmetry. In 1961, Sheldon Glashow, now at Boston University, developed a model based on two gauge symmetries that described both the electromagnetic force and the weak force, which is carried by particles now known as the W boson and the Z boson. There was a hitch, however: Because the weak force acts at extremely short range—far shorter than the width of an atomic nucleus—theorists knew the bosons that convey it must be massive, as the more massive a gauge boson is, the shorter its range. But simply tweaking the Lagrangian to give the W and Z particles mass spoiled the very gauge symmetry that predicted their existence.

To salvage gauge symmetry as the origin of forces, theorists needed to find a way to give force-carrying particles mass without wrecking the symmetry.

**The rest of the gang.** The other theorists who, in independent teams, figured out the "Higgs mechanism" include (*from left*) Tom Kibble, Gerald Guralnik, Carl Hagen, Francois Englert, and Robert Brout. Brout died in 2011.

### The solution

That's exactly what Higgs and five others did, although they weren't particularly thinking about the W and Z bosons. Instead, they were toying with a concept called "spontaneous symmetry breaking," a process that occurs whenever the inner workings of a system possess a symmetry that gets lost as the system settles into its lowest energy state. For example, a marble in a round-bottomed bowl settles in the middle, the point of greatest symmetry. But if the center of the bowl has a hump like the "punt" in a wine bottle, the marble won't stay in the middle but will run downhill in some random direction. The symmetry of the bowl remains in the setup, but the marble's "choice" of direction makes it harder to see.

Spontaneous symmetry breaking had already been used to describe magnetism, superconductivity, and the formation of crystals. Years before the discovery of quarks, a pair of theorists had even developed a rough theory of the interactions of protons and neutrons through the strong force. Particle theorists hoped the concept would illuminate other issues, too.

But there was a snag, as Jeffrey Goldstone, now at the Massachusetts Institute of Technology in Cambridge, pointed out in 1961. He considered the simplest example, a quantum field that interacts with itself to produce an energy landscape or "potential" much like the wine-bottle bottom (see sidebar, p. 1289). In that case, the field can minimize its energy not in the usual way by vanishing but rather by taking on a nonzero strength in the vacuum. Some theorists speculated that the vacuum might not be as bland as they had assumed and might contain a hidden quantum field instead.

Unfortunately, Goldstone proved, any such field should produce massless particles known generally as Goldstone bosons. Such massless particles aren't seen flitting about. So Goldstone's theorem suggested that spon-

## Why the 'Higgs'?

The physics behind the Higgs boson was first reported in August 1964 by Francois Englert and the late Robert Brout of the Free University of Brussels. Yet the particle bears the name of Peter Higgs of the University of Edinburgh in the United Kingdom. Why? Mistaken citations could be at fault, Frank Close of the University of Oxford in the United Kingdom wrote in his book *The Infinity Puzzle*.

Benjamin Lee, a Korean-American theorist who died in 1977, apparently used the term "Higgs boson" as early as 1966. But what made the term stick may have been a seminal paper Steven Weinberg, now at the University of Texas, Austin, published in 1967. In it, Weinberg cited a paper of Higgs's from *Physics Letters*, volume 12, and his key paper from *Physical Review Letters*, volume 13, before the paper by Englert and Brout from *Physical Review Letters*, volume 13. In fact, Higgs's first paper appeared 2 weeks after Englert and Brout's paper, and his key paper 5 weeks later still. Weinberg cemented the error in 1971 by mistakenly citing Higgs's earlier paper as being in volume 12 of *Physical Review Letters*, making it appear that he had clearly been first. That error propagated through the literature for decades, appearing in the 2010 version of the *Review of Particle Physics*, the standard reference in the field. Weinberg acknowledged the mix-up in an essay in *The New York Review of Books* in May 2012. **–A.C.**

Steven Weinberg

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