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Research paper

The discovery and importance of the higgs boson

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Abstract

This work presents the importance of the existence of the Higgs boson, a particle with a mechanism capable of generating mass for other elementary particles, where interacting particles receive mass and those that do not interact, do not receive mass. The work shows the understanding of the mechanism for the interactions of particles with the Higgs boson and analysis of the experiments carried out at CERN, together with other detectors such as CMS and ATLAS, in the search over 50 years for the physicist Peter Higgs, suggesting a new theory necessary for the existence of the mechanism that would generate mass for the other particles. Even with the scientific advance through the discovery of the Higgs boson and its explanation within the Standard Model, we still have questions to be answered by not explaining gravitational interaction, hierarchy problem, extra dimensions, supersymmetry, dark matter, among others. The discovery and importance of the Higgs boson is another achievement for science, int the sense that we are on the right path, even recognizing the limitations of equipment and investments, but in the search for the truth and answer in favor of a more structured society, such as improved health, living in an environment with less pollution, advancement in technology, resulting in several positive factors for humanity.

Keywords: *Higgs' Boson; Higgs Mechanism; Standard Model; Higgs Field; Detection.*

1. Introduction

The Scottish physicist Peter Higgs made a proposal of an elementary particle in 1964, due to the association of a new mechanism, a fundamental field that could explain the origin of mass of elementary particles or any massive body. There was great expectation for experimental evidence of its existence, where in full operation in 2010 from CERN (European Center for Particle Physics), it would be possible to detect it. Over the years with this expectation, it became known as the "God particle", where this term came about because it caught the attention of the lay public on the part of journalists, not physicists. The media, such as magazines, newspapers, radio and internet, already publicized the search for the particle [1].
The search for this particle for almost 50 years is due to the confirmation of the existence of a mechanism that would explain why the existence of mass in some particles and not others, predicted by the Standard Model. If it were indeed a "God particle", it would make no sense to detect it experimentally, it would be enough to accept it and use it to justify the mass of bodies [1].
Scientists from CERN, have announced that a new particle has been discovered, suggesting it is the Higgs boson, after 50 years of research, and the announcement was cautions. The particle mass was between 125 and 126 GeV, agreeing with the standard model prediction, but more experimental data would still need to be obtained as there were some inconsistencies. The experimental data showed an excess in the level of decay, where the proposal should decay with a certain frequency in pairs of photons [2].

2. Development

The Standard Model is the best physics theory to date on the nature of matter, as identifies and specifies the interaction of the basic constituent particles. The model describes a system composed of 17 subatomic particles, including the Higgs boson, which constitute the Universe, as well as the description of fundamental interactions such as electromagnetic, weak, and strong, of the four existing ones, excluding the four existing ones, excluding the gravitational one.
The fourth interaction, which is the gravitational one, associated with the field and the gravitational force, is a Standard Model problem and the Higgs interaction would be another fundamental interaction [3].
Leptons and quarks are fundamental constituent particles of matter in the Standard Model, and it is through the exchange of bosons that are the mediating particles that the interaction occurs. Particles that do not interact with the Higgs field will have no mass. Experimental evidence in 1973 at CERN, it was observed that due to the exchange of Z_0 bosons the occurrence of a neutral weak current, where Glashow, Salam, and Weinberg, received the Nobel Prize, for the work of unifying the weak and electromagnetic forces through the model electroweak.
When the Higgs field that is throughout the universe receives enough energy, it creates a particle, the Higgs, which would be the excitation of the Higgs field. When this Higgs interacts with other particles, it transfers energy in the form of mass, from the field to the elementary particle and depending on the intensity of this interaction, the Higgs field will determine the amount of mass of this particle [2].

Glashow (1961) described a theory that unified the electromagnetic interaction with the weak one, acting on charged particles, but due to the short range of the weak interaction, experimentally, the mediating particles of the theory, which would be vector bosons, should be very massive, which should not be massive to guarantee renormalizability [4].

There was a development between 1967 and 1968, by Steven Weinberg and Abdus Salam, for the Higgs mass generation mechanism in the electroweak Glashow model, where vector bosons, fermions, quarks and leptons, would acquire mass through the temperature-dependent phase transition of the universe, in which at the beginning of the universe, the electroweak force bosons were not massive, and as the universe temperature decreased, the phase transition reached a critical temperature, generating a force field, know as the Higgs field, i.e. what constitutes the electroweak model is the generation of mass for vector bosons through the interaction of the Higgs field [2].

But in the Standard Model, how does the particle mass generation mechanism work? Why the need for the Higgs boson? How important is it?

The notion of mass within an epistemological profile is to consider it as amount of matter, where the mass of a body is the amount of matter in that body [5].

Obviously, we have different points of view for certain regimes and systems, for example, in Einstein's perspective for in the theory of relativity, mass is energy and that for Newton, mass is the ratio between force and acceleration. But the question, regardless of whether it is quantity or energy, is: Why are there particles that have mass and others don't?

One of the possible answers is the use is the study of symmetry and spontaneous breaking of symmetry. The universe does not have perfect symmetry and there it is said that there was a break of symmetry, because at its foundation it was symmetrical.

The term spontaneous symmetry breaking is when symmetry breaking is preserved by physical laws, but its cause occurs when a system does not preserve the symmetry that would be present according to physical laws [6].

The Standard Model says that all mediating particles would have zero mass, with W and Z particles having mass. Photons and gluons have zero mass, a priori, but W and Z have mass, which generates the discussion of this conflict.

The spontaneous breaking of symmetry in the weak interaction is this question of the existence of the masses of W and Z. It is in this context of the proposal for the Higgs mechanism, proposes the existence od a new boson and a new field [1].

The Standard Model is a theory consistent with special relativity and quantum mechanics, very good at describing the interactions of nature, but not complete due to not including gravitation as well as neutrino oscillation. But how does your general equation work? As the Standard Model starts from matter observed in nature, the Lagrangian can be written in the form:

$$\mathcal{L} = -\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \bar{\Psi}_j\gamma^\mu(i\partial_\mu - g\tau_j.W_\mu - g'Y_jB_\mu - g_s\mathbb{T}_j.\mathbb{G}_\mu)\Psi_j + \left|D_\mu\phi\right|^2 + \mu^2|\phi|^2 - \lambda|\phi|^4 - (y_j\bar{\Psi}_{jL}\phi\Psi_{jR} + y'_j\bar{\Psi}_{jL}\phi_c\Psi_{jR} + conjugate) \quad (1)$$

If we look at figure 1, we will see that the six quarks, the three charged leptons and the three associated neutrinos, as well as the corresponding antiparticles are represented by Ψ. The representations W and B, are the four mediating bosons of the electroweak interaction and the gluons by G. the terms that use W, B and G, represent the Kinect energy carried by the bosons W^+, W^-, Z, γ and g, representing the interaction of the bosons with each other. Bosonic particles are surrounded by fermionic particles, Ψ matrices. They show how quarks and leptons interact through the mediating bosons W, B and G. The processes that are observed in nature are equation 1. The question is: What physics do the last two terms of this equation show us?

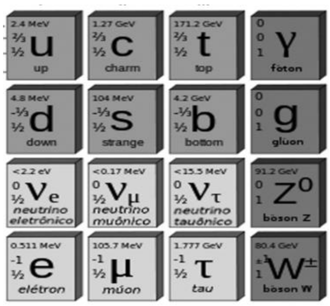

Fig. 1: Three Family of Fermions in Different Shades of Gray [2].

For the Standard Model to have *gauge* symmetry, that is, for the system to have local or global transformations, the particles must be non-massive, and charged quarks and leptons are massive. Peter Higgs suggests a mechanism for giving mass to massive elementary particles, the ϕ Higgs boson. So, the answer to answer the question, would be description of the physics of the Higgs boson ϕ, where the quadratic terms, describe the kinetic energy, mass and self-interaction of the Higgs boson and the last term, describes the interaction of this boson with matter, generating mass. But how does the Higgs mechanism work?

Gauge theory is good for explaining electrodynamics, but insufficient for describing electroweak interactions, as local gauge invariance requires massless gauge bosons, which contradicts experiments that observe values for the masses of bosons $W^{\pm}$ and Z^0, we have 80.39 *GeV* and 91.18 *GeV*, in the sequence [7].

The idea of the Higgs mechanism is to make the vacuum behave like a viscous fluid, where the Higgs field permeates the vacuum, and particles that carry a weak charge, such as bosons, quarks, and leptons, can interact with it. With this fluid, making the particles move more slowly, which would correspond to the acquisition of mass, because particles without mass travel at the speed of light through a vacuum.

Particles gain mass when they interact with the Higgs field, and those that have no mass do not. What about the mass of the Higgs boson? Where does your dough come from? The Higgs boson itself interacts with the Higgs field, hence the existence of its mass [6].

The detection of the Higgs boson confirms the conjecture of the Higgs field and mechanism, since the existence of this field implies the existence of this boson, as it is the mediating particle of the Higgs interaction [1].

The Higgs field is a complex scalar field. But if we consider as a real scalar field ϕ, we have for the Lagrangian:

$\mathscr{L} = 1/2(\partial_\mu\phi)^2 - (1/2\mu^2\phi^2 + 1/4\lambda\phi^4)$ (2)

Where the second term is the potential $V(\phi)$, for $\lambda > 0$ and $\mu^2 < 0$, we have same structure for the quadratic terms of the Lagrangian of equation (1). As $\phi \rightarrow -\phi$ the Lagrangian of equation (2) is invariant and the potential $V(\phi)$ is of the form of figure 2.a, satisfying in the form:

$$\frac{\partial V}{\partial \phi} = \phi(\mu^2 + \lambda\phi^2) = 0, \text{ whence } \phi^2 = -\frac{\mu^2}{\lambda} \equiv v^2 \quad (3)$$

Corresponding to vacuum the point $\phi = 0$ of equation (2). The vacuum does not correspond to the minimum value of the field and the mass m of the ϕ field is imaginary. Which would be a problem. But how to fix? By shifting the scalar field ϕ, its minima vertically to $V = 0$, according to figure 2.b.
The definition of a new field ϕ' shifted from ϕ in the form $\eta = \sqrt{-\mu^2/\lambda}$, where this field η can be interpreted as quantum fluctuations of ϕ. [8].

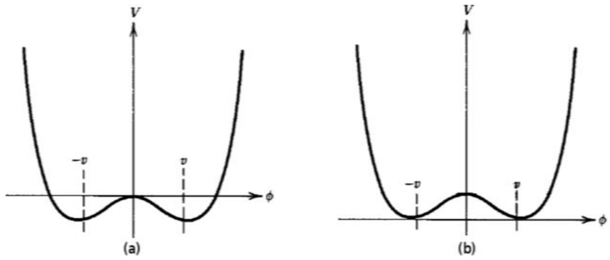

Fig. 2: (a) Potential $V(\phi)$. (b) Displaced potential [2].

So, if you do $\phi' = \phi + \eta$ in equation (2), we get:

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu\phi'\right)^2 - \frac{1}{2}((\sqrt{-2\mu^2})^2 \phi'^2 - \lambda\eta\phi'^3 - \frac{1}{4}\lambda\phi'^4) \quad (4)$$

The symmetry breaking of equations (2), generated mass for the ϕ field, where $m_\phi = \sqrt{\mu^2} \rightarrow m_{\phi'} = \sqrt{-2\mu^2}$.
In equation (4), the ϕ' field has real and positive mass, and the vacuum corresponds to the zero of this same field. Due to the cubic term of the field, we no longer have transformation symmetry. The complex scalar field ϕ in the Higgs Lagrangian is of the form:

$$\phi = \sqrt{\frac{1}{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} \quad (5)$$

With the description of the Lagrangian [8].

$$\mathcal{L} = \left(\partial_\mu\phi\right)^\dagger(\partial^\mu\phi) - \mu^2\phi^\dagger\phi - \lambda\left(\phi^\dagger\phi\right)^2 \quad (6)$$

Being invariant by local phase change $\phi \rightarrow e^{iq\alpha(x)}\phi$. If we take the expected value of the Higgs field, for $\phi_1 = \phi_2 = \phi_4 = 0$ and $\phi^2{}_3 = -$ $- \mu^2/\lambda$, we have:

$$\phi = \sqrt{\frac{1}{2}}\begin{pmatrix}0 \\ \sqrt{-\frac{\mu^2}{\lambda}}\end{pmatrix} \quad (7)$$

And for a displacement similar to the previous description, for the bosonic fields W^+, W^-, Z and γ, in covariant form:

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + ig\frac{1}{2}\tau.W_\mu \quad (8)$$

The Higgs shift generates symmetry breaking, where particles acquire mass. This formalism is known as the Higgs mechanism [9].
The parameter λ was defined from its measurement of the mass of the Higgs boson in 2002, by the CMS and ATLAS experiments carried out at the LHC [10], [11].
The mass of the scalar is of the form:

$$m_h = \sqrt{\frac{\lambda}{2}}v \quad (9)$$

Whence

$$m_h \cong 125{,}7 \pm 0{,}5\ GeV \quad (10)$$

Where the parameter λ is the self-coupling of the Higgs boson and v = 246 GeV, the expected value of the Higgs field in vacuum [12].
After the detection of the $W^{\pm}$ and Z^0 bosons, the Higgs boson became a priority in particle physics, because its existence was not only supported by the need for a mechanism that generates mas, but the biggest motivation was the violation of unitary, for example in the process $e^+e^- \rightarrow W^+W^-$, considering only the photon and the Z^0 boson as mediators, the cross section would grow with energy, not conserving the probability, but if has the Higgs as a mediator, the cross section no longer increases with energy, maintaining the unitary theory, hence the importance of the Higgs boson in order not to violate the unitarity of the theory [13].
Reading the experimental issue, on July 2, 2012, CERN officially announced the observation in the ATLAS and CMS experiments, a sign that could be the Higgs boson. As there are experimental and theoretical problems, as it does not solve all kinds of problems for the Standard Model, such as gravitational interaction, neutrino oscillation, antiparticles, dark matter and energy, cosmic inflation, excess parameters, hierarchy problem in interactions, among, others, there are proposals for extensions of the Standard Model and alternative models [2].
In the case of the detection of the Higgs boson [2], he says two beams of particles are accelerated in opposite directions, one clockwise and the other anticlockwise, close to the speed of light, for further studies of the production of events occurred by the collisions and: "The production of the Higgs boson in proton-proton collisions occurs through several channels (reactions), whose branching ratios depend on the mass of the Higgs. The branching ratio of a decay in a specific way in relation to the total number of particles that decay" [12].
There are several works to solve open questions, such as extras dimensions, which considers universes with N-dimensions for N = 4 + n, where n is the number of extra dimensions and 4, are the spatial dimensions and more the temporal, where the dimensions extras would be in Park-length compressed form, where the graviton would also interact in these new dimensions. In the case of supersymmetry, which considers the existence of a supersymmetric partner for each elementary particle, that is, for each fermion there is a boson, with identical mass and coupling constant.
The idea of supersymmetry is in the foundation of the universe, in the initial moments and with the cooling this symmetry has been broken. That's why they are on an energy scale above that is not accessible to current accelerators. This model offers a solution to be hierarchy problem and a possible solution for dark matter. So far there is no experimental confirmation of supersymmetry [2].

3. Conclusion

Peter Higgs worked hard with the mechanism that suggested the existence of a particle describe by a scalar field over 50 years of work, where it is finally detected by the LHC, which earned him the Nobel Prize in 2012. The Higgs mechanism shows us its importance for generating mass for elementary particles and maintaining unitarity.
Despite is discovery and importance, we still have open questions, such as how neutrinos have mass, the existence of dark matter, as the mechanism does not clarify all the solutions.
One of the answers was solved, why the masses of the particles, but Physics continues in the search for answers to more questions, where for elementary particles, depending on the model and observation, it will require detection equipment for high energies, which we currently do not have.
We are certainly on the right path for science, because when we search for the truth and answers to questions, one way or another we will find it, because we realize that when describing proposals and models for the interpretation of scientific phenomena, it is to celebrate when the discovery arrives, as it reveals that we are on the way to a better, promising future, discovering new paths, resulting in the improvement of life in all aspects such as health, environment with less pollution, technological advancement, among other relevant factors for society.

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