



Review Article

The Journey Through Time Towards the Discovery of the Higgs Boson - A Review

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Abstract: The Higgs mechanics is very powerful, it furnishes a description of the electroweak theory in the standard Model which has a convincing experimental verification. But although the Higgs mechanism had been applied successfully, the conceptual background is not clear. The Higgs mechanism is often presented as spontaneous breaking of local gauge symmetry. But local gauge symmetry is rooted in redundancy of description, gauge transformation connect states that cannot be physically distinguished. Gauge symmetry is therefore not symmetry of nature, but of our description of nature. The spontaneous breaking of such symmetry cannot be expected to have physical effects since asymmetries are not reflected in the physics. If spontaneous gauge symmetry breaking cannot have physical effects, this causes conceptual problems for the Higgs mechanism, if taken to be described as spontaneous gauge symmetry breaking. In a gauge invariant theory, gauge fixing is necessary to retrieve the physics from the theory. This means that also in a theory with spontaneous gauge symmetry breaking, a gauge should be fixed. But gauge fixing itself breaks the gauge symmetry, and thereby obscures the spontaneous breaking of the symmetry. It suggests that spontaneous gauge symmetry breaking is not part of the physics, but an unphysical artefact of the redundancy in description.

Keywords: CERN, LHC, Higgs, Symmetry, Asymmetry

1. Introduction

Particle physics is an outgrowth of nuclear physics, which began in the early 1930s with the discovery of the neutron by Chadwick, the invention of the cyclotron by Lawrence, and the 'invention' of meson theory by Yukawa (Y. Nambu, 2007). The appearance of an ever increasing array of new particles in the subsequent decades and advances in quantum field theory gradually led to our understanding of the basic laws of nature, culminating in the present standard model. When we faced those new particles, our first attempts were to make sense out of them by finding some regularities in their properties. Researchers invoked the symmetry principle to classify them. A symmetry in physics leads to a conservation law. Some conservation laws are exact, like energy and electric charge, but these attempts were based on approximate similarities of

masses and interactions.

Nevertheless, seeing similarities is a natural and very useful trait of the human mind, The near equality of proton and neutron masses and their interactions led to the concept of isospin SU(2) symmetry (W. Heisenberg, 1932). On the other hand, one could also go in the opposite direction, and elevate a symmetry to a more elaborate gauged symmetry.

In 1964, papers on the subject of symmetry breaking and the possibility to create masses for gauge bosons of the weak interaction had been published independently by three research groups (Englert and Brout, 1964; Higgs, 1964; Guralnik, Hagen et al.; 1964). According to (Close F. 2011), only Higgs "drew attention to the consequential existence of a massive scalar particle, which now bears his name". The other researchers did not mention this boson since "it was obvious" the corresponding field, the mechanism, and the boson were named after Peter Higgs. A few years later, (Weinberg, S. 1967)

and Salam, A. 1968) showed that the electromagnetic and weak interactions could be combined into a single theory of the electroweak interaction based on the breakthrough of the Higgs mechanism. At this time they were not aware that (Glashow S. 1964) had already developed a theory to solve this problem. Glashow also noted that electrodynamics properties of baryons in the unitary solving puzzle.

Symmetry scheme (with S. Coeman), ‘*phy. Rev. let.* 6, 423.’ Discovered the mathematical structure that allowed the electromagnetic and weak forces to be treated as different manifestations of a single phenomenon- the electroweak force. In addition to the familiar photon associated with the electromagnetic force, Glashow’s model required electrically charged W bosons and an electrically neutral Z boson. The immediate theoretical difficulty, when Glashow produced his model, was associated with the fact that his W and Z had to be massive. This was necessary to understand why the weak force is so feeble compared with the electromagnetic force. However, it created a mathematical problem. Calculation beyond the simplest approximation gave nonsense: some processes were predicted to occur with a probability of infinite present. A solution to a similar problem in the theory of the electromagnetic force had been found in 1947, using a technique known as renormalization, but worked because the photon has no mass. The fact that the W and Z have large masses seemed to leave an insuperable infinity puzzle.

In 1967, Nuclear Physics article, CERN (The European Organization for Nuclear Research) theorist John Ellis, together with colleagues Mary Gaillard and Dmitri Nanopoulos ended with “an apology and a caution”. Their widely cited article titled “A phenomenological profile of the Higgs boson”, concluded with the words: “We apologize for to experiments for not having any idea what is the mass of Higgs boson...and for not being sure of its couplings to other particles, except that they are very small. For these reasons, we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.”

Nature consists of two different types of particles: fermions (“matter”) and bosons (“radiation”). Fermions have to occupy different quantum states with the consequence that it is not possible to have two fermions with exactly identical quantum numbers. Examples of fermions are electrons, protons, and neutrons. Bosons, on the other hand, are not subject to such a restriction and they may occupy identical quantum states. The photon (“light”) is a boson with zero mass and it is responsible for the electromagnetic interaction. In the second half of the 20th century, the standard model evolved as the fundamental model of elementary particle physics. It describes three of the four fundamental forces of nature, i.e. electromagnetic, weak, and strong interactions together with the corresponding subatomic particles. So far, gravitation could not be included in this description (A. Bath et al.; 2013).

The Higgs boson is named after Peter Higgs (Higgs et al 1967) one of six physicists proposed the mechanism that suggested the existence of such a particle. Although higgs

name has come to be associated with this theory several researchers between 1960 and 1972, each independently developed different part of it. In mainstream media the Higgs particle has often called the “God particle” from 1993 book on the topic though the nickname is strongly disliked by many physicist including Higgs, who regarded as inappropriate sensationalism.

Coming to the early history of spontaneous symmetry breaking. It is best known as a phenomena in condensed-matter physics. The earliest example is perhaps the theory of ferromagnetism as formulated by (Werner Heisenberg 1928); the feature of spontaneous symmetry breaking is that you have some continuous symmetry that is broken by the ground state of the condensed-matter system. If it is of infinite volume, which of ferromagnet never is, then the ground state degenerate. But if we were in an infinite ferromagnet then there would be a spontaneous magnetization, which could point in any direction, and we would think that the system was no longer rationally invariant.

One important breakthrough was the development of the unified electromagnetic and weak interaction. Among other ideas, this was based on the concept of broken symmetries and a mechanism for the provision of mass to the otherwise massless vector bosons of the weak interaction, the so-called Higgs mechanism (A. Bath et al.; 2013).

2. Standard Model

The theories and discoveries of thousands of physicists since the 1930s have resulted in a remarkable insight into the fundamental structure of matter: everything in the universe is found to be made from a few basic building blocks called fundamental particles, governed by four fundamental forces. Our best understanding of how these particles and three of the forces are related to each other is encapsulated in the Standard Model of particle physics. Developed in the early 1970s, it has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena. Over time and through many experiments, the Standard Model has become established as a well-tested physics theory.

3. Matter Particles

All matter around us is made of elementary particles, the building blocks of matter. These particles occur in two basic types called quarks and leptons. Each group consists of six particles, which are related in pairs, or “generations”. The lightest and most stable particles make up the first generation, whereas the heavier and less stable particles belong to the second and third generations. All stable matter in the universe is made from particles that belong to the first generation; any heavier particles quickly decay to the next most stable level. The six quarks are paired in the three generations – the “up quark” and the “down quark” form the first generation, followed by the “charm quark” and “strange quark”, then the “top quark” and “bottom (or beauty) quark”. Quarks also come in three different “colours” and only mix in such ways as

to form colourless objects. The six leptons are similarly arranged in three generations – the “electron” and the “electron neutrino”, the “muon” and the “muon neutrino”, and the “tau” and the “tau neutrino”. The electron, the muon and

the tau all have an electric charge and a sizeable mass, whereas the neutrinos are electrically neutral and have very little mass. (<http://home.web.cern.ch/about/physics/standard-model>).

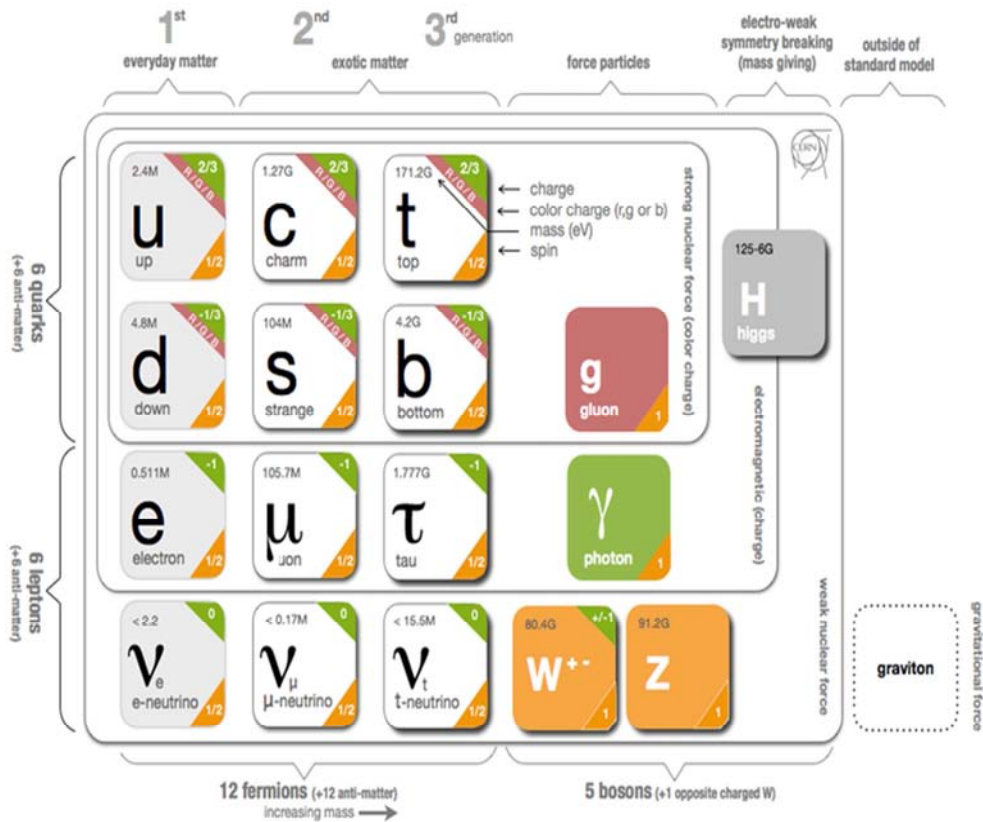


Figure 1. Standard Model (periodic table of elementary particles). The first three blocks are fermions while the last block is the bosons. G. Bernardi (LPNHE, CNRS/IN2P3, U. of Paris VI&VII(2010)).

In the standard model the fundamental particles are divided into the three families of fermions (6leptons and 6 quarks) and the bosons responsible for the electromagnetic (photon), the weak (W^{\pm}/Z^0 bosons), and the strong nuclear interactions (gluons). Under local transformations, these physical interactions are invariant, hence the corresponding field theories are gauge-invariant and the carriers of these interactions are called gauge bosons. Since these gauge bosons all have a spin of 1, they are classified as vector bosons, e.g. the photon is a massless gauge vector boson. The Higgs boson on the other side has a spin of 0 and is therefore classified as a scalar boson. The W^{\pm}/Z^0 bosons are originally massless but they obtain a mass through the (scalar) Higgs boson which interacts with all fundamental particles through the universal Higgs field. The addition of the Higgs boson is required to remove the infinities in the field equations by enabling the formulation of a renormalizable quantum field theory for the electroweak interaction. As a result, the standard model and the Higgs boson are inextricably intertwined. Therefore, it is clear that the detection of the Higgs boson in 2012 was an important milestone for the experimental verification of the standard model (“the breakthrough of theyear”). (Cho, A., 2012).

4. The W and Z Boson

These together are known as the weak bosons or lies specifically, intermediate vector boson. These are elementary particles that mediate the weak interaction. Their symbols are W and Z, the W and Z have positive and negative electric charge of one element charge respectively and each other antiparticles. The Z bosons are electrically neutral. The three particles have a spin of 1 and W bosons have a magnetic moment while the Z has none. All three of these particles are very short. The W and Z bosons are almost 100 times as massive as proton, heavier, even than entire atoms of ion. Their masses are significant because they act as force carries of quite short range fundamental forces. W bosons are best known for their role in nuclear decay. E.g. decay of cobalt-60 while Z boson is its own antiparticles, thus all of its flavour quantum numbers and charges are zero.

5. Fermions

In particle physics, fermion a name coined by Pauli-Dirac is any particle characterized by Fermi-Dirac statistic. It obeys Pauli exclusion fermions include all quarks and leptons. No

two identical fermions can occupy the same single-particle energy state. Thus in terms in which two or more indices are the same cannot be included in the summation. The indices are not independent of one another, and a direct evaluation of $(N, V, \text{ and } T)$ for fermion is very difficult.

6. Bose-Einstein Statistics

Fermi-Dirac statistics are one of two kinds of statistics exhibited by identical quantum particles, the other being Bose-Einstein statistics. Such particles are called fermions and bosons respectively, the terminology is due to Dirac theorem [1902-1984]. In the light of the spin-statistics theorem, and consistent with observation, fermions are invariably spinors (of half-integral spin), whilst bosons are variably scalar or vectors particles (of integral spin). In general, in quantum mechanics, the variable state of a homogeneous many-particles system in thermal equilibrium, for given total energy, are counted as equiprobable. For system of exactly similar (identical) fermions or bosons state which differs only in the permutation of two or more particles are not only counted as equiprobable. They are identical (call this permissibility). Fermions differs from bosons in that no two fermions can be exactly the same 1-particle state. This further restriction follows from the Pauli Exclusion Principle. The thermodynamics properties of gases of such particles were to understand the consequences of these two restriction; consider a system N weakly-interacting identical particles, with state given by the various 1-particle energies together with their degeneracies. From permissibility, the total state of a gas is fully specified by giving the number of particles with energy in each C_s possible states.

7. Renormalization

Renormalization techniques were first introduced in quantum electrodynamics in order to get rid of ultra-violet divergences. This is a techniques used to remove infinities, it is also a method used in quantum mechanics in which unwanted infinities are removed from solution of equation by redefining parameters such as the charge and mass of subatomic particles. This requires the existence of Higgs boson. A renormalized theory is one that, given a few parameters can be applied to calculate experimentally observable quantities to any desired precision. A non renormalizable theory, in contrast, has no predictive power beyond a certain limit: the theory is incomplete, and the solutions to certain problems are nonsense.

8. Higgs Boson

The higgs mechanisms: To understand the Higgs mechanism, imagine that a room full of physicists quietly chattering is like space filled only with the Higgs field....



Figure 2. Illustration I.



Figure 3. Illustration II.

From Figure 2 illustration I, a well-known scientist walk in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step.

This increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field. If a rumour across the room, it create the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.



Figure 4. Illustration III.

A difficulty in searching for the Higgs boson is that its mass is virtually unconstrained. As determined by experiment, the mass must be greater than about 5GeV . Theory presents no clue as to how heavy the Higgs boson could be, except the particle would generate some of the same difficulties it has been designed to solve if its mass were 1TeV , which is approximately 1,000 times the mass of the proton. At that point theory suggests the weak vector bosons could no longer be viewed as elementary particles; they could be composite structure made of smaller particles.

9. The Large Hadron Collider

The large Hadron collider (LHC) is the world's largest and most powerful particle accelerator. It first started up on 10 September, 2008, and remains the latest addition to CERN's accelerator complex. The LHC consists of a 27-kilometre ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way. Inside the accelerator, two high-energy particles beams travel at close to the speed of light before they are made to collide. The beams travel in opposite direction in separate beam pipes—two tubes kept at ultrahigh vacuum. They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. The electromagnets are built from coils of special electric cable that operates in a superconducting state, efficiently conducting electricity without resistance or loss energy. This requires chilling the magnets to -271.3°C —a temperature colder than outer space. For this reason, much of the accelerator is connected to a distribution system of liquid helium, which cools the magnets, as well as to other supply services. Thousands of magnets of different varieties and sizes are used to direct the beams around the accelerator. These include 1232 dipole magnets 15 meters in length which bend the beams, and 392 quadrupole magnets, each 5-7 meters long, which focus the beams. Just prior to collision, another type of magnet is used to “squeeze” the particles closer together to increase the chances of collisions. The particles are so tiny that the task of making them collide is akin to firing two needles 10kilometres apart with such precision that they meet halfway.

10. LHC Computing Model and Aim of LHC

In 2010, T. Junk of Fermi National Accelerator Laboratory, proposed a computing model and the main aim of LHC is to smash protons moving at 99.999999% of the speed of light into each other and so recreate conditions of a fraction of a second after the big bang.



Figure 5. The first full LHC cell (~ 120m long): 6 dipoles + 4 quadrupoles; successful test at nominal current (12KA) M. Carena (Fermi National Accelerator Laboratory, 2010).

11. Conclusion

The Higgs mechanism is generally described as the spontaneous breaking of local gauge symmetry, and the Higgs mechanism furnishes the mass generation of the W and Z gauge bosons in the electroweak theory important physical consequences. It has been shown that the Higgs mechanism does not rely on spontaneous gauge symmetry breaking and so is not threatened by the absence of physical implications of the spontaneous breaking of gauge symmetry. It is the non-zero vacuum expectation values of the Higgs fields that has physical implications.

Conclusively, In March 2013, the detection of the Higgs boson was confirmed by CERN. Also, in October 2013, Peter Higgs and Francois Englert were awarded the Nobel Prize for physics for their contribution to the standard model of elementary particle physics and the prediction of the boson named after Peter Higgs. (A. Bath et al., 2013)

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