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Prospects of the Higgs boson: an overview

Abstract

The discovery of the Higgs boson at the Large Hadron Collider (LHC) was a significant breakthrough in particle physics. However, many questions about its properties and its place in the universe remain unanswered. This article explores the current state of Higgs boson research, focusing on its mass measurements, interactions, and alignment with the Standard Model. Additionally, it discusses future prospects in Higgs boson studies, including the potential of the High-Luminosity LHC (HL-LHC) to provide more precise data and uncover new insights, as well as the role of upcoming colliders in expanding our understanding of this fundamental particle and potential new physics beyond the Standard Model.

Keywords: Higgs Boson, Standard Model, Large Hadron Collider (LHC).

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Introduction

In the 1960s, the concept of the scalar field and Higgs boson was proposed to introduce Large Lector Bosons while maintaining gauge invariance.[1] Experimental searches at the Large Electron-Positron Collider (LEP) in the following decades helped narrow down the mass of the Higgs boson.[2] Subsequently, the Large Hadron Collider (LHC) confirmed the existence of the Higgs boson with a mass close to 125 GeV.[3] This discovery validated the Standard Model but raised further questions, leading to ongoing research on the properties of the Higgs boson, its role in electroweak symmetry breaking, and potential extensions beyond the Standard Model.[4]

Higgs production at the LHC

a. *Gluon gluon fusion*

Gluon-gluon fusion is a prominent mechanism for producing Higgs bosons within the Large Hadron Collider (LHC). This process involves gluons generating a Higgs boson through a heavy quark loop.[5] It capitalizes on the strong interaction between top quarks and the Higgs field. The cross section of gluon-gluon fusion depends on both the collider's energy and the mass of the Higgs boson, albeit with inherent theoretical uncertainties[6] (Figure 1).

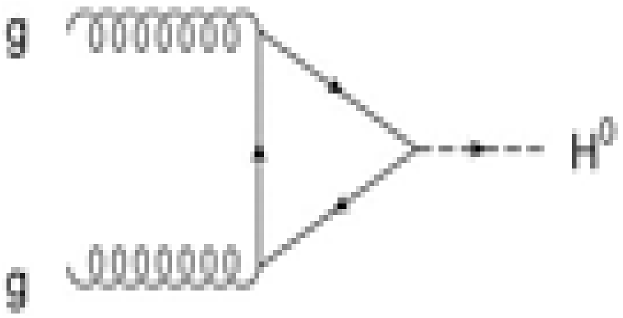

Figure 1 Gluon Gluon Fusions.

b. *Vector-boson fusion*

Vector-boson fusion, a process in which quarks emit vector bosons (W or Z), resulting in the creation of Higgs bosons, serves as a secondary method of production. Although its cross sections are initially lower than those of gluon-gluon fusion, they become comparable at elevated Higgs masses (Figure 2).

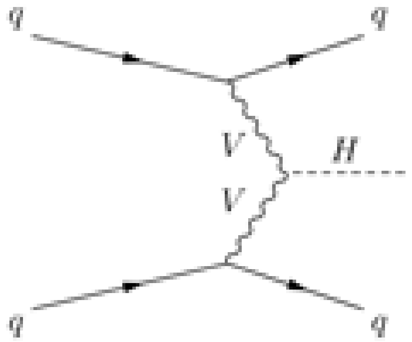

Figure 2 Vector Boson Fusion Production.

c. *Associated VH production*

In the context of associated VH production, a particle with high energy emits a vector boson (W or Z), which subsequently interacts with another particle, resulting in the generation of a Higgs boson. This production mechanism is characterized by lower cross sections when compared to gluon-gluon fusion.

d. *Associated ttH production*

The production of Higgs bosons with two top quarks enables the direct measurement of the top-quark Yukawa coupling.[7] Despite lower cross sections, the detection of this process through top quark pairs contributes significantly to experimental observations[8] (Figures 3&4).

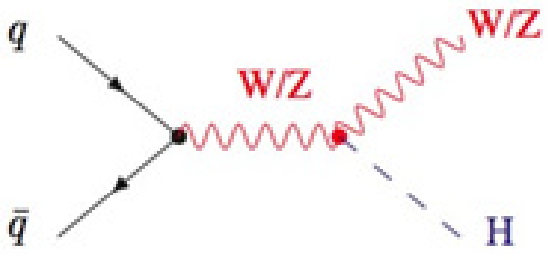

Figure 3 Associated VBF Production.

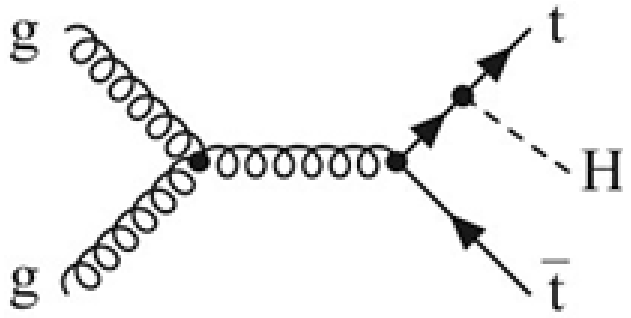

Figure 4 Associated ttH Production.

e. *Higgs boson production in association with a single top quark*

The occurrence of Higgs boson production with a single top quark (tH) is relatively rare but holds the potential to unveil valuable insights regarding the magnitude and sign of the top Yukawa coupling[10] (Figure 5).

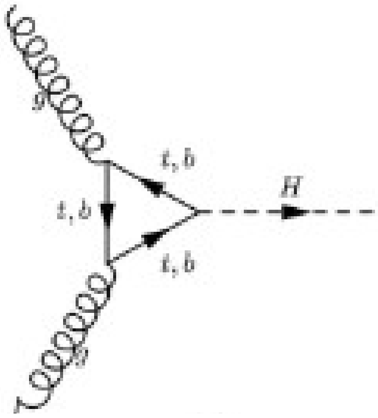

Figure 5 Association with a Single Top Quark.

Decays of Higgs boson

The decay processes of the Higgs boson play a crucial role in comprehending its properties and verifying its adherence to the principles of the Standard Model (SM) in particle physics. These decay mechanisms serve as critical tools for examining its behavior, confirming its anticipated interactions within the SM framework, and providing profound insights into the realm of particle physics.[11]

The complete width of a 125 GeV Standard Model (SM) Higgs boson is $\Gamma_H = 4.07 \times 10^{-3}$ GeV, with a relative uncertainty range of (+4.0 to -3.0)%. Its primary decay channels encompass $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{\square} \rightarrow 4f$, $H \rightarrow WW^{\square} \rightarrow vv^{\square}$, and $H \rightarrow gg$.

f. *Decay width calculations*

The decay width represents the rate at which a particle transitions into other particles and is symbolized by Γ (Gamma).

To determine the decay width Γ across different decay channels, one can employ the amplitude |M| and phase space integrals, as outlined by.[9] The calculation of the decay width proceeds as follows:

For $H \rightarrow ff^-$ (fermion-ant fermion) decay:

$$\Gamma\left(H \rightarrow ff^-\right) = \frac{m_h m_f^2}{8v^2}\left(1 - \frac{4m_f^2}{m_h^2}\right)^{\frac{3}{2}} \tag{1}$$

For $H \rightarrow WW^-$ decay:

$$\Gamma\left(H \rightarrow WW^-\right) = \frac{\alpha m_h^3}{16\pi m_W^2 \sin^2\theta_w}\left(1 - 4\tau_w + 12\tau_w^2\right)\left(1 - 4\tau_z^1\right)^{\frac{1}{2}} \tag{2}$$

Where:

$$\tau_w = \left(\frac{m_h}{m_W}\right)^2, \tau_z = \left(\frac{m_h}{m_Z}\right)^2$$

For $H \rightarrow ZZ^-$ decay:

$$\Gamma\left(H \rightarrow ZZ^-\right) = \frac{\alpha m_h^3}{32\pi m_Z^2 \sin^2\theta_w}\left(1 - 4\tau_z + 12\tau_z^2\right)\left(1 - 4\tau_z^1\right)^{\frac{1}{2}} \tag{3}$$

The decay into gluons, $H \rightarrow gg$, is mediated by heavy quark loops in the SM, with top quarks contributing dominantly:

$$\Gamma\left(H \rightarrow gg\right) = \frac{\alpha m_h}{8\sin^2\theta_\omega}\frac{m_h^2}{m_\omega^2}\frac{\alpha_s^2}{9\pi^2}\left|I_f\left(\tau_q\right)\right|^2 \tag{4}$$

Where $\tau_q = \left(\frac{m_h}{m_q}\right)^2$ and

$$I_f\left(\tau_q\right) = 3\int_0^1\int_0^1 \frac{1 - 4xy}{1 - xy\tau_q}dydx.$$

The decay of the Higgs boson into gluons, primarily mediated by top quark loops, is also explored.[12]

Higgs boson future prospects

The advancement of Higgs boson research hinges on the utilization of cutting-edge particle colliders to delve into unresolved inquiries in physics. Future Circular Colliders play a crucial role in this endeavour, engineered to be adaptable, accurate, and immensely potent, boasting unparalleled energy capabilities.[13]

a. High-Luminosity Large Hadron Collider (HL-LHC): A major upgrade program for the LHC at CERN, aimed at significantly increasing collision rates and allowing for higher precision studies of the Higgs boson and new physics.

b. Electron-Positron Colliders: Such as the proposed Circular Electron-Positron Collider (CEPC), offering cleaner collisions for precise Higgs boson property measurements.

c. Higher Energy Proton-Proton Colliders: Like the Future Circular Collider (FCC), with higher collision energies to probe for new physics beyond the Standard Model.[15]

Precision measurements

The High Luminosity Era of LHC (HL-LHC) will significantly increase collision rates, allowing for precise measurements of the Higgs boson's properties and potential deviations from the Standard Model.[16]

Rare decays:

Recent research uncovers initial evidence of rare Higgs boson decay processes, offering potential indirect evidence of particles beyond the Standard Model.[17] Future experiments like the Belle II experiment and the proposed Future Circular Collider (FCC) will contribute to studying these rare decay channels.[18]

Search for new particles:

Ongoing upgrades to the LHC and future colliders like the HL-LHC offer opportunities to explore new particles and phenomena beyond the Standard Model.[20]

Grand unified equation and higgs mechanism:

Future theoretical and experimental efforts, including precision measurements at high-energy colliders, may provide clues towards formulating a unified equation encompassing all fundamental forces.[19]

Results and discussion

g. Results

i. The current status and properties of the higgs boson

Higgs Boson and Mass Generation: Graphs depicting Higgs boson production cross sections at different energies (Figure 6) highlight mass generation mechanisms.

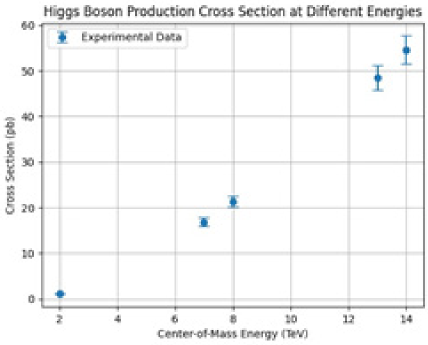

Figure 6 Higgs Boson Production Cross Section at Different Energies.

Experimental confirmation: Empirical evidence, illustrated by the progression of Higgs Boson Mass measurements such as those shown in Figure 7, confirms the accuracy of theoretical forecasts.

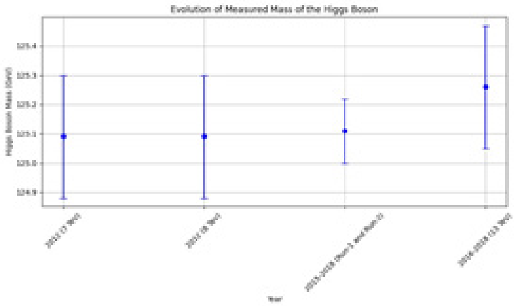

Figure 7 Current Higgs Boson Mass.

Decays of higgs boson

The calculations of decay width depicted in Figure 8 uncover the different decay modes and their contributions to the overall decay width, with the dominant decay of the Higgs Boson being into gluons

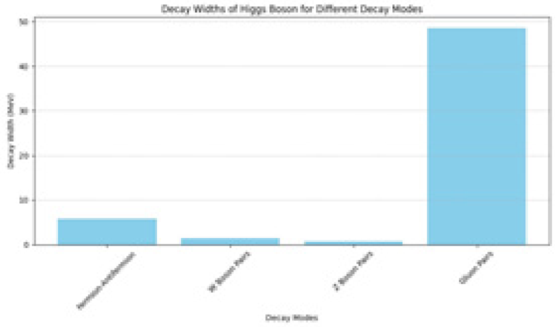

Figure 8 Higgs Boson Decay Width.

ii. Higgs boson properties

Spin, CP properties, and coupling modifiers, illustrated in Figure 9, affirm Standard Model predictions.

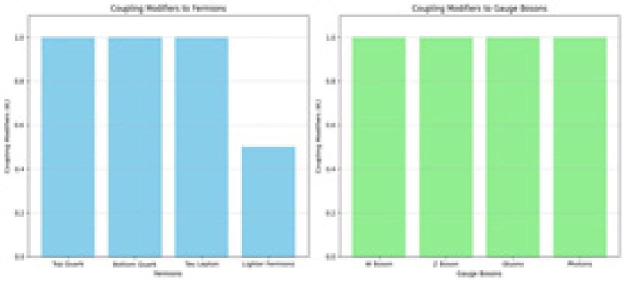

Figure 9 Coupling Modifiers.

iii. Future prospects

Comparison of future collider types (Table 1) outlines avenues for further Higgs boson studies.

Table 1 Comparison of collider types for Higgs measurements

Aspect	HL-LHC	Electro Positron	n-Higher Energy Proton	FCC
Prec. Meas.	✓			
Rare Decays	✓		✓	✓
Search for New Particles	✓	✓	✓	✓
Cosmo. Imp.	✓			
Gravito and Higgs Interactions	ns✓	✓	✓	✓
Grand Unified Equation	✓	✓	✓	✓

h. Discussion

i. Current status

The data presented in figures 9, 8, 7, and 6 exhibit analysis outcomes from experiments conducted at CMS and ATLAS

Laboratories. Recent progress in both experimental accuracy and theoretical comprehension has validated Standard Model projections concerning the behavior of the Higgs boson. Detailed assessments of its characteristics, infrequent decay phenomena, and interactions have deepened our comprehension.

ii. Future prospects

The ambitious strategies set for the High-Luminosity Era of the LHC and proposed colliders such as the Future Circular Collider (FCC) bring advanced capacities for investigating the Higgs boson. These initiatives are geared towards examining theories that go beyond the Standard Model and tackling fundamental queries in particle physics through cooperation and progress in theory. Table 1 outlines a comparison of different types of colliders for studying the Higgs boson.

Conclusion

The exploration of the Higgs boson has bridged theory and experiment, confirming the Standard Model's predictions. Ongoing research with advanced colliders promises deeper insights into

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fundamental physics, showcasing the collaborative efforts driving our understanding of the universe's building blocks.

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