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The Higgs Boson
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What is it?

The Higgs boson is a hypothesized *elementary particle* that, if confirmed, would provide the mechanism by which the other elementary particles in the universe have mass.

Elementary particles are the smallest fundamental units of matter. We used to think atoms were the smallest, and then we discovered that the atomic nucleus existed and it was made up of two types of subatomic particles, protons and neutrons. We now know that the protons and neutrons are themselves made of elementary particles called quarks. With this understanding, all of the matter around us is made up of just quarks and electrons. We have discovered over the last 80 years that electrons are a member of a class of other elementary particles called leptons.

We also can divide up elementary particles into two groups, called *fermions* and *bosons*, which are defined by a quantum mechanical property known as "spin". Fermions have half-integral spin (like ½, 3/2, etc.) while bosons have integral spin (like 0, 1, 2, etc.).

Quarks and leptons are fermions. We believe that the forces that cause quarks and leptons to attract or repel each other are carried by bosons.

The Standard Model (SM) of elementary particle physics is a theory that explains how quarks and leptons interact in terms of three forces: The electromagnetic force, strong nuclear force, and weak nuclear force. The bosons that carry the electromagnetic force are *photons*. *Gluons* are the bosons that carry the strong nuclear force, and *W* and *Z bosons* carry the weak nuclear force. Gravity, the fourth known force, is not part of the SM, but its hypothesized carrier is a boson called a *graviton.*

The Higgs boson is notable in that its interactions with the other particles give these particles their mass, a fundamental constituent of our universe. The Higgs boson is also notorious as the only particle in the SM that has not been directly observed.

Okay, but what does it do?

The Higgs boson gives each type of particle its own mass. Its existence is needed to explain a number of the features of the SM, as importantly, it provides us with an understanding of why some particles have very large masses while others are quite light.

Physicist Peter Higgs proposed what we now call the Higgs field, and hypothesized that it spreads through the universe. All particles would acquire mass by interacting with this field. As is the case with the other interactions, at a quantum level this Higgs interaction predicts that we should be able to produce and detect the boson associated with the field, or the Higgs boson.

The mass of a given type of particle would be the result of interaction with the Higgs field. Because the boson is predicted by the field, finding the Higgs boson would be evidence that the Higgs field exists.

One example of an inconsistency in the Standard Model that the Higgs boson remedies is the lack of symmetry between the particles that carry electromagnetic force (photons, which are massless) and particles that carry the weak nuclear force (W and Z bosons, which are actually much more massive than an atom of hydrogen).

This lack of symmetry was an obstacle to the unification of these two forces under the same theoretical framework, called the electroweak theory. This theory is part of the Standard Model. However, if the Higgs field exists, then photons and W or Z bosons would be essentially manifestations of the same type of boson, with their differences coming from how they interact with the Higgs field.

This model of the electroweak force has been tested for over twenty years through a large number of experiments performed at high-energy particle accelerators around the world. The model has been successful in predicting many of these results, and it can be considered one of the best tested theories of elementary particle physics today.

Yet, one of its key elements, the Higgs boson, has not been observed.

Why is the Higgs boson important?

If the Higgs boson is found, then the Standard Model will be further validated.

If the Higgs boson is not found, then original problems with the Standard Model would need other explanations. There are other theories, besides the Higgs boson, that would help explain these inconsistencies. However, it may also indicate the model has fundamental flaws.

How do you find it? (CERN detectors)

Most elementary particles are found by colliding together pairs of elementary particles, using large amounts of energy that can result in the creation of other particles. To do this, particles must be accelerated towards each other at high speeds in a particle accelerator. The results of the collisions are then recorded by large detectors surrounding the collision point. Data from the detectors must then be analyzed in detail to determine what was produced in the collision.

The Large Hadron Collider (LHC) at the CERN laboratory in Geneva, Switzerland has been built over the last two decades to create these collisions. The LHC collides protons together at the very highest energy achieved in a laboratory, 8 tera-electron Volts (TeV). The LHC had its first lengthy data-collecting period in 2011, when it ran at 7 TeV. It has now been colliding protons at 8 TeV since spring 2012.

Very occasionally, a Higgs boson would be produced in these collisions. However, there are many other collisions that are very similar to those that produce Higgs bosons. They are considered “background” events, and they have to be quantified. When we see a significant excess of “Higgs-like” events above the expected backgrounds, we can claim evidence for the existence of a Higgs boson.

How will it be measured?

Thanks to Einstein’s famous equation, $E = mc^2$, where c is the speed of light in vacuum, we know that mass and energy are proportional. Therefore, elementary particle masses aren’t measured using familiar units like grams, but rather a unit of energy called the electron Volt divided by the speed of light squared, abbreviated eV/c^2. For convenience, people often use the same unit – eV – in referring to mass and energy. One billion electron Volts – a thousand-million electron Volts - is a giga electron volt, or GeV.

There are some clues to what the mass of the Higgs boson might be. Combined data from earlier experiments performed at the Fermilab Tevatron, the LHC Large Electron Project, and most recently the ATLAS and CMS experiments suggests its mass is above 114 and below 141 gigaelectron Volts (GeV), with a statistical confidence of 95 per cent (this means that the chances of it being outside this range are less than 1 in 20). Measurements from a proton-antiproton collider at the Fermilab laboratory outside of Chicago, IL, known as the Tevatron, have also excluded Higgs boson masses from 147 GeV to 180 GeV.

In particle physics, the “confidence level” – the probability that what is being seen is coming from background sources – is stated using units of "standard deviations" or sigmas. An observation, for example, with a confidence level of at least five sigmas in particle physics is often considered very strong evidence and considered a discovery. This translates into a probability of being wrong of about 0.00003%, or 3 chances in 10 million.

Who's looking?

Only a few accelerators operate at high enough energies to produce the collisions required to create and observe the Higgs boson. The only one currently operating is CERN's Large Hadron Collider, a 27-km-circumference tunnel, 100 m underground, that is producing 8 TeV proton-proton collisions. Two large collaborations have build detectors designed, in part, to search for the Higgs boson.

1. The CMS, or Compact Muon Solenoid, is one detector in the LHC that is specifically looking for the Higgs Boson.
2. The ATLAS (**A T**oroidal **L**HC **A**pparatu**S)** project, also at the LHC, is trying to find the Higgs boson. There are over 100 Canadian researchers that are part of the ATLAS experiment, listed **here.**

Experiments at the Fermilab's Tevatron accelerator in Illinois also have been searching for the Higgs boson until being shut down earlier this year. The most recent results of those experiments, released in preliminary form on July 2, 2012, have ruled out the existence of a Higgs boson with a range of masses between 147 and 180 GeV and 100 to 103 GeV. Both experiments see evidence for a Higgs boson with a mass somewhere between 115 and 140 GeV, but it is not conclusive (see http://arxiv.org/abs/1207.0449).

Searches for the Higgs boson also were performed by experiments studying electron-antielectron collisions at the Large Electron Project at CERN in the 1990's. They rule out a Higgs boson with a mass less than 114 GeV.

What's next?

If the results from the two separate experiments at CERN suggest that the Higgs boson exists, and they are in agreement about the approximate mass, then the search for the Higgs boson will intensify with the experiments continuing to collect and analyze additional data and possibly combine their results. The LHC will continue to run in 2013 till late fall, and both experiments will collect more data. The next batch of results should be released as soon as it is available.

It's possible that the Higgs boson predicted by the Standard Model doesn't exist, and future data may be able to confirm this. If this is the case, then elementary particle physics will be turned upside down, and experiments will intensify their efforts to seek out what actually is the reason for the mass in our universe.

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