JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

The Higgs Boson: Discovery, Implications, and Future Prospects

Satish Rai Saini

(Assistant Professor)

Abstract: The discovery of the Higgs boson in 2012 at CERN's Large Hadron Collider (LHC) was a milestone in particle physics, confirming the Brout-Englert-Higgs (BEH) mechanism as the source of mass for elementary particles. This paper reviews the origins of the Higgs boson, the experiments leading to its discovery, its role within the Standard Model, and ongoing research efforts to probe its deeper properties. Furthermore, we explore its potential implications for physics beyond the Standard Model, including dark matter, electroweak symmetry breaking, and early universe cosmology. Future collider experiments are expected to refine our understanding and search for possible extensions to the Higgs sector.

***IndexTerms* -** Higgs boson, LHC, BEH, dark matter, universe cosmology.

1. Introduction

The Higgs boson is a fundamental particle in the Standard Model of particle physics, first theorized in 1964 by physicist Peter Higgs and others. It plays a crucial role in explaining why elementary particles have mass, through the mechanism known as the Higgs field. This field permeates the universe, and when particles interact with it, they acquire mass. The discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012 was a groundbreaking achievement in physics, confirming a key aspect of the Standard Model and leading to a Nobel Prize in Physics for Higgs and François Englert in 2013. The study of the Higgs boson continues to provide insights into the fundamental nature of the universe, including potential connections to dark matter and physics beyond the Standard Model.

2. Theoretical Background

The concept of the **Higgs boson** emerged in the early 1960s as physicists sought to explain how fundamental particles acquire mass. Peter Higgs, François Englert, and Robert Brout, along with other researchers, proposed the existence of a quantum field, now known as the **Higgs field**, that fills all of space [1]. This idea was crucial because, according to the Standard Model of particle physics, fundamental particles should initially be massless. However, real-world observations contradict this, as many particles, such as electrons, W and Z bosons, and quarks, have mass.

2.1 The Role of the Higgs Field

The Higgs field is an invisible energy field that exists everywhere in the universe. When certain fundamental particles interact with this field, they experience resistance, similar to an object moving through a medium like water or molasses. This interaction **slows them down** and, in doing so, effectively **grants them mass**. The more strongly a particle interacts with the Higgs field, the more massive it becomes.

2.2 **W and Z Bosons and the Higgs Mechanism**

The Higgs mechanism is particularly important in explaining the mass of the **W and Z bosons**, which mediate the **weak nuclear force**—one of the four fundamental forces of nature. In the absence of the Higgs field, the Standard Model equations suggest that the W and Z bosons should be **massless**, similar to the photon, which mediates the electromagnetic force. However, experiments show that the W and Z bosons are actually quite massive (about 80 and 91 times the mass of a proton, respectively) [2]. The Higgs mechanism resolves this contradiction by allowing these bosons to gain mass through their interaction with the Higgs field.

2.3 The Discovery of the Higgs Boson

While the Higgs field explains mass, the theory also predicts the existence of a corresponding particle—the **Higgs boson**. This particle was first observed in **2012 at CERN's Large Hadron Collider (LHC)**, confirming the existence of the Higgs field and the mass-giving mechanism [3]. The discovery was a milestone in physics, leading to the **2013 Nobel Prize in Physics** for Peter Higgs and François Englert.

The Higgs boson is fundamental to our understanding of the universe. Without it, the Standard Model would be incomplete, and key particles necessary for forming atoms and molecules—such as quarks and electrons—might not have mass. The discovery of the Higgs boson not only confirmed a decades-old theory but also opened doors to new physics, including possible connections to **dark matter**, **the unification of forces**, and **physics beyond the Standard Model**

3. Discovery and Experimental Confirmation

The search for the Higgs boson culminated in its discovery in 2012 at a mass of approximately 125 GeV. ATLAS and CMS detected its decay into multiple channels, including photon pairs and four-lepton states, with a statistical significance exceeding five standard deviations. The Nobel Prize in Physics was awarded to Higgs and Englert in 2013 for their theoretical contributions.

The discovery of the Higgs boson was a significant milestone in particle physics, confirming the mechanism that gives mass to elementary particles. The ATLAS and CMS experiments at CERN's Large Hadron Collider played crucial roles in this achievement. The detection of the Higgs boson involved observing its decay into various channels, such as photon pairs (H→γγ) and four-lepton states (H→ZZ*→4l), with a statistical significance exceeding five standard deviations [4]. This discovery led to the awarding of the Nobel Prize in Physics to Peter Higgs and François Englert in 2013 for their theoretical contributions to the understanding of mass in subatomic particles.

4. Properties and Interactions

The Higgs boson, discovered in 2012, has been observed decaying into various particles, including fermions and gauge bosons, confirming its role in mass generation. Precision measurements of its couplings to these particles have shown consistency with Standard Model (SM) predictions. For instance, decays into bottom quarks and tau leptons have been observed, providing evidence of the Higgs coupling to fermions [5].

However, despite these confirmations, questions remain regarding potential deviations that could hint at new physics beyond the Standard Model. The current precision of Higgs coupling measurements still allows for possible discrepancies that might suggest new phenomena. For example, certain models predict modifications in Higgs interactions due to mixing effects or loop contributions from new particles, which could lead to observable deviations in coupling strengths.

To explore these possibilities, ongoing and future experiments aim to achieve more precise measurements of the Higgs boson's properties. The High-Luminosity Large Hadron Collider (HL-LHC) and proposed future colliders, such as the Future Circular Collider (FCC), are designed to provide higher precision in Higgs measurements [6]. These efforts are crucial for detecting potential deviations from SM predictions, which could offer insights into new physics.

5. Beyond the Standard Model

The Standard Model (SM) of particle physics, while successful in explaining many fundamental phenomena, leaves several questions unanswered. Various theoretical extensions have been proposed to address these gaps, particularly by modifying the Higgs sector. These extensions often predict new particles and interactions that could provide insights into unresolved issues such as dark matter and the matter–antimatter asymmetry in the universe [7].

5.1 Supersymmetry (SUSY):

Supersymmetry posits a symmetry between fermions and bosons, predicting a partner particle for each SM particle. In the Minimal Supersymmetric Standard Model (MSSM), the Higgs sector is expanded to include two Higgs doublets, resulting in five physical Higgs bosons: two neutral CP-even (h and H), one neutral CP-odd (A), and two charged (H^+ and H^-) bosons [8]. This extended Higgs sector leads to rich phenomenology and offers potential solutions to several SM limitations. Notably, SUSY provides a natural candidate for dark matter: the lightest supersymmetric particle, often a neutralino, which is stable and weakly interacting. Additionally, certain SUSY models can facilitate mechanisms for baryogenesis, potentially explaining the observed matter–antimatter asymmetry in the universe.

5.2 Additional Higgs Bosons:

Beyond SUSY, other theories propose the existence of additional Higgs bosons. For instance, the Two-Higgs-Doublet Model (2HDM) introduces a second Higgs doublet, resulting in a total of five Higgs particles, similar to the MSSM [9]. These models can accommodate phenomena such as CP violation and flavor-changing neutral currents, which are not adequately explained by the SM. The discovery of additional Higgs bosons would have profound implications, potentially shedding light on new physics and offering explanations for dark matter and baryogenesis.

5.3 Composite Higgs Models:

Composite Higgs models propose that the Higgs boson is not an elementary particle but a bound state of more fundamental constituents, analogous to how protons and neutrons are composed of quarks [10]. In these models, the Higgs emerges as a pseudo-Goldstone boson from a new strongly interacting sector. This approach addresses the hierarchy problem by naturally explaining the Higgs boson's relatively light mass compared to the Planck scale. Composite Higgs models often predict the existence of additional resonances and partners of SM particles, which could be probed in high-energy collider experiments.

5.4 Connections to Dark Matter and Baryogenesis:

The Higgs boson may play a pivotal role in addressing two significant cosmological mysteries:

Dark Matter: Certain extensions of the SM suggest that the Higgs boson could interact with dark matter particles. For example, in Higgs-portal models, the Higgs field mediates interactions between SM particles and dark matter candidates. Experiments are actively searching for signs of such interactions, including invisible Higgs decays where the Higgs boson decays into stable dark matter particles that do not interact electromagnetically, making them challenging to detect directly [11].

Baryogenesis: The observed dominance of matter over antimatter in the universe suggests processes that favor the production of baryons over antibaryons, a phenomenon known as baryogenesis [12]. The Higgs field could contribute to such processes. For instance, during the electroweak phase transition in the early universe, interactions involving the Higgs field might have led to conditions necessary for baryogenesis, such as CP violation and departure from thermal equilibrium. Models like electroweak baryogenesis explore these possibilities, proposing mechanisms where the Higgs dynamics facilitate the generation of the baryon asymmetry.

6. Future Research and Collider Experiments

The pursuit of a deeper understanding of the Higgs boson is a central focus in particle physics, driving the development of advanced collider experiments. These future facilities aim to refine measurements of the Higgs boson's properties, including its self-coupling, charge-parity (CP) characteristics, and potential for exotic decays, thereby addressing unresolved questions in fundamental physics.

6.1 High-Luminosity Large Hadron Collider (HL-LHC):

Scheduled to commence operations around 2030, the HL-LHC is an upgrade of the current LHC at CERN. This enhancement will increase the collider's luminosity, allowing for a more substantial accumulation of data. The HL-LHC is expected to produce approximately 15 million Higgs bosons annually, a significant increase from the three million produced in 2017. This abundance of data will enable physicists to study the Higgs boson in greater detail, including its production mechanisms, decay channels, and interactions with other particles. Notably, the HL-LHC will facilitate precise measurements of the Higgs boson's self-coupling, which is crucial for understanding the mechanism of electroweak symmetry breaking and the stability of the universe.

6.2 Future Circular Collider (FCC):

The FCC is a proposed next-generation particle collider that would surpass the capabilities of the HL-LHC. Envisioned as a 91-kilometer circumference circular collider, the FCC aims to achieve collision energies significantly higher than those of the LHC. This ambitious project is expected to provide unique opportunities to explore the Higgs boson's properties with unprecedented precision. By producing a vast number of Higgs bosons, the FCC would allow for detailed studies of rare decay modes and interactions, potentially revealing physics beyond the Standard Model.

6.3 International Linear Collider (ILC):

The ILC is a proposed linear electron-positron collider designed to complement the capabilities of circular colliders like the LHC and FCC [13]. Operating at collision energies tailored for Higgs boson production, the ILC would provide a clean experimental environment to study the Higgs boson's properties with high precision. Its design aims to facilitate detailed investigations into the Higgs boson's interactions, mass generation mechanisms, and potential couplings to new particles, thereby offering insights into unexplored aspects of fundamental physics.

Collectively, these future collider experiments represent a concerted effort by the scientific community to deepen our understanding of the Higgs boson and its role in the fundamental structure of matter. By probing its self-coupling, CP properties, and potential for exotic decays, researchers aim to uncover new physics phenomena that could address longstanding questions about the universe's fundamental forces and constituents.

7. Conclusion

The discovery of the Higgs boson in 2012 marked a pivotal moment in particle physics, confirming the mechanism by which elementary particles acquire mass through interaction with the Higgs field. Subsequent studies have validated the Higgs boson's properties and interactions as consistent with Standard Model predictions. However, the precise nature of the Higgs sector remains an open question, with various theoretical models proposing extensions that could address phenomena unexplained by the Standard Model, such as dark matter and the matter–antimatter asymmetry.

Future collider experiments, including the High-Luminosity Large Hadron Collider (HL-LHC), the proposed Future Circular Collider (FCC), and the International Linear Collider (ILC), aim to explore these possibilities by providing more precise measurements of the Higgs boson's properties. These endeavors are crucial for detecting potential deviations from Standard Model predictions, which could offer insights into new physics.

References

1. Schwarzschild, B. M. (2013). Englert and Higgs are awarded the Nobel Prize in Physics. *Physics Today*, *66*(12), 10-12.
2. Szleper, M. (2014). The Higgs boson and the physics of $ WW $ scattering before and after Higgs discovery. *arXiv preprint arXiv:1412.8367*.

3. Rhodes, C. J. (2013). Large Hadron Collider (LHC). *Science progress*, *96*(1), 95-109.
4. Salvucci, A. (2014). *The Higgs boson in the H→ ZZ (*)→ 4l decay channel with the ATLAS detector at the LHC*. [Sl]:[Sn].
5. CMS collaboration. (2020). Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt {s}= $13 TeV. *arXiv preprint arXiv:2011.03652*.
6. FCC collaboration. (2019). HE-LHC: the high-energy large hadron collider: future circular collider conceptual design report volume 4. *European Physical Journal Special Topics*, *228*(5), 1109-1382.
7. Farnes, J. S. (2018). A unifying theory of dark energy and dark matter: Negative masses and matter creation within a modified ΛCDM framework. *Astronomy & Astrophysics*, *620*, A92.
8. Carena, M., Haber, H. E., Logan, H. E., & Mrenna, S. (2002). Distinguishing a minimal supersymmetric standard model Higgs boson from the SM Higgs boson at a linear collider. *Physical Review D*, *65*(5), 055005.
9. Eriksson, D., Rathsman, J., & Stål, O. (2010). 2HDMC–two-Higgs-doublet model calculator. *Computer Physics Communications*, *181*(1), 189-205.
10. Panico, G., & Wulzer, A. (2011). The discrete composite Higgs model. *Journal of High Energy Physics*, *2011*(9), 1-38.
11. D'Eramo, F. (2007). Dark matter and Higgs boson physics. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, *76*(8), 083522.
12. Riotto, A. (1998). Theories of baryogenesis. *ICTP summer school in high-energy physics and cosmology*, 326-436.
13. Benedikt, M., Blondel, A., Janot, P., Klein, M., Mangano, M., McCullough, M., ... & Zimmermann, F. (2019). Future circular colliders. *Annual Review of Nuclear and Particle Science*, *69*(1), 389-415.