The Search for the Higgs Boson

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Abstract
Particle physics involves complex theories that are necessary in order to successfully explain the behaviour of particles, forces and matter. The Standard Model incorporates forces and particles into a successful explanation of the subatomic world, however, it is not a complete theory. Although the Standard Model attracts criticism, particle physicists still seek to build on this model to successfully explain the subatomic world around us. Theories to unify all the fundamental forces in nature are being developed in the hope of explaining how the Universe works. Theorists and experimenters must work together in order to provide the investigations that are so important for the advancement of particle physics and our understanding of the Universe.

Introduction

Particle physicists share with all physicists the goal of explaining the world. Although the theories related to particle physics are complex, they are required in order to successfully explain the behaviour of particles, forces and matter. The standard model of particle physics incorporates forces and particles into a successful explanation of the subatomic world.

Investigations into crucial parameters and the Higgs Boson are being conducted using state of the art particle accelerators, in order to experimentally prove theory that is presented in the Standard Model. Although certain problems may be found with the Standard Model, it is not a reason to completely disregard investigations in particle physics. It is only through pursuit of knowledge that it is possible to advance physics and our understanding of the universe.

The Standard Model

The Standard Model is a theory that describes the nuclear strong, nuclear weak and electromagnetic fundamental forces as well as the particles that make up all matter. It is a quantum field theory, meaning it is consistent with both quantum mechanics and special relativity. The four fundamental forces in nature are shown in Table 1.

Table 1: Fundamental Forces

Interaction	Example	Relative Strength
Nuclear Strong	Binds protons and neutrons	1
Electromagnetic	Stability of matter	10^{-2}
Nuclear Weak	Gives distinction between protons and neutrons	10^{-7}
Gravity*	Too weak to be seen at subatomic levels	10^{-38}

*Not described by the Standard Model of Particle Physics

Classical or Newtonian physics usually describes interactions on a macroscopic level and can be demonstrated by the gravitational and electromagnetic forces. The interaction between bodies is described by a potential, where bodies follow smooth trajectories. In *quantum mechanics*, the trajectory is replaced by a probability distribution. The potential, now given by wavefunctions, is still smooth and continuous.

At very small distances, the continuous potential used to describe interactions must be abandoned due to the quantum nature of the particle interactions. Also, at small lengths, the nuclear strong and nuclear weak forces come into play. Although it does not describe the gravitational force, the Standard Model is the most complete theory of particle physics that exists, and describes the strong force and the electroweak force (a combination of the weak force and the electromagnetic force) in a combined *quantum field theory*.

The Standard Model's quantum field theory describes how interactions are mediated by the exchange of virtual particles called *bosons*. Essentially, bosons transmit fundamental forces between the matter particles. 'The gauge bosons or force carriers have properties – mass, spin, charge – which in fact determine the behaviour of the force.' (Lederman, 1993, p. 48)

Bosons form one of the two classes of fundamental particles that make up the standard model. The other class is Fermions, which are the particles that make up matter. All fermions have an antiparticle associated with them. Table 2 shows the different classes of fermions and bosons, and the interactions that they experience under the standard model.

Table 2: Particles of the Standard Model

Particle Type	**Particle Class**	**Examples**	**Interaction under the standard model**
Fermions (matter particles)	Leptons	Neutrinos and charged particles (eg. Electrons)	Neutral leptons feel week interaction, charged feel weak and electromagnetic interaction
	Quarks	Six flavours (u,d, s,c,b,t) each with colours (red, green, blue)	Strong, weak and electromagnetic interaction
Bosons (force transmitting particles)	Mesons	Gluons, photons	Strong, weak and electromagnetic interaction
	W, Z	weak interactors	Weak interaction and electromagnetic interaction

The theory behind the Standard Model is what particle physicists call gauge theory. There are many different examples of gauge theory, such as general relativity. Different bosons in the standard model transmit different forces. Photons are responsible for the electromagnetic interaction, W and Z bosons – the weak nuclear force, and Gluons – the strong force. All these particles are referred to as gauge bosons because they obey the gauge theory of quantum electrodynamics.

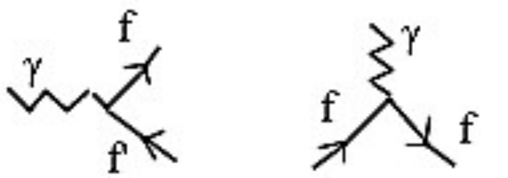
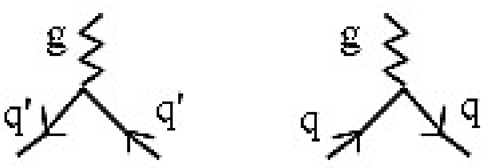
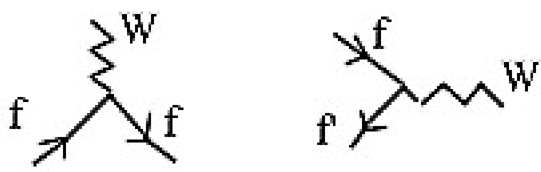
Quantum Electrodynamics (QED) has given more precise predictions than any other theory in particle physics, '. . .the resulting theoretical predictions have been verified experimentally with quite extraordinary precision.' (Martin et al, 1997, p. 12). This theory of electromagnetism models forces between fermions by coupling them to bosons. QED predicts a zero rest mass photon, meaning that a photon has an infinite range of force, consistent with experimental results. Examples of some QED processes are shown in Table 3, where Feynman diagrams have been employed to show the significance of photon and electron interactions in each case.

Another gauge theory is employed for the strong interaction in the Standard Model – Quantum Chromodynamics (QCD). This is used to describe how gluons couple to quarks via the strong interaction. The model of QCD has recently been extended through Gross, Politzer and Wilczek's theory of asymptotic freedom (See Nobelprize.org, 2004). They discovered a property of the strong interaction that explains why quarks may behave almost as free particles only at high energies. Free quarks, however, have never been observed – they are found in the form of bound states called hadrons. The two types of hadrons are baryons (consisting of 3 quarks) and mesons (consisting of a quark and an antiquark). This brings rise to the fact that quarks have never been completely isolated.

At close distances, quarks exert relatively weak forces on each other. As the quarks separate, however, the force becomes much stronger. Before the separation of quarks occurs, a new quark-antiquark meson has been formed from the energy input. 'This curious property is a result of the fact that gluons are not simple, dumb messenger particles. They actually exert forces on each other.' (Lederman, 1993, p. 336) This is a major difference between QED and QCD, as photons do not interact with each other.

The weak force is described by an interaction involving either charged W bosons, or neutral bosons. The following diagrams illustrate certain examples of interactions for the weak force, QED and QCD. They are shown through a pictorial representation first put forward by Feynman in the 1940's. Particle lines are labelled and intersect at vertices, which must conserve charge and other quantum numbers.

Table 3: Example Interactions for QED, QCD and Weak Force

QED		Photons, g, can couple to any charged fermion, f
QCD		Gluons, g, couple to quarks, q
Weak Interaction		Weak force couples to all fermions (given example for charged weak vortex with W boson)

The Standard Model has had the greatest acceptance in particle physics to date. It is the only theory that can describe the nuclear strong, nuclear weak and electromagnetic fundamental forces as well as the particles that make up all matter. The standard model predicted the existence of W and Z bosons, the gluon, the top and charm quarks before these particles were observed. Their predicted properties were later confirmed through experiments with good precision, but the theory has been unable explain values for quark and lepton masses.

Some physicists claim that a theory so fundamental should be able to predict these values that can only be experimentally measured. 'The model contains 19 free parameters, such as particle masses, which must be determined experimentally. These parameters can not be independently calculated.' (Wikiverse, 2003) Another serious problem with the Standard Model is that it does not account for gravity. Since the completion of the Standard Model, many efforts have been made to address both of these problems.

Challenges to the Standard Model

Although the Standard Model has been able to explain certain experimental results, it is not a complete theory of fundamental interactions, because it does not describe the gravitational force. Some physicists claim it also has shortcomings in its application to cosmology and elementary structure.

Physicists have debated the elementary nature of quarks and leptons. Speculation exists as to whether quarks and leptons are truly fundamental, or if these particles are composed of smaller entities. It is not expected that more structure will be seen for these particles because scattering behaviour is not found. Analogous results to Rutherford scattering are not seen at nuclei level, thus explaining that quarks and leptons are found to be point like. In fact, protons are mostly empty space with a small core in the middle. No structure has been observed down to 10^{-19} metres.

A cosmological application comes about in relation to the material nature of the Universe. In most interactions, matter and antimatter are created and annihilated in pairs. Yet the observed universe is made from matter. The most favoured solution to this problem is that shortly after the big bang, antimatter decayed under different conditions to matter. This is referred to an asymmetry, favouring matter over antimatter. The Standard Model can satisfy all necessary conditions for this asymmetry to occur, but there are still difficulties in using the asymmetry to generate the right amount of matter. Further adjustment of this model needs to be undertaken.

Another difficulty in cosmology is that the Standard Model provides no mechanism to explain cosmic inflation, which is believed to have taken place at the beginning of the Universe. This is a consequence of the gravitational force not being included in the model.

The Higgs Mechanism

Physicists' most engaging task is to try and formulate a unification between all forces in nature, in order to bring the gravitational force into some kind of particle model that overcomes some of the shortcomings of the Standard Model. Success has already been found in unifying the electromagnetic and nuclear weak forces through the electroweak theory.

In 1954, the work of Yang and Mills provided a breakthrough in particle physics (Yang and Mills, 1954). While trying to develop a theory of the strong interaction analogous to QED, they actually uncovered a deep connection between the weak and electromagnetic interactions. They found that at short distances (10^{-18m}) the coupling strengths of the two interactions became comparable. A gauge theory symmetry was required to give the theory the required level of high-energy behaviour. This, however, left a requirement of a zero mass gauge boson.

Jeffery Goldstone independently reached a similar conclusion. He used a spontaneous symmetry breaking model whereby the interaction dynamics possess symmetry while the ground state does not. The particle he found possessed only kinetic energy, which in quantum field theory implies that its mass is zero. 'Goldstone has examined another model, in which the manifestation of "broken" symmetry was the nonzero vacuum expectation value of a boson field. Here again there appeared a spinless particle of zero mass.'(Goldstone, 1962, p. 965)

The work of Peter Higgs changed particle physics in 1960 when he introduced the Higgs field and gave mass to the carriers of the electroweak theory. He did this using a special combination of a gauge theory and a spontaneous symmetry-breaking model. A spontaneous symmetry breaking model can be imagined as a complex scalar field whose value at each point in space is $H(x, y, z)$ and a field potential energy of $V(x, y, z) = \left(|H(x, y, z)|^2 - v^2 \right)^2$, where v^2 is the associated energy coefficient.

Higgs was able to alter the model proposed by Goldstone in his paper 'Broken symmetries, masslesss particles and gauge fields' (Higgs, 1964, p. 508). He showed that the introduction of a new form of symmetry combination known as gauge invariance reversed some of the assumptions made by Goldstone. Higgs found that he now had a theory in which there was a massive spin one particle that is able to carry a force, and one left over massive particle that did not have a spin at all. This was the *Higgs boson*.

The Higgs bosons are defined as elementary particles that are predicted by the standard model in order to carry the Higgs field. They are necessary in order to explain why the bosons of the electroweak force have mass. The Higgs field is an undetectable field filling the universe which has associated with it a previously unknown boson, the Higgs particle, which has mass. This would allow any photon-like particle to become massive by swallowing up a Higgs boson. It is thought that all-massive particles get their mass this way.

Physicists have been searching unsuccessfully for evidence of the Higgs boson for several decades. It is a mystery that the Higgs boson has not been found if it is so important for giving particles mass. Nevertheless, the Higgs boson is essential for the Standard Model of particle physics. Finding this special particle is the key to understanding matter and the Universe. 'This boson is so central to the state of physics today, so crucial to the structure of matter, yet so illusive, that I have given it a new nickname: The God Particle.'(Lederman, 1993, p. 22)

Searching for the 'God Particle'

Unlike most research undertaken at a nuclear level, generating evidence for the Higgs boson cannot be done using current accelerators. This is because the energy levels needed are beyond the reach of present accelerators.

The development of the Superconducting Super Collider (SSC) in the late 1980's to 1990s was a project designed to enhance the research of high-energy physics in the United States. The purpose of the SSC was to investigate the basic nature of matter and to experimentally confirm the existence of the Higgs boson. It was to be the most powereful particle accelerator in the world. Though support of the SSC lasted for ten years, the abrupt withdrawal of funding for the project resulted in its termination.

The SSC was designed to contain 2 proton beams, each with an energy of 20 trillion electron volts (TeV). The two beams of protons circle in opposite directions in two intersecting rings, each of which consists of thousands of superconducting magnets. When the proton beams intersect in chambers called interaction regions, some protons from each beam will collide with protons from the other, causing their constituent particles to interact. Special detectors measure the energy and trajectory of these interactions and the information is recorded for analysis.

The idea was first conceived at a conference in high energy physics in Colorado, and it quickly gained the support of the high energy physics community. 'The workshop became the reference point for much of the later development of the accelerator, and served to convince most of the high energy physics community that the new accelerator was their top priority.' (Taylor, 1993)

Great effort was taken in presenting the SSC proposal to the United States Congress. Lederman describes in his book 'The God Particle: If the Universe is the Answer, What is the Question' how he personally went to a lot of detail to promote the project to the leaders of the United States. '. . . a ten minute exposure to high energy physics would be useful when the proposal was discussed at a cabinet meeting. How do you teach a president high-energy physics in ten minutes!'(Lenderman, 2003, p. 378) It was the difficult subject matter that led to its ultimate downfall.

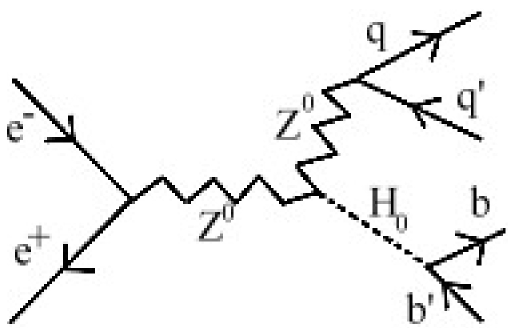
The supercollider never received support in the public sector for similar reasons. 'The Super Collider never captured broad support form the American public, in no small part because its scientific promise was difficult to understand even to those who are scientifically literate.' (O'Leary, Brown, 1993, Press Release). It is difficult to persuade members of the public to contribute money to support a project when they do not understand the purposes and procedures of the project they are being asked to support.

The abrupt termination of the SSC due to the withdrawal of funding by the United States Congress put a temporary stop on the pursuit of knowledge of the origins of our Universe and the fundamental dynamics of matter. The United States has been accused of being unreliable in supporting international research projects because of the handling of the SSC project. 'The termination of the super collider adds to a long list of large international projects that the United States has suddenly and unilaterally killed or drastically altered.' (O'Leary, Brown, 1993, Press Release).

Although design and construction continued until 1992, bad management and poor communication with the media troubled the project. There were rumors that difficulties with the magnet design had arisen and arguments between the people responsible for the project broke out. The project was disbanded by the American Congress ultimately because the estimated final costs rose from an initial five billion to eleven billion dollars.

One of the more recent attempts to find the Higgs boson was at the Large Electron-Positron collider at CERN in 2000. This entailed an excited boson decaying to a less energetic boson and a Higgs boson as shown in the following Feynman diagram.

Figure 1: Electron-Positron Interaction



The experiment recorded a slight excess of Z decays suggesting possible evidence of the Higgs boson. However, there were two few events of this nature observed to be certain that the prediction was the correct interpretation of events.

The Large Hadron Collider is another accelerator that physicists are intending to use for research. The European Organization for Nuclear Research (CERN) began planning the collider in the early nineties and it is due to be switched on in 2007. It has the ability to collide beams of protons at an energy of 14 TeV using supercondicting magnets added to the Large Electron Positron Collider on the France-Switzerland border. The design model is currently being improved, using the work of Koutchouk et al from July 2004. A long range beam is believed to effect the accuracy of the collider, and this is in the process of being rectified. 'Long-range beam-beam collisions may limit the dynamic aperture and beam lifetime in colliders. Their effect can be compensated by a current-carrying wire mounted parallel to the beam.'(Koutchouk et al, 2004)

Particle Physics and Controversy

Some physicists are skeptical about new projects such as the Large Hadron Collider. A memorable debate occurred in 1998 between particle physicist Robert Cahn and condensed matter physicist Pablo Jensen. Jensen argued that even if we do know all the fundamental laws, we couldn't say anything useful about our every day world. He says that particle physics is irrelevant to understanding the world and only macroscopic concepts are needed. 'Our everyday world is irremediably macroscopic, and only macroscopic concepts are needed to understand it.' (Jensen, 1988) Does this mean that we should only pursue knowledge if it has a use or application?

Later in 1998, Robert Cahn presented a rebuttal to the criticism given by Pablo Jensen. He stressed the importance of development of accelerators to extend the models in particle physics. 'We cannot understand these particles by themselves because they are intimately connected to others accessible only in high energy collisions.' (Cahn, 1998) Cahn acknowledges that there are problems with the Standard Model, but this is not a reason to completely disregard investigations in particle physics. Pursuit of the truth is always possible and there must be an end point to the discoveries and theories.

The Future of Particle Physics

Cahn's view is shared by a number of theoretical particle physicists, whose ultimate goal is to find a model where all fundamental forces of nature can be combined. If grand unification of all the interactions is possible, then all the interactions we observe are different aspects of the same unified interaction. Current data and theory suggests that the varied forces of QCD, QED and the weak interaction merge into one force when the particles being affected are at a high enough energy. Such an energy, believed to be around 10^{15} GeV, would unify the forces with one coupling constant.

Some physicists are attempting to unify gravity with the other fundamental forces through the idea of quantum gravity. The concept of supersymmetry is needed to build a consistent theory. Supersymmetry requires every matter particle to have a massive shadow force particle and every force carrier to have a massive shadow matter particle. An estimated energy needed to see the effects of quantum gravity are around the order of 10^{19} GeV (See Bashford, 2004, part 6).

Experiments at CERN are underway to increase the energy production of accelerators in order to see some of the effects proposed by *grand unification* and *quantum gravity*. However, current accelerators can only achieve energy of the order of 10^4 GeV. Although it may be some time before higher energies can be reached, investigations are important for the advancement of particle physics. New knowledge begins with the theorist and is transferred to the experimentalist in order to test and prove the theory.

Particle physicists have been working with quantum, relativistic and gravitational physicists in order to develop a new theory where all laws of modern physics can work together. The idea of adding extra dimensions to incorporate gravity, electromagnetic, weak and strong interactions is currently very popular. The extra dimensions are described as curled up or compacted, and do not affect ordinary low energy physics. By unifying the field equations from electromagnetism and relativity, physicists have come up with a 10 dimensional model called *string theory*. There is evidence to suggest that string theory may be related to the effects of dark matter in the universe, although the model has a long way to go. Research and development is the key to understanding models of such complexity.

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