The Solace of Quantum

The Search for the Higgs Boson

By Benjamin Miller

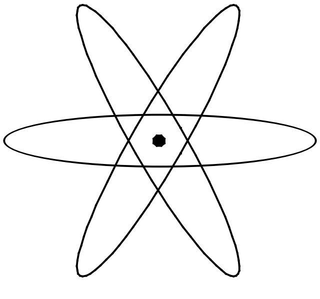
After 45 years of searching, nobody has ever found a Higgs boson. Sighting the particle, first predicted to exist in 1964, would support the existence of the Higgs mechanism—a proposed process by which elementary particles throughout the entire universe gain mass (1). Failure to find one, however, could constitute an enormous blow to our understanding of the universe on the subatomic level (1). But more than 200 feet under the border between Switzerland and France, a 27-mile ring of concrete and superconducting magnets is our next great hope for reconciling the observed with the predicted. The Large Hadron Collider (LHC), scheduled to become fully operational some time this year (2), will be able to definitively test for the presence of the mysterious Higgs boson. With experimental confirmation of the Higgs boson, and, with any luck, the ability to study those specimens, physicists will be able to strengthen substantially our understanding of the fundamental forces of the universe and the nature of the indivisible building blocks of matter and energy.

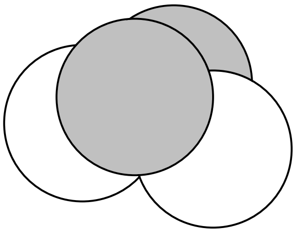
> “Not just a mathematical concept devoid of physical meaning, the term in the Standard Model that the Higgs fills actually gives mass to matter at the most fundamental level through a field that fills the entire universe.”

All Greek to Me: Fundamental Forces and Fundamental Particles

The ancient Greeks, observing how visible and tactile matter could be broken into smaller and smaller pieces, to the point that the pieces would be too small to see, posited that there must be some ultimate indivisible unit: the atom, from the Greek word for uncuttable (3). Twenty-three centuries later, Ernest Rutherford intentionally broke a nitrogen atom’s nucleus apart, giving rise to protons, neutrons, and electrons as the new indivisible building blocks of matter, but soon after, even protons and neutrons became divisible as well (3). Adding to Newton’s laws and Maxwell’s equations for electricity and magnetism, the physics of the 20th century gave us The Standard Model, a new equation which spawned a host of new forces and new particles (4)

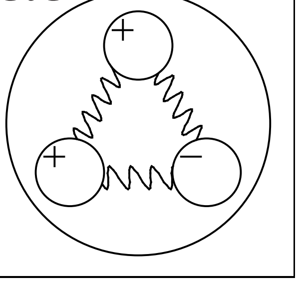
These new forces branch downward from the original smallest particle to yet smaller and smaller particles. Atoms, no longer defined as indivisible, contain a positively charged nucleus clinging onto a set of negatively charged electrons through the electromagnetic force. Atomic nuclei, a frightening source of energy, are agglomerations of protons and neutrons held together by the weak force. Even those protons and





The Smallest Particle

Once thought to be the most elementary building block of matter, the atom, shown far left, is made up of a nucleus encircled by various orbiting electrons. Left, an alpha particle, the nucleus of a helium atom, is made up of two protons and neutrons. Even the proton is composed of smaller particles: two up-quarks and one down-quark are held together by the strong nuclear force, mediated by gluons.



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The LHC

Figure 1. The Large Hadron Collider, deep under this serene countryside in Europe, is scheduled to be fully functional sometime this fall. Inside the 27-kilometer ring of superconducting magnets, rendered to the left, quantum particles will be accelerated to relativistic speeds and smashed into oblivion, potentially creating a Higgs boson.

neutrons can be broken apart into quarks, if one overcomes the strong force keeping the quarks together. Today the most elementary particles we know belong to one of two families, fermions and bosons. In general, fermions make up matter as we know it, while bosons mediate the forces and interactions between matter that cause the world to behave the way we observe it to behave (5).

Most familiar to the naked eye is the photon's mediation of the electromagnetic force: shoot a beam of ultraviolet light at a molecule of ozone and it will absorb the incoming energy packet—a photon—causing one or more of its electrons (one of the fundamental fermions) to become excited (6). Ultimately, the photon has mediated a change in the electromagnetic coupling between the electron and its nucleus. In the case of ozone, the entire molecule breaks down, the ultraviolet radiation is absorbed, and our skin remains safe for another day (6). In a light-emitting diode (LED) the entire process is reversed: an electric current runs through the diode, causing electromagnetic excitement, and, in order to burn off some of that extra energy, the diode emits photons—that is, a twinkle of light (7).

On the subatomic level, the strong and weak forces work to hold nuclei together, in much the same manner as electrons are held to their atoms by the electromagnetic force. Several quarks, a sub-category of fermions, are held together by the strong force, a force that is as manifested physically as the spontaneous creation and absorption of gluons, a type of boson (5). Several protons and neutrons, then, are bound together by the weak force—mediated by the W and Z bosons—into an atomic nucleus. These fundamental forces and fundamental particles are united in the Standard Model of physics, at its simplest form, a single equation that describes each of these particles as unique combinations of different charges, masses, and spins (3). Using the Standard Model, physicists have predicted the existence of seventeen fundamental particles. Matter, as we now understand it, is composed of twelve fermions, six quarks and six leptons. Matter's interactions are governed by five bosons—the W and Z bosons, the gluon, the photon, and the Higgs. Physicists, furthermore, have confirmed the Standard Model's predictions with high precision, observing each and every one of those particles, except the Higgs boson (2).

The Higgs, at the level of the mathematical underpinning of the Standard Model, is simply the remainder required to balance the equation that represents the Standard Model. Not just a mathematical concept devoid of physical meaning, however, the term in the Standard Model that the Higgs fills actually gives mass to matter at the most fundamental level through a field that fills the entire universe (1). Just as a charged particle's path bends as it passes through the electromagnetic field of a magnet, particles traveling through the Higgs field experience a drag and decelerate, in effect gaining some inertial mass. But unlike the electromagnetic field, which is extremely localized to its source, the Higgs field is infinite and uniform, stretching with the same magnitude indefinitely across the universe (1). A common analogy used to describe a particle's interaction with the Higgs field is that of a celebrity (the particle) walking through a crowded cocktail party (the field), causing the party-goers to clump and cluster around the celebrity as he or she tries to move through the room (8). Since the Higgs field does not vary over space, the mass of a fundamental particle also does not vary over the extent of the universe; rather any particle's mass is solely dependent on its particular interactions with the field. President Faust walking through a party may only cause a small commotion, but President Obama can often barely make it from one side of the room to the other in his public appearances. The photon, a massless particle, does not interact with the field at all, while the W and Z bosons—weighing in above iron atoms—interact quite strongly with the field (9).

The Higgs boson itself is a very special phenomenon within the Higgs field. Rather than occurring as the result of a particle traveling through the Higgs field, the Higgs boson is, in many senses, due to the lack of a particle. In our cocktail party metaphor, the Higgs boson is like a rumor started at one end of the room: it has no body of its own, but still causes an apparent cluster of partygoers to move across the room as the rumor is discussed in one location before spreading to a new cluster right next to it. Ultimately some residual energy floating through the universe can bunch up the Higgs field to create a mass where none existed before—the Higgs boson (1). The search for the Higgs boson is a search to confirm the existence and effect of the Higgs field and, ultimately, to confirm why and how the elementary particles that make up the universe around us have mass.

Finding The Missing Particle

The previous inhabitant of the massive particle accelerator now known as the LHC, was the Large Electron-Positron Collider (LEP), which attempted to directly produce a Higgs Boson by smashing an electron (e-) into a positron (e+), creating a Z boson and leaving behind an energy wake—our cocktail party's rumor—that could, with some small probability, produce a Higgs boson, clear evidence of the Higgs field interacting with matter and energy. Scientists, however, were unable to generate a large enough energy wake to produce a Higgs boson in the LEP (10), leading the European Council for Nuclear Research (Conseil Européene pour la Recherche Nucléaire, abbreviated CERN) to begin retrofitting the particle accelerator in November 2000 to collide hadrons (any particle made of multiple quarks, such as protons and neutrons) rather than electrons and positrons.

The simplest scheme for producing a Higgs boson in the Large Hadron Collider is entirely analogous to the electron-positron collision, but with heavier particles: the collision of a quark with its anti-quark would create a neutrally charged Z boson and a Higgs boson (9). Another scheme for Higgs production involves a pair of quarks interacting to briefly produce a W or Z boson, which might quickly decay back into a new pair of quarks and a Higgs (5), but the most commonly cited procedure for producing a Higgs boson is the fusion of two gluons, because, of all each of these tests gluon fusion carries the highest probability of actually producting a Higgs boson (5). Despite the low likelihood of creating a Higgs in any given collision, taken out over a large enough sample size, the failure to produce a single particle would statistically deny the existence of the Higgs boson and would force physicists to drastically overhaul the Standard Model.

Finding the Higgs boson, on the other hand, would go a very long way toward cementing the last brick of the Standard Model of physics into place. Confirmation of the existence of the Higgs field would open new doors for physics. In the coming months, once the LHC is finally complete, physicists may finally complete its half-century journey to find the Higgs boson and its 24-century journey to inspect matter down to its most indivisible components.

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