# Higgs Boson: Newly discovered elementary particle

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# Higgs Boson: Newly Discovered Elementary Particle

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## Abstract

The Higgs boson has been discovered recently by the ATLAS and CMS experiments at CERN's Large Hadron Collider (LHC). It is an important particle because it is responsible for the mechanism called 'Higgs mechanism' by which all elementary particles acquire mass. The discovery of this particle completes the Standard Model (SM) of the particle physics. In this article, we discuss the role of Higgs field and the Higgs boson in the theory of fundamental particles and their interactions. We also discuss the recent results about the Higgs boson at the LHC briefly.

## 1. Introduction

The Standard Model (SM) [1–4] of particle physics is completed by the discovery of an elementary particle known as Higgs boson. The day July 4, 2012 has been a landmark day in the history of science due to the observation of a new resonance which is most likely to be the elusive Higgs boson announced by CERN. This particle is confirmed on 14th March, 2013, in the 'Moriond' conference, held in Italy. On 8th Oct. 2013, the Noble Prize in physics for 2013 has been announced to award to two great scientists Peter Higgs and Francois Englert for getting proof of their theoretical results experimentally through CERN in Geneva.

The SM [1–4] of particle physics is the most complete theoretical framework which describes the fundamental constituents of matter of the observed universe and the fundamental forces (strong, weak and electromagnetic force) acting among these constituents. According to the SM, there exists a boson called the Higgs boson which is responsible for providing mass to all the elementary particles (quark, leptons) and to the mediator particles which carry a force among them. Thus the experimental observations on Higgs boson was an absolute necessity because without experimental evidence the SM was incomplete which is now completed through the experimental evidence of Higgs boson. The SM matter particles are made up of 6 quarks (u, d, c, s, b, t) and 6 leptons (e, $\mu$, $\tau$, $\nu_e$ , $\nu_\mu$ , $\nu_\tau$ ) [2]. The electromagnatic force which is mediated by a massless force carrier particle (photon). Since photon have rest mass zero, it moves with speed of light [8]. The weak force which is mediated by the force carrier W and Z bosons, the third force is strong nuclear force which is mediated by 8 massless force carrier particles called 'gluons'. The quark and leptons are matter particles with half-integer spin quantum number and follow Fermi-Dirac statistics and so named as fermions. The Fig-1 and Fig-2 represent elementary particles of the SM and fundamental forces of nature respectively.

What do you mean by the mass of a particle/a body? According to Wilczek [3], mass is a primary quality of matter. According to Newton [5], mass is that quantity of matter which is present inside the body or a particle. In the universe almost all particles have mass (except the particles photon, gluon, graviton etc), but there is an unsolved question tiil today: What is the origin of mass? According to the SM of particle physics, some time about $10\times10^9$ years ago all the matter of the universe was packed into a superdense small agglomeration subsequently being hurled in all directions at enormous speeds by a cataclysmic explosion i.e. the big bang. Just after the big bang [6,7] all particles were massless. After passing the time of big bang the universe got cold and the temperature fell down a critical value. After that critical value of temperature, an invisible field is generated in whole space of universe that is called ‘Higgs field’. The particle associated with the Higgs field is called ‘Higgs boson’. Theoretically this field is assumed to be scalar. If we want to see that where is this field exist, we will be unable to see that field, but we can assume this field as the field between particle and air in space and field between fish and water in the pond.

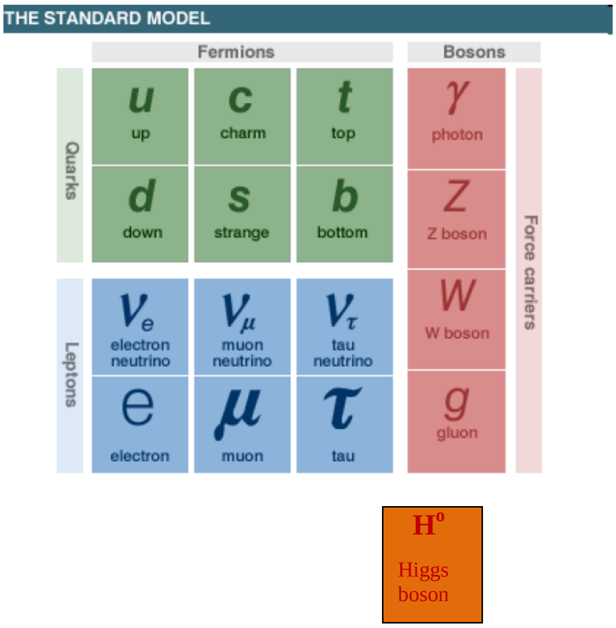


**Fig 1:** The Standard Model elemenary particles (basic constituents of matter and force carriers)

| Forces | Particles Experiencing | Force Carrier Particle | Range | Relative Strength |
|---|---|---|---|---|
| Gravity (acts between objects and mass) | all particles with mass | graviton (not yet observed) | infinity | much weaker |
| Weak Force (governs particle decay) | quarks and leptons | $W^+, W^-, Z^0$ (W and Z bosons) | short range | |
| Electromagnetic (acts between electrically charged particles ) | Electrically charged particle | ϒ (photon) | infinity | |
| Strong Force (binds quarks together ) | quarks and gluons | g (gluon) | short range | much stronger |

**Fig 2:** The four fundamental forces of nature.

The important property of this field is that the Higgs field is exactly the same in strength everywhere in space whereas the electromagnetic and gravitational field vary from place to place. If the particles are moving in the uniform Higgs field these particles are accelerated i.e. their velocities are changed because the Higgs field exert the certain amount of resistance or drag, this resistance applied by the Higgs field is the origin of inertial mass. The process explaining the inertial mass through Higgs field is called 'Higgs effect'.

The idea of using a scalar field to be as the origin of mass appeared in the domain of high energy physics and it received the name 'Higgs mechanism' [7]. On the other hand the relationship of mass with gravity is very old. Such deep connection has been emphasized in a qualitative way many times. According to Mach [8] inertia is related to the global distribution of energy of all particles in the universe. From the historical point of view this idea led Einstein to develop a new theory of gravitation. However, the dependence of inertia on global structures of the universe was lost. Otherwise a mechanism of mass generation came from microphysics. Indeed, the Higgs model produced an efficient scenario for generating mass to all bodies which goes in opposite direction of Mach's proposal.

The Higgs boson, the final particle of SM, has been confirmed experimentally at CERN in Geneva. It was theoretically predicted by Englert, Brout, Higgs, Guralinik, Hagens and Kibble [9-11] in 1964. It is an important particle because all elementary particles acquire mass through the field generated by this particle, i.e. through the phenomenon Higgs mechanism.

# 2. Known Information about Higgs boson

Search for the Higgs boson was one of the principal aim at the very beginning of the Large Hadron Collider at CERN. The LHC is an accelerator which makes to collide the proton beams. In 2011, the energy of protons in each of beams amounted as 3.5 TeV, and hence the total collision energy of two beams was 7 TeV. In the domain of physics, mass is measured in units of energy, in accordance with the Einstein relation $E_0 = mc^2$ between the mass and rest energy. The used unit of energy is the electron volt (eV), and its derivatives are MeV, GeV, TeV, ($10^6$, $10^9$, and $10^{12}$eV respectively). The mass of electron in this unit is 0.51 MeV, proton mass is approximately 1 GeV and mass of the heaviest known elementary particle the t-quark is 173 GeV. The mass of the new particle Higgs boson amounts to 125-126 GeV [to be more precise, 125.3±0.4 (stat.) ± 0.5(syst.) GeV from the CMS data [12] and 126.0 ±0.4(stat..) ± 0.4 (syst.) GeV from the ATLAS data [13], where the statistical and systematic uncertainties are indicated]. The Higgs boson is an elementary (not composite) particle.

This observed new particle Higgs boson has no electric charge. Since it is unstable it can decay in different ways. It was discovered through LHC [12, 13] in the study of decay into two photons, $H \rightarrow \Upsilon\Upsilon$ and into two electron-positron and/or muon-antimuon pairs, $H \rightarrow e^+e^- e^+e^-$, $H \rightarrow e^+e^- \mu^+\mu^-$, and $H \rightarrow \mu^+\mu^-\mu^+\mu^-$. Processes of the second kind proceed into two stages. First the new generated particle decays into two known heavy neutral particles which are two Z bosons, one of which is virtual and so each of Z boson's decay into an $e^+e^-$ or $\mu^+\mu^-$ pair. This process is written as $H \rightarrow ZZ^* \rightarrow 4l$, where the particle indicated through (*) is virtual particle and l is one of the leptons $e^{\pm}$ or $\mu^{\pm}$. Both the CMS and ATLAS collaborations also report a certain excess events which can be due to the decay $H \rightarrow WW^* \rightarrow I\nu I\nu$, where W boson is another one known heavy, electrically charged particle (so, a $W^+W^-$ pair is produced first) and $\nu$ is the electron or muon neutrino. This excess, however, presently does not have high statistical significance.

Generally elementary particles are characterized by spin, means, the internal angular momentum. It is half integer (fermions) or integer (bosons) in unit of Planck constant ħ. The elementary particles have a non-zero spin equal to ½ in the case charged leptons (electron, muon and τ-lepton.) neutrinos and quarks, and 1 in the case of photon and the other particles (the graviton spin must be equal to 2 but the particle not yet observed). From the recent evidences it is clear that the new particle has an integer spin, i.e. it is a boson. Furthermore, its spin cannot be equal to unity because a particle having spin 1 cannot decay into two photons, its spin should be 0, 2 or higher. Although no direct experimental measurement of the new particle spin exists. It is extremely difficult to deal with a particle of spin 2 or higher. So the new particle Higgs boson's spin is most probably equal to zero. From the LHC it is observed that production of Higgs boson is the result of the collision between two beams of protons of higher energy.

The life time of Higgs boson is very small. The experimentally available data permit estimating the lower limit of its lifetime such as $\tau_H \geq 10^{-24}$ s. Its lifetime in the SM prediction $\tau_H = 1.6\times10^{-22}$ s [14]. In order to comparison, the t-quark lifetime is $\tau_t=3\times10^{-25}$ s [15]. On the basis of this data we see that direct measurement of the new particle lifetime is not likely to be possible at the LHC.

The SM with a single elementary Higgs boson is the only theory in which the Englert-Brout-Higgs field (because this field is searched by these scientists Englert, Brout and Peter Higgs ) is more precisely provide masses to all elementary particles, so the interaction of each of these elementary particles with the Higgs boson is strictly fixed. If the mass of the particle is larger, the interaction of this particle to the Higgs boson is stronger. This is why for the stronger interaction there is higher probability of the Higgs boson decay into a pair of particles of the given kind of variety. Higgs boson decays into pair of quite heavy particles $t\bar{t}$, ZZ and $W^+W^-$ are forbidden by energy conservation. The next heavy quark is b-quark with the mass $m_b$=4 GeV and it is already observed that the Higgs boson decays into $b\bar{b}$ pair. Also the interesting is the decay of the Higgs boson into a pair of quite heavy τ-leptons $H\rightarrow \tau^+\tau^-$ ($m_t$ = 1.8 GeV) this should occur with a probability of 6% [14].

The Higgs boson is produced alone through the collision between two beams of protons at the Large Hadron Collider by fusion of gluons [Fig 3.a] or together with a $t\bar{t}$ pair [Fig 3.b] or together with a single W or Z boson [Fig-3.c] or finally together with a pair of high energy light quark (the fusion of vector bosons [Fig 3.d]). It is very simple to identify that the particles produced together with the Higgs boson, and therefore the various production mechanisms can be studied separately at the LHC. This gives the information about the interaction of the Higgs boson with W±, Z-bosons and t-quark.

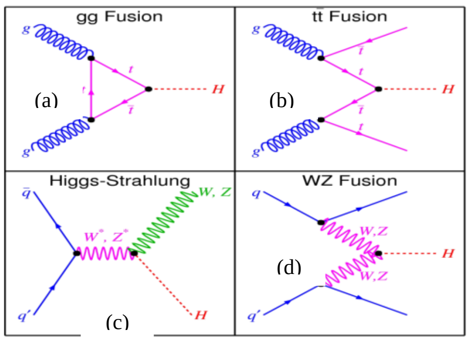


Fig 3: Feynman diagrams describing production of Higgs boson in pp collision; g, q and q' stands for gluon, a light quark (u,d), & a light antiquark inside a proton.

## 3. Requirement and Properties of the Higgs boson

The theory which is predicting the Higgs boson has been thoroughly developed and described in detail (see in the ref.[16,17]). Here we are trying to present some explanations at a very intuitive and qualitative level.

Elementary particle in quantum theory is a quantum of certain field and vice versa, each field has its own particle-quantum corresponding to it. The well-known example is the electromagnetic field and its quantum i.e. photon. This is why a question can be reformulated as: why is a new field necessary? Very simple and short answer of this question is that symmetries of the theory of the microworld, the SM or some other more complicated theory – forbid elementary particles to have masses, while the new field (called 'Higgs field') breaks these symmetries and allows the existence of particle masses. According to the simplest version of the theory i.e. the SM, all the properties of the new field and correspondingly of the new boson with the exception of its mass, are again predicted, clearly on the basis of the symmetry arguments.

The existence of Higgs boson is theoretically predicted by the great scientists Englert, Brout, Higgs, Guralinik and Kibble [9-11] in 1964. After 1964, many physicists were trying to prove it experimentally, because it can solve many unanswered questions regarding the mystery of the universe. On 14th March 2013, the 'Moriond conference' held in Italy has confirmed the existence of Higgs particle [18].

**Properties:** Some properties of Higgs boson are explained as follows:

**(a) Spin:** A massive particle of spin s has 2s+1 states with different spin projections onto a given axis. For example, the spin of an electron (s= ½) can be directed in its rest frame either upward ( $s_z = + ½$ ) or downward ( $s_z = - ½$ ). The Z-boson has a non-zero mass and spin s= 1; therefore it has three states with different spin projections; $s_z$ = +1, 0 or -1. Since the massless particle travel with the speed of light, this is why the situation of those particles is totally different. It is impossible to pass a reference frame where such a particle is at rest. We can nevertheless deal with its helicity, the spin projection onto the direction of motion. Although the photon spin is equal to unity, there can only be two such projections; along and against the direction of motion. This is precisely how the right-handed and left-handed polarizations of a photon (light) are determined. The third state with zero spin projection, which should have existed if the photon had mass, is forbidden by the internal symmetry of electromagnetic. This internal symmetry also forbids the photon to have mass.

The Higgs boson is a massive particle with spin zero. It is only one spin zero elementary particle known up-to today although there are many known composite particles with spin zero.

**(b) Coupling:**

- There are some observations about the coupling of the Higgs boson to elementary particle, i.e. Higgs particle couples to elementary particles proportionally to their mass. More massive particle means this particle have stronger interaction with the Higgs boson [19].
- According to the Standard Model, neutrinos are massless particles. It means that the Higgs boson does not couple with neutrinos. Also it does not couple directly with photons and gluons. However, coupling can be induced in indirect way called quantum fluctuation.

**(c) Influence of Higgs boson**

- The Higgs boson can emit pairs of very heavy particles such as top quark, which is possible according to the Heisenberg's uncertainty principle. Immediately the Higgs boson can absorb the emitted particle, but these virtual particles can emit photons or gluons (in the meantime). Higgs-photon-photon and Higgs-gluon-gluon couplings are then created. However, they are expected to be rather small, as they imply intermediate interactions of the virtual particles to photons and gluons, which have a small intensity.
- Higgs boson is self-interacting. The magnitude of triple and quadratic self-interaction is proportional to its mass [20].

**(d) The Higgs Field:**

The Higgs field which is generated by the Higgs boson has an important property that this field is exactly the same in strength everywhere in space whereas the magnetic and gravitational fields vary from place to place.

If the particles are moving in the uniform Higgs field these particles are accelerated i.e. their velocities are changed, because the Higgs field exerts a certain amount of resistance or drag, this concept of resistance applied by the Higgs field, is the origin of inertial mass.

## 4. Spontaneous symmetry breaking:

The connection between laws of physics and symmetry is very strong. In 1918 the mathematician, Emmy Noether proved that the existence of a symmetry in the mathematical description of the universe implies the existence of a conservation law related to that symmetry. Equivalently, *Every symmetry of nature yields a conservation law; conversely, every conservation law reveals an underlying symmetry*. But some broken symmetries can also exist. For example, in a homogeneous sample of iron at room temperature, there is always a magnetic field pointing in some directions; the sample is actually a magnet, they would discover that not all directions in the space surrounding them are equivalent; an electron moving across the magnetic field is subjected to a Lorentz force, unlike an electron moving along the magnetic field. Thus, the magnetic field inside the sample breaks the symmetry with respect to the rotations in space. The angular momentum conservations is therefore not fulfilled inside a magnet. Here, we are dealing with spontaneous symmetry breaking. In the absence of external influences (for example, Earth's magnetic field), magnetic fields in different samples of iron can point in different directions, and none of these directions can be considered preferable. The original symmetry with respect to rotations still exists, but it manifests itself in that the magnetic field inside the sample can point in any direction. But because of magnetic field did arise; symmetry inside the magnet happened to be broken. At a more formal level, the equations (the Hamiltonian, the Lagrangian) controlling the interaction of iron atom with each other and with the magnetic field are symmetric with respect to rotations in space, but the state of the system comprising these atoms, i.e. the iron sample, is not symmetric. This is precisely the essence of the phenomenon of spontaneous symmetry breaking. We are here considering with the ground state, having the least energy. A sample of iron eventually occurs in that state, even if initially it was not magnetized.

We know that spontaneous breaking of certain symmetry occurs when the equations of the theory are symmetric, while the ground state is not. The term 'spontaneous' is used in this case because the system itself, without our participation, chooses a nonsymmetrical state, because it is the most advantageous state from the stand point of energy. From the above example it is clear that if symmetry is spontaneously broken, the conservation laws based on it are not fulfilled; our example concerns the angular momentum conservation. We stress that the complete symmetry of a theory can violate only partly; in our example of the complete symmetry with respect to all rotations in space, only symmetry with respect to rotations around the magnetic field direction remains manifest and unbroken. The mechanism for generating the masses of particles of spin-1 (in nature, there are $W^{\pm}$ and Z-bosons) by spontaneous symmetry breaking was proposed in the context of elementary particle physics by theoreticians Francois Englert and Robert Brout [9], and somewhat later by physicist Peter Higgs [10, 21]. This occurred in 1964. They were inspired by the idea of spontaneous symmetry breaking (but in theories without vector fields i.e. without spin-1 particles) introduced in elementary particle physics in 1960-1961 in the work of Nambu [22], Nambu and Jona-Lasinio [23, 24]. Vaks and Larkin [25] and Goldstone [26, 27]. Unlike the previous authors, Englert, Brout and Higgs considered a theory (conceptual at the time) that involved both scalar (spin- 0) field and a vector (spin- 1) field. In this theory an internal symmetry exist, quite similar to the gauge invariance of electrodynamics, but unlike in electrodynamics, the internal symmetry is spontaneously broken by a homogeneous scalar field present in the vacuum. A remarkable result obtained by Englert, Brout and Higgs, was the demonstration of the fact that this symmetry breaking automatically implies that a spin- 1 particle- the vector field quantum- becomes massive.

A straight forward generalization of the Englert-Brout-Higgs mechanism, with fermions and their coupling to the symmetry-breaking scalar field included into the theory, also results in the generation of fermion masses. Everything starts shaping up: The Standard Model is obtained by a further generalization involving the inclusion of several vector fields instead of one (photons and $W^{\pm}$ and Z-bosons; gluons are a separate story; they have nothing to do with the Englert-Brout-Higgs mechanism) and different type of fermions. This generalization is actually quite nontrivial; it was initiated by Glashow [28]. The Higgs mechanism was incorporated into modern particle physics by Steven Weinberg and Abdus Salam, and is an essential part of the SM [29,30].

# 5. Conclusions

The discovery of Higgs boson was a giant step in the history of science, justifying the 2013 Nobel Prize to Francois Englert and Peter Higgs [31], who perhaps represent all the high energy (and condensed-matter) theorists who made major contributions [32]. CERN director general ‘Rolf Dieter Heuer’ said in a interview on 8$^{th}$ Oct. 2013 “The properties of the Higgs boson could point to field for investigation to find dark matter or dark energy. By 2017 or 2018 CERN may have result tests to indicate the level of energy necessary to study such new particles as Higgs boson”.

The description of the strong and electroweak interactions of fermions and gauge boson and a final vital ingredient i.e. the spin zero Higgs boson is possible only by the Standard Model of particle physics. The particle Higgs boson is important because it is responsible for the Higgs mechanism by which all particles acquire mass. Now in all over the world mostly scientists are trying to prove this thing.

The discovery of this particle not only completes the SM but also raises new questions and has implications for other areas of physics including the birth of the universe. Although the Higgs boson belongs to the SM of particle physics its study is a very challenging and fascinating topic which interplays between different branches of physics like particle physics, condensed matter physics and cosmology.

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