The Higgs particle, or something much like it, has been spotted

Further work will show whether it's the last piece of the standard model or a sign of new physics.

Almost 50 years ago, three nearly simultaneous papers independently laid the theoretical foundations for what would come to be known as the Higgs mechanism.[1] In the standard model of particle physics, the mechanism calls for a scalar field, embodied by a spin-0 particle, that interacts with other fundamental particles and thereby endows them with mass. The Higgs boson was the last remaining unobserved particle predicted by the standard model.

On 4 July the leaders of the CMS and ATLAS collaborations at CERN's Large Hadron Collider (LHC) announced the discovery of a new particle with Higgs-like properties at a mass of 125 GeV.[2,3] Figure 1 shows the new particle in relation to other known fundamental particles. Seven months previously, the teams had seen tantalizing hints of such a particle (see PHYSICS TODAY, February 2012, page 16). Since then, they've doubled their data and achieved the five-standard-deviation statistical significance necessary to be deemed a discovery. The CDF and D0 collaborations, working with data from the Tevatron at Fermilab, report complementary but less significant signs of the Higgs, consistent with the CERN results.[4]

The next step for CERN physicists is to check the particulars of the particle's production and decay rates and compare them with the standard model's predictions. They may find that they've discovered a new particle that gives mass as the standard model Higgs does but that heralds physics beyond the standard paradigm.

How can you have mass?

The Higgs particle is the quantum of the Higgs field, just as the photon is the quantum of the electromagnetic field. Particles that interact with the Higgs can and must travel slower than the speed of light—the defining feature of a massive particle. (For more on the Higgs mechanism, see the box on page 14.)

Most of the mass in our everyday experience doesn't arise directly from the Higgs mechanism. Protons and neutrons aren't elementary particles—they're made up of three quarks each, plus an ever-fluctuating sea of quark–antiquark pairs and gluons. The masses and energies of those constituent particles combine to give the nucleons' characteristic masses of just under a GeV each.

But the electron is a fundamental particle, so its mass is entirely attributed to the Higgs mechanism. Although the electron mass is just a tiny fraction of even the lightest atomic masses, it's crucial in determining the sizes and binding energies of atoms. If the electron were much less massive, the Bohr radius would be much larger, and atoms would be more readily ionized and less easily coaxed into forming chemical bonds. Matter as we know it owes its existence to the Higgs mechanism.

Does that mechanism operate exactly as specified by the standard model? Or is there something else going on? The standard model itself offers no insight into why the electron mass is 511 keV rather than some other value, but is there some physics beyond the standard model, yet to be discovered, that might?

Production and decay

Higgs bosons are made by colliding high-energy particles—protons with protons at the LHC, protons with antiprotons at the Tevatron. The overall collision energy needs to be much more than the mass of the prospective Higgs, because the Higgs is actually produced from a collision of quarks, antiquarks, or gluons, each of which carries only a fraction of the proton's total energy. The greater the energy of the proton or antiproton beams, the greater the likelihood that a single constituent collision will have enough energy to produce a Higgs.

Completed in 1983, the Tevatron—so named for its once unique capability to accelerate particles to TeV energies—operated with a collision energy of 2 TeV (1 TeV per beam) from March 2001 until its final shutdown in September 2011. The LHC started running with 7-TeV collisions in March 2010 and upgraded to 8 TeV in April 2012.

The Higgs has an expected lifetime of just 10^{-22} seconds; its existence, mass,

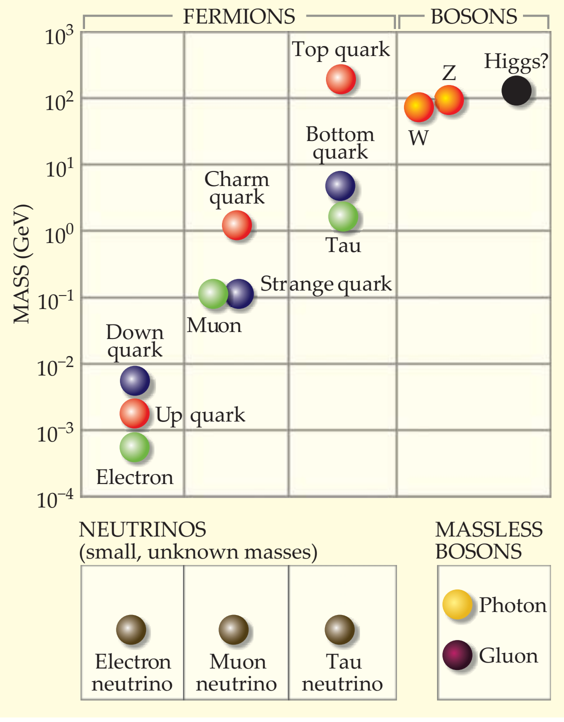


Figure 1. Fundamental particles of the standard model and their approximate masses. Three generations of fermions form the building blocks for matter; forces are carried by the fundamental bosons. Except for the newly discovered particle, all the fundamental bosons have spin 1; the putative Higgs is the first observed fundamental particle with spin 0.

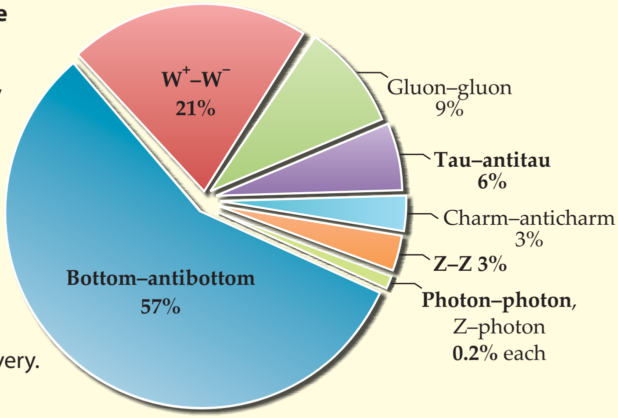


Figure 2. Decay-mode branching fractions of a 125-GeV Higgs boson, as predicted by the standard model. The five modes in bold constituted the ATLAS and CMS teams' searches. Specifically, the two rarest modes they considered, Z–Z and photon–photon, were the basis for the discovery.

and other properties must be inferred from the particles into which it decays. The standard model doesn't predict the Higgs's mass, but it does predict the rates of its production and decay modes as a function of mass. Figure 2 shows the standard-model expectations for a Higgs of 125 GeV, the mass that was eventually found.

Not all decay modes are equally easy to detect or equally informative. Each of the final-particle combinations in figure 2 can also result from other processes, so finding the Higgs requires teasing out a Higgs signal from a much larger non-Higgs background. And with around one Higgs expected to be produced per 10^{10} proton–proton collisions, that's no small feat. (So far, the LHC has produced on the order of 10^{15} collisions in each of the two detectors.)

Quarks and gluons can't be observed in isolation. They turn into jets—collimated sprays of hadrons—that can be difficult to make sense of. The CERN teams aren't even trying to observe the charm–anticharm and gluon–gluon decay modes. The bottom–antibottom mode is a possibility, due to its greater expected branching fraction and more distinctive jets.

The tau–antitau mode is also tricky to detect. Taus are very short-lived, and their decay products are difficult to distinguish from background and always include at least one neutrino. Because neutrinos are invisible to the ATLAS and CMS detectors, the Higgs mass resolution is not as good in this channel as in some of the others. Still, the tau–antitau decay is part of the CERN groups' analyses.

Also included are decays into pairs of massive gauge bosons, Z^0Z^0 or W^+W^-. A 125-GeV Higgs doesn't have enough mass to make two Z particles (91 GeV each) or two W particles (80 GeV each), so in each case, at least one must be a virtual particle: a short-lived disturbance in the W or Z field. W and Z particles usually decay into quarks and antiquarks, which manifest as difficult-to-identify jets. But a W particle can also decay into a fast-moving observable lepton (electron, muon, or one of their antiparticles) plus a neutrino, and a Z can decay into an observable lepton–antilepton pair. The CERN teams looked for events in which both of the W or Z particles decayed via those modes. The four-charged-lepton mode of the ZZ decay was the more useful because of its lack of neutrinos.

Most useful of all was the photon–photon mode. High-energy photons are easy to detect, and both ATLAS and CMS were equipped with high-resolution electromagnetic calorimeters to measure their energies. The photon–photon decay is expected to be rare—just 0.2% of all Higgs decays, or hundreds of events over the entire LHC run so far—but it is less so than the four-lepton mode, whose events number merely in the dozens.

In all, five decay modes are expected to be detectable thus far. Together, they probe Higgs coupling to quarks, leptons, and massive gauge bosons, and they offer a test of the standard model's prediction that the Higgs field should couple to all three. It could have been otherwise: Had the Higgs been massive enough to decay into two real (nonvirtual) W or Z bosons, those two decay modes would have crowded out all the others, with only a small branching to a top–antitop decay if it, too, was energetically accessible.

The case for discovery

Over the years, research teams at the LHC, the Tevatron, and the Large Electron–Positron Collider (LEP, the

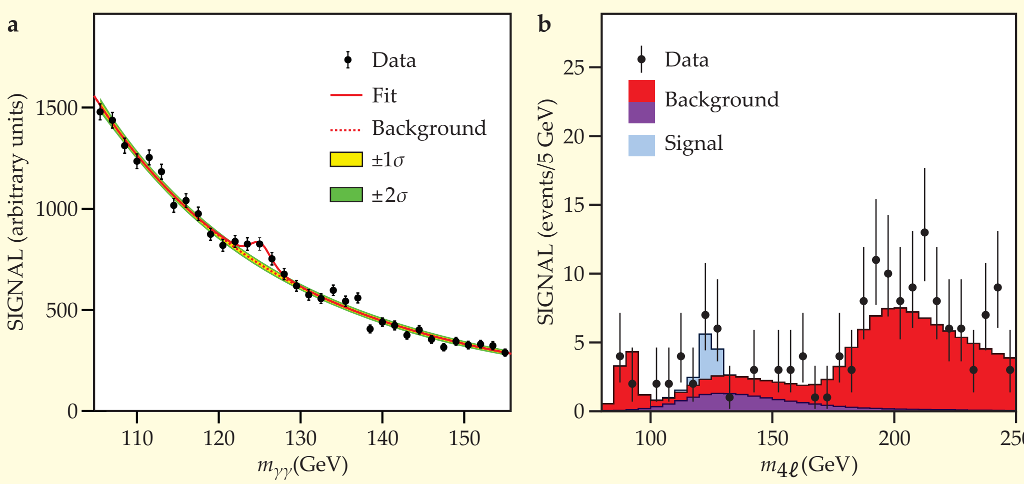


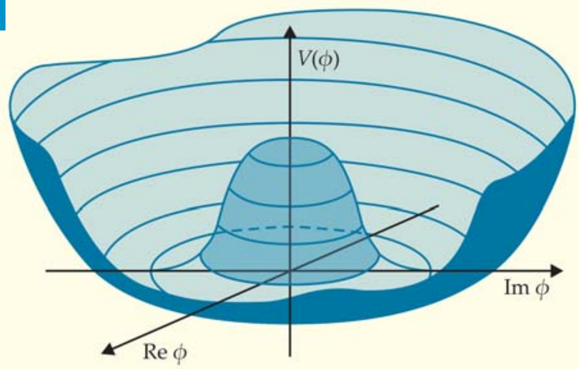
Figure 3. (a) The two-photon (γγ) mode as observed by the CMS team. The dotted red line is the expected background from non-Higgs processes, and the thin yellow and green stripes are the expected uncertainties of the background predictions. The bump at 125 GeV is attributed to Higgs decays. (Adapted from ref. 2.) **(b)** The ATLAS team's data for the four-lepton (4ℓ) mode. The peak attributed to the Higgs, again at 125 GeV, is shaded in light blue. (Adapted from ref. 3.)

LHC's predecessor at CERN) have ruled out most of the possible Higgs masses. As of the end of the LHC's 2011 run, all that was left was a narrow band from about 115 to 130 GeV. If there were a Higgs with a mass outside that range—and if it behaved as the standard model says it should—evidence of it would have been seen. The 2011 data showed hints of something going on within that range, but they weren't statistically significant enough to constitute evidence of a new particle. There was still a reasonable chance that the observations could be the result of a random fluctuation. It was up to the 2012 run to confirm (or rule out) the particle's existence.

Since last December, the LHC's collision rate and beam energies have both increased. Just three months of 2012 yielded as many collisions as all of 2011, and each collision was 30% more likely to produce a 125-GeV Higgs. The increase exacerbated an existing problem known as pile-up: With so many proton–proton collisions happening nearly simultaneously, it's difficult to disentangle the potentially interesting events from the uninteresting ones. The teams developed new methods for dealing with pile-up and for capturing as many of the potential Higgs decays as they could. As a result of those improvements, the discovery that was expected to happen at the end of this year came in July.

The discovery claim rests almost entirely on the two "easy" decay modes that allow for high-resolution mass identification: two photons and four charged leptons. Figure 3a shows the CMS team's data for the photon–photon mode. The new particle shows up as the peak at 125 GeV, and the dotted red line shows the background that would be expected in the particle's absence. The peak is significant, but it's not the end of the story. What sealed the case was the peak the

Gauge symmetry saved, mass endowed



In its original incarnation, the Higgs mechanism was designed to give mass to the gauge bosons that carry the weak force and to preserve a basic symmetry of the theory of weak interactions. Although many physicists may not be familiar with the gauge particles associated with the weak force, almost all are well acquainted with one gauge boson—the photon, which transmits the electromagnetic force. In quantum field theories, particles are expressed as fields; the photon field is a four-vector potential $A^\mu = (V/c, A_x, A_y, A_z)$ that incorporates the scalar (V) and vector (**A**) potentials, quantized versions of fields familiar from classical electrodynamics. Maxwell's equations are invariant under the "gauge" transformation $V \to V - \partial\Lambda/\partial t$, $\mathbf{A} \to \mathbf{A} + \nabla\Lambda$ for an arbitrary $\Lambda(\mathbf{x},t)$. Similar gauge symmetries apply to the standard model of particle physics and generate the interactions between gauge bosons and other fundamental particles.

The electromagnetic force is long-range and the photon is massless. The weak force is short-range, and as a consequence its gauge carriers must be massive. It's easy enough, in principle, to accommodate massive particles in a quantum field theory: Just include in the potential energy a term of the form $\frac{1}{2}m^2A^2$, where A^2 is the four-dimensional analogue of dotting the vector potential into itself. That quadratic mass term, however, breaks gauge invariance. Moreover, its inclusion in the quantum field theory leads to pathological infinities. Sometimes symmetries can tame such infinities, so theorists were motivated to try to preserve the symmetry under gauge transformations.

To do so, they introduced a complex field ϕ, which has a kinetic energy and a potential energy. A straightforward, well-known mathematical procedure instructed them how to do so in a way that preserves gauge invariance, and that algorithm leads to an interaction proportional to $\phi^*\phi A^2$. Ultimately, that interaction will be responsible for the gauge field's mass; what's missing is a final key ingredient: spontaneous symmetry breaking.

The theory of electrodynamics is rotationally invariant, but you'd never know that looking at a magnetic domain in a ferromagnet. There the atomic spins point in a particular, apparently preferred direction. Magnetic domains are exemplars of spontaneous symmetry breaking, the necessity of a system to choose a particular configuration from among many that are equally allowed by nature. The field ϕ also needs to make a choice. In the Higgs mechanism, its potential energy is given by $V(\phi) = \lambda(\phi^*\phi - \mu^2)^2$, which is illustrated in the figure as a function of the real and imaginary parts of ϕ. The potential has a ring of equally good minima: all points with a magnitude μ. Yet ϕ must choose to lie at a particular minimum; in the more precise language of quantum field theory, it must have a specific vacuum expectation value. The particular value chosen by the field doesn't matter, so let's set the value to be the real number μ and define a new field H by $\phi = H + \mu$. In terms of the new field H—the Higgs field—the interaction term $\phi^*\phi A^2 = \mu^2A^2 + \ldots$. Voilà, the gauge-field potential energy now includes a term of the form $\frac{1}{2}m^2A^2$, indicative of a massive particle. The Higgs field, too, has a mass, proportional to $\mu\sqrt{\lambda}$, inherited from the potential $V(\phi)$.

The symmetry structure of the full standard model is more complicated than in the simple model presented above, but the essentials of the Higgs mechanism are the same. Introduce a scalar field in a well-defined, gauge-invariant way. Once the field chooses a vacuum expectation value, its couplings to the fundamental fields of the theory give mass to the associated particles. The Higgs coupling constant λ, however, is not known a priori, and it cannot be related to fundamental parameters of other fields. Therefore, it is not possible to readily predict the Higgs mass.

The Higgs mechanism was not the first context in which particle physicists considered spontaneous symmetry breaking. By 1961 Jeffrey Goldstone had proved that a spontaneously broken quantum field theory necessarily includes a massless particle, now called a Goldstone boson. But the Higgs mechanism, because it involves gauge symmetries, violates the conditions for Goldstone's result to apply. That allows the mechanism to perform its vital function of generating only massive particles.

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CMS researchers saw at the same mass in the four-lepton data. ATLAS's data are similar—their four-lepton data are shown in figure 3b—which further rules out the possibility that the observation was a statistical fluke. But the 5σ threshold for discovery was met by each group's data independently.

Both teams also looked for the W^+W^- decay mode and found signals consistent with a particle at 125 GeV. The CMS team additionally looked at the bottom–antibottom and tau–antitau modes; what they found was consistent with a 125-GeV Higgs, but it was also consistent with no Higgs at all.

The final analysis of the Tevatron data[4] complements the CERN teams' findings. Because the Tevatron operated at a much lower energy than the LHC does now, it produced fewer particles at 125 GeV—but it also had lower background levels. As it turned out, the Tevatron was particularly sensitive to a production mode that forms a Higgs particle together with a W or Z boson. By looking for Higgs decay products together with W or Z decay products, the Fermilab teams observed an excess of events in the bottom–antibottom Higgs decay mode—not a discovery by itself, but corroborating evidence.

Stay tuned

A new particle has been discovered; the next step is to learn more about it. So far, it behaves very much like the standard model says the Higgs should. It's an electrically neutral boson, most likely of spin 0, that couples strongly to particles known to be massive. Its production and decay rates are consistent with the standard model's predictions, but their uncertainties are still large. As the LHC collects more data, the modes of the particle's production and decay will become better known and its consistency with the standard-model Higgs either strengthened or refuted.

If the particle isn't the Higgs of the standard model, then what is it? A likely alternative is that it's still *a* Higgs—a particle associated with a field that endows fundamental particles with mass—but in a framework beyond the standard model. Several theories that extend the standard model include a particle that behaves almost, but not quite, like the standard-model Higgs does. For example, the so-called minimal supersymmetric standard model calls for not just one but five Higgses—the lightest of which looks much like the Higgs of the standard model.

The standard model has done an excellent job of predicting how the known particles should interact via the strong, weak, and electromagnetic forces, but it's incomplete. It has nothing to say about gravity, dark energy, or dark matter, and it offers no insight into why the particle masses are what they are, or why the forces have the relative strengths they do. Any deviation between the newly discovered boson's behavior and the standard model's predictions could open the door to new physics that could help answer those questions.

The LHC was scheduled to shut down in November for repairs, maintenance, and an upgrade to its final collision energy of 14 TeV. That shutdown has been postponed for three months so that the teams can collect more data on the new particle.

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Archimedes's principle gets updated

When a fluid is complex, a venerable buoyancy law breaks down.

The fate of an object in a simple homogeneous fluid is easy to guess. If it weighs more than the fluid it displaces, it sinks; otherwise, it floats, just as Archimedes predicted 23 centuries ago. In both natural and industrial settings, though, the suspending fluid is usually complex, filled with several other dispersed species in a variety of sizes and densities.

Some of that complexity may be deliberate. Food scientists or cell biologists, for instance, often add heavy salts or colloidal nanoparticles to an already crowded fluid to create a density gradient in the solvent that will separate the different components in suspension. Proteins, nucleic acids, cell organelles, and other components sink or float to levels where their densities match that