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Analysis on the relationship between the Higgs boson and the standard model

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Abstract. In 1964, Peter Higgs proposed the Higgs mechanism, a theory explaining the generation mechanism of the property "mass" for gauge bosons. After that, physicists proposed many theories and experiments to prove the existence of the Higgs boson. Then in 2013, the European Organization for Nuclear Research (CERN) discovered the Higgs boson, and in the next ten years, physicists did a large amount of research about the boson, the other possible kinds of Higgs boson, and the pairs of Higgs boson. However, it is hard to prove those theories through experiments mainly due to the large mass of the Higgs boson. In this paper, the author discusses the process of particles getting mass and the significance of the Higgs boson. The history of the Higgs boson and its impact on the world is summarized, and some probable predictions of the future research orientation are proposed by summarizing the past research papers and concluding from those articles. Overall, physicists can do more research on the interactions between the Higgs bosons, whose sensitivity can be used to discover those possible particles in the future.

Keywords: Standard model, Higgs boson, Higgs mechanism, Couple of Higgs bosons, Possible development of SM.

1. Introduction

In particle physics, everything in the world is made up of particles. However, particles such as photons have no mass, which means that there is something "giving" those particles mass. To explain this fact, Peter Higgs proposed the Higgs mechanism, which is a theory explaining that the entire universe is filled with a special field, and the particles get mass through interactions with the field called the Higgs field. The Higgs boson is just the wave in the Higgs field, and it is also the evidence of the theory. In this paper, the author analyzes the process of fundamental particles interacting with the Higgs field through spontaneous symmetry breaking, and the quantum field theory (QFT) is used as the background of the Brout-Englert-Higgs mechanism so that particles get mass. Additionally, the experimental method of the European Organization for Nuclear Research (CERN) discovering the Higgs boson in the accelerator is also introduced. Overall, research on the Higgs boson has great significance, as it has a great impact on this macro world. First and foremost, the Higgs boson helps create the world. The boson gives mass to the atoms so that the Earth and all human beings can be formed. Second, it is also a way towards the theory of everything (TOE), which is important for scientists, since the electroweak theory, one of the theories that can be developed towards the TOE, needs the Higgs boson so that it can combined with the standard model (SM), as well as the strong force theory.

2. How Higgs boson is discovered

2.1. The need for Higgs boson in theory

The standard model (SM) was built in the 1970s. It contains basic information about fundamental particles, for example, their mass, spin, and charge. The SM was built on the electroweak theory and the quantum field theory, while the electroweak theory once met some problems when it was being built, and the problem was solved through the Higgs boson. Once the electroweak force was first proposed, there was a problem existing since the mass of W and Z bosons were not the same as the result showed by the experiments, and the other parts of the theory performed successfully. To solve the problem, physicists proposed the Brout-Englert-Higgs mechanism, which depends on spontaneous symmetry breaking. Nowadays, the SM, which was built on the electroweak theory, has its cornerstone as the electroweak spontaneous symmetry breaking (EWSB) [1]. The EWSB, discussed in the following part, needs the Higgs boson as its exchange particles. They need the existence of the Higgs boson based on the Brout-Englert-Higgs mechanism. The above is the reason why physicists need the Higgs boson in theory, and those requirements let the researchers do experiments to discover the Higgs boson in their accelerators.

2.2. Discovering the Higgs boson in accelerators

In 2013, the CERN announced that they discovered the Higgs boson, and it took CERN almost 50 years to discover it. As the Higgs boson has a mass 120 times more than that of protons, it is quite hard to produce and detect it. Since the large mass of the Higgs boson leads to the extremely short lifetime of it (10^{-22}seconds) means that the particle can only be found in the lab through the accelerator, and it also needs a huge amount of energy to produce it. To create a place that can conduct such an experiment, CERN created the largest accelerator in the world called the Large Hadron Collider (LHC), and the Higgs boson was found in the accelerator. Another problem for physicists is how to detect the Higgs boson. Since it decays almost immediately after it formed, therefore, the choice is to detect the production of Higgs boson decays. The particles produced from the boson's decay are the only evidence that the Higgs boson once existed and leaves behind. These traces have to be detected and precisely measured by particle detectors. After the particles are detected, physicists need to find out if the collision forms the Higgs boson. Although it is impossible to know which collision produced the Higgs boson, scientists can know the fact that the Higgs boson is produced by analyzing enough collisions. Then, after some statistical analysis, the signal figure can show if there is a particle produced with a mass in the range of mass of the Higgs boson.

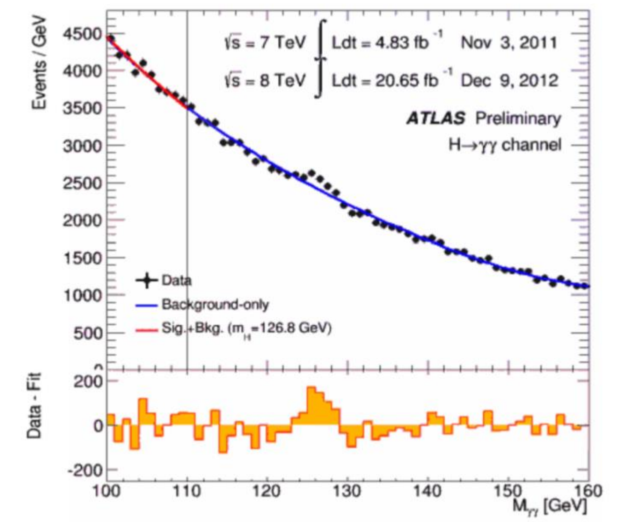

Figure 1. The statistical figure [2].

As seen in Figure 1, there is a small difference between the experiment data and the predicted data. In the theory's prediction, the mass of the Higgs boson should be between the range of $120\mathrm{GeV/c^2}$ and $135\mathrm{GeV/c^2}$, then since the CMS and ATLAS observed excesses of events in their 2011 datasets of proton-proton (pp) collisions at centre-of-mass energy $\sqrt{S} = 7\mathrm{TEV}$ at the LHC, which were compatible with the prediction of the Higgs boson production in SM, and the energy created was between the range of 124GeV and 126GeV. After some more statistical calculations and experiments, the figure drawn through the experimental data contained a peak that can be considered as the evidence of Higgs boson produced during the experiment [3]. Physicists are sure that a new particle is discovered due to the statistical answer. The statistic gave the probability as about 5 sigma which means that in the probability, it is about one in three and a half million, and that can tell physicists if the discovery is meaningful.

3. How fundamental particles get mass

Since the Higgs boson is the product particle of the Higgs field, this paper first explains the background of the Higgs field as it follows the QFT, and then it is easier to explain the other points. According to the QFT, all fundamental particles are actually quantum fields, and the particles are products of the fields. Higgs boson is the product of the Higgs field. The Higgs field fills the entire universe and has potential energy following Formula (1):

$$V(\phi) = 2\phi + \phi + \lambda(\phi + \phi)2 \tag{1}$$

Also, when calculating the energy, the physicists still need to calculate the lagrangian which equals the kinetic energy of the Higgs field minus the potential energy of the Higgs field, and it can be calculated through Formula (2):

$$\mathscr{L} = \left[\frac{1}{2(\partial_\mu \eta)(\partial^\mu \eta)} - \mu^2\eta^2\right] + \left[-\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\left(\frac{q\mu}{\hbar c\lambda}\right)^2 A_\mu A^\mu\right] + \left\{\frac{\mu}{\lambda}\left(\frac{q}{\hbar c}\right)^2 \eta(A_\mu A^\mu) + \frac{1}{2}\left(\frac{q}{\hbar c}\right)^2 \eta^2(A_\mu A^\mu) - \lambda\mu\eta^3 - \frac{1}{4}\lambda^2\eta^2\right\} + \left(\frac{\mu^2}{2\lambda}\right)^2 \tag{2}$$

Then, the mass of the Higgs boson produced by the Higgs field can be calculated through Formula (3):

$$m_A = 2\sqrt{\pi}\left(\frac{q\mu}{\lambda c^2}\right) \tag{3}$$

That is how physicists calculate which range of mass the Higgs boson will be. Another background theory is the spontaneous symmetry breaking which lets the Higgs field give particles mass. Firstly, symmetry breaking is an important part of physics, since the Higgs mechanism works through it. According to the Lorentz-covariant field theory, the symmetry is broken spontaneously under a Lie group, and that process contains zero-mass particles [4]. When the conserved currents associated with the internal group couple to the gauge field, the process above will fail, and the result of the failing is that the spin-one quanta of some of the gauge fields get mass, while the coupling tends to zero, the longitudinal degrees of freedom of the particles will go over into Goldstone bosons [4].

Then after calculating the lagrangian, two different solutions can be obtained, since one of the solutions occurs in the vacuum, and the other solution, however, shows that there are some gauge bosons produced which are called Goldstone bosons. The Goldstone bosons play an important role in the process of Higgs mechanisms. The Higgs field can interact with the Goldstone bosons, and it can "eat" the Goldstone bosons to add one degree of freedom, then it can have more energy and mass to give mass to other particles [5]. That process lets the Higgs field give so much mass to other particles. But the spontaneous symmetry breaking lets the Higgs field get the ability to give other particles mass. In addition, the Higgs field owns a property called Higgs potential, and due to the quantum fluctuation, the energy of Higgs potential changes with time. But it still can be calculated through Formula (4):

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$$V(H) = \mu^2 H^2 + \lambda H^4 + c_o \tag{4}$$

In Formula (4), μ is a complex number, so its square is minus while $\lambda>0$, and λ is the Higgs field self-coupling. The c_o is an arbitrary normalization constant independent of H which has no physical consequences as long as we remain within the SM where only differences in energy are important [6]. Thus, the Higgs potential can be drawn as Figure 2 shows.

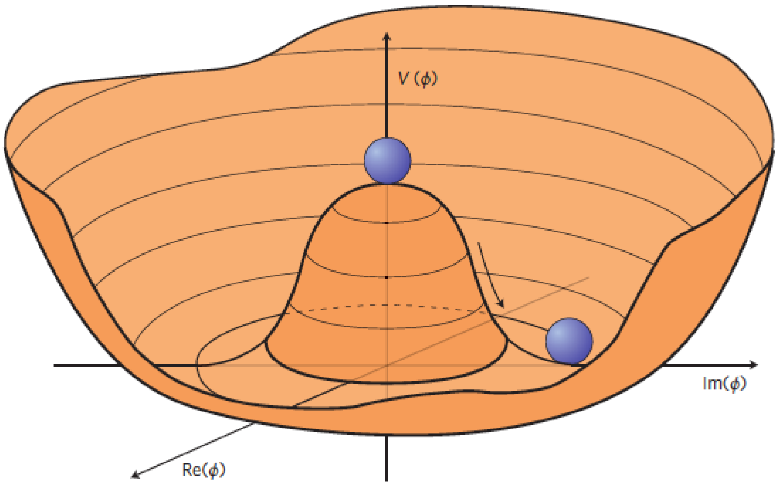

Figure 2. Higgs potential [7].

Since the mass of the Higgs boson is defined by the Higgs potential, the Higgs potential can be considered as it can define the mass given to the other particles. To let more particles have more mass, the Higgs field has the ability to interact with Goldstone bosons. It can “eat” the Goldstone bosons, and then the Higgs field can get one more degree of freedom. Then, it can have more mass to give other particles and give more particles mass.

Then, the theories and processes can be combined together. At first, the Higgs field causes the symmetry to break spontaneously, and it has the ability to gain and pass mass to other particles. While at that time, the Higgs field did not have enough Higgs potential. There are Goldstone bosons formed in the spontaneous symmetry breaking and those gauge bosons interact with the Higgs field, adding degrees of freedom to the Higgs field so that the field can have more mass. After the above process, the elementary particles including some bosons and most fermions interact with the Higgs field, getting mass through the interaction. Those particles that interact with the Higgs field deeply can get more mass than those particles that do not interact with the field much deeper.

4. Other problems about Higgs boson

Although the Higgs boson was discovered in LHC and has helped solve a lot of questions, there are still many problems about it. The most famous one is the Hierarchy problem which contains the cosmological constant and the Higgs boson. The mass difference between the Higgs boson and the Planck mass is too big, so it is hard to explain this problem through the theory. After being renormalized, the mass of the Higgs boson is small. At the Electroweak scale (about 246GeV), the bare one is huge due to radiative corrections growing quadratically with the ultraviolet (UV) cutoff, which is assumed to be given by the Planck scale Λ_{PI}Pl~1019 GeV [8]. Another one is the other possible ways to produce the Higgs boson. There are four main ways to produce the Higgs boson in the accelerator: through the fusion of two gluon particles (gluon-fusion, or ggF); through the fusion of weak vector bosons (VBF); or in association with a W or Z boson (VH), or one or more top quarks (ttH+tH) [9].

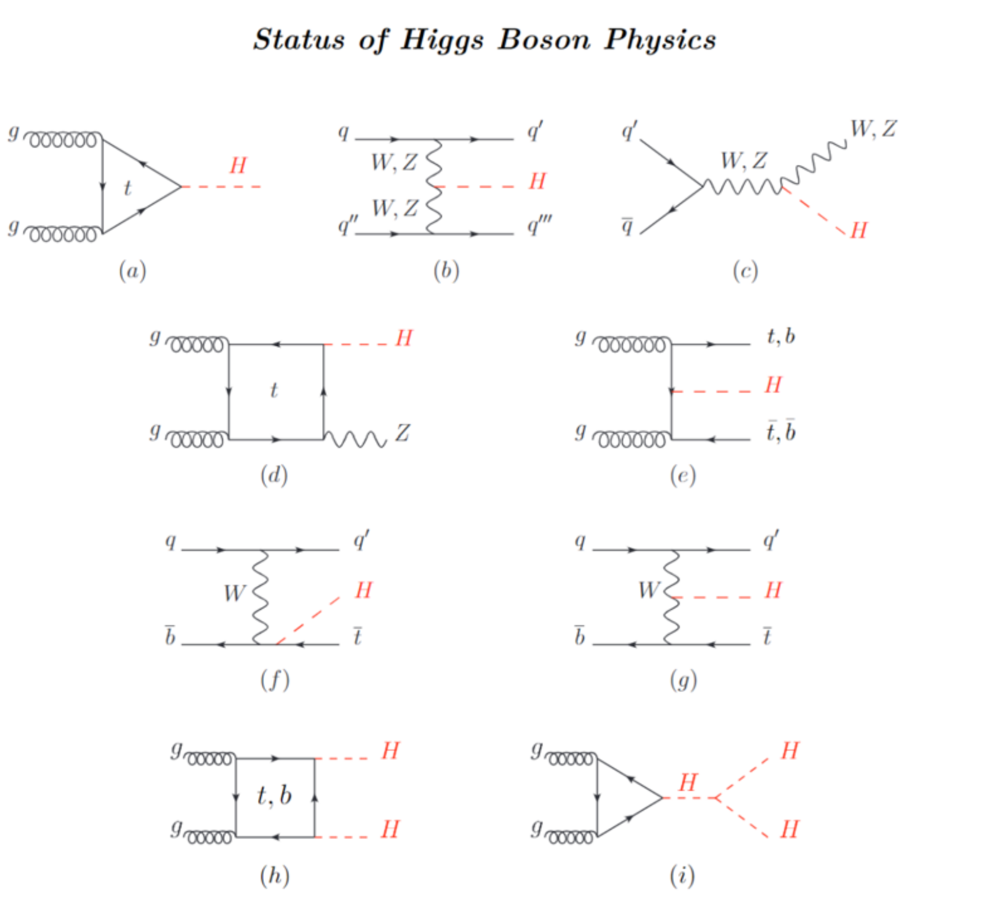

Figure 3. Main leading order Feynman diagrams contributing to single Higgs boson production [10].

In Figure 3, those Feynman diagrams show all the production ways about how to produce the Higgs boson that people know. In the figure, (a) shows the gluon fusion; (b) shows the Vector-boson fusion; (c) shows the Higgs-strahlung (or associated production with a gauge boson at tree level from a quark-quark interaction); (d) shows the associated production with a gauge boson (at loop level from a gluon-gluon interaction); (e) is associated with a pair of top/bottom quarks; (f-g) is in association with a single top quark and double Higgs production through (h), a top- and bottom-quark loop; (i) is the self-coupling of the Higgs boson [10]. Another important discovery is a couple of Higgs bosons. Since some interaction can produce a couple of Higgs bosons, it is hard for people not to think about if there are other kinds of Higgs bosons that are not discovered, or if there is an interaction between a couple of Higgs bosons, for instance, how they may interact with each other and make some changes to the Higgs field. For physicists, knowing how the pairs of Higgs bosons will do is really helpful to build a new theory called the Beyond standard model (BSM). These problems are waiting to be solved.

5. Conclusion

In this paper, the author mainly discusses the basic information about the Higgs boson, including its properties when it is considered as a particle, as well as the properties of the field which is the base of the Higgs boson. Then, there is an extended discussion about how the Higgs boson gives other particles mass. It is complicated for it to finish the process as it needs a base of theory including other theories and fields, for example, symmetry breaking is a main need for the Higgs mechanism, the Higgs potential determines how much mass the field and particle can pass to other particles, and the interaction with the Goldstone bosons can be considered as necessary as the spontaneously symmetry breaking. The degree of freedom of the Higgs field can be determined through the complex interaction between them. In

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addition, there are also many small factors, for instance, the quantum fluctuation, which has some influences on the energy of the Higgs field, or its lagrangian that determines the mass passed. All the information above explains the process of the Higgs boson giving mass, which can be called the Higgs mechanism. Overall, current research on the Higgs boson has obtained great achievement, and in the future, physicists can learn about the pairs and other kinds of Higgs bosons so that they can build a better theory that contains more things.

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