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Feasibility Analysis on Producing Higgs Boson via Particle Collisions

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Abstract:

As a matter of fact, with the rapid development of accelerators techniques in recent years, lots of new particles have been observed contemporarily. Among various observed novel particles nowadays, Higgs Boson production is one of the most attracting one. With this in mind, this study presents feasibility analysis on producing Higgs Boson via particle collisions based on various sets of experiments. To be specific, this study will outline the objective of studying the feasibility of producing HBs via particle collisions, emphasizing the experimental approaches used, theoretical calculations, as well as potential implications. According to the analysis, the current observation results are analyzed and evaluated. Based on the evaluations and estimations, this study presents the current limitations in terms of various fields as well as demonstrate the prospects for further research. Overall, these results shed light on guiding further exploration of Higgs Boson as well as offer a guideline for improvements.

Keywords: Higgs Boson; particle collisions; colliders.

1. Introduction

The Standard Model (SM) of quantum mechanics explains four fundamental forces except gravity and classifies all known basic particles and predicts the behavior of these particles and their interactions through exchange particles known as gauge bosons. While the theory accurately describes phenomena at the subatomic level, it required a mechanism to find out how particles get mass, which led to the proposal of the Higgs field, an essential part of the SM, introduced by physicists Peter Higgs and others in the 1960s [1-3]. The Higgs Boson (HB) is the quantum excitation of the Higgs field. The discovery of the HB was crucial in confirming the mechanism that allows the SM particles, particularly W and Z bosons, to acquire mass. Data from experiments at the Large Hadron Collider (LHC) showed evidence of HB production in high-energy collisions, validating this theory. For instance, in 2012, both the ATLAS and CMS experiments reported detecting a new particle whose mass is approximately 125 GeV, consistent with the prediction of HB in the SM [4].

The HB plays a central role in the process of mass generation via the Higgs mechanism. In the SM, the Higgs field permeates all over the universe, and particles' interaction with this field let them get mass. The intensity of a particle's interaction with this field determines its mass. Particles like photons, which don't interact with the Higgs field, keep being massless, while particles like the W and Z bosons, which interact strongly with the field, acquire significant mass. This mechanism resolves a fundamental problem in particle physics by explaining how the weak force can be short-range despite being mediated by gauge bosons [5]. The discovery of the HB provided strong experimental evidence for this mechanism. Data from the CMS experiment in 2012 revealed that HBs produced via gluon-gluon Fusion (GGF) decayed into photon pairs, with the observed invariant mass peak at around 125 GeV/c², consistent with theoretical predictions. This decay channel, although rare, was crucial because it provided a clean signal for identifying the HB amidst background noise [6].

One primary objective of particle physics experiments is to investigate the feasibility of producing HBs in high-energy collisions, like those occurring at the LHC and other proposed future colliders. At the LHC, HBs are predominantly produced through the process of GGF, where two high-energy gluons from colliding protons interact to generate a HB. This production mechanism has been extensively studied since the Higgs discovery in 2012 [7]. Data from the CMS and ATLAS experiments have provided insights into the cross-section for Higgs production. It's approximately 43 picobarns at an energy of 13 TeV, according to LHC Run 2 results. The experiments also explored alternative generating channels, like vector boson fusion (VBF) and associated production with top quarks or W/Z bosons. These different production modes are crucial for understanding how the HB interacts with other particles in the SM. Although the LHC has successfully produced HBs, further experiments, such as the HL-LHC, aim to produce even larger datasets, improving the precision of these measurements and allowing for the observation of rarer production channels, thus expanding our understanding of the HB.

Producing HBs in particle collisions is only the first step; detecting and measuring their properties presents significant experimental challenges. The HB decays almost immediately after it is produced, leaving behind a set of decay products that must be carefully analyzed to confirm the presence of the Higgs. The most common decay channels, with each channel offering unique challenges in terms of background noise and detection efficiency. For example, the bottom quark decay is common but difficult to detect due to the overwhelming background of b-quark production from other processes. The ATLAS experiment observed this decay with a significance of 5.4 sigma in Run 2 data, but the measurement remains less precise compared to other channels like diphoton. Future colliders aim to improve these precision measurements by providing more data and utilizing more advanced detector technology. The HL-LHC is expected to improve the precision of Higgs coupling measurements by a factor of two, allowing researchers to study rare decays and test the SM with unprecedented accuracy.

2. Descriptions of the HB

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Feasibility of Producing HBs Through Particle Collisions

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3. Experiments Designs

3.1 Methods for Detecting HBs (Decay Channels)

One of the primary decay channels used to detect the HB is the diphoton channel (the Higgs decays into two photons). This channel, despite having a relatively small branching ratio of about 0.23%, is considered a "clean" channel because photons are easily detectable and there are fewer background processes that mimic this signal. Both ATLAS and CMS detected a significant excess of diphoton events in 2012, leading to the initial discovery of the HB.

Another key decay channel is the four-lepton channel HZZ*4l, where the Higgs decays into two Z bosons, each of which further decays into pairs of charged leptons (electrons or muons). This channel has a lower branching ratio but offers a very clear signal due to the clean identification of four leptons. This decay mode was also instrumental in confirming the HB discovery and has since been used to measure its mass with great precision. In addition to these channels, other important decay modes include H 甒 W* (the HB decays into two W bosons), and Hbb (the HB decays into a pair of bottom quarks). This channel, while accounting for about 58% of all Higgs decays, is more challenging to detect due to large background processes that produce similar signatures. Nevertheless, both ATLAS and CMS have succeeded in observing this decay channel, providing further confirmation of the HB's interactions with fermions.

3.2 Challenges in Experimentation

One of the primary challenges in HB detection, and particle physics experiments in general, is dealing with background noise. Proton-proton collisions at the LHC produce a vast number of particles and events in each interaction, most of which are irrelevant to the production and decay of HBs. These background events, originating from SM processes like QCD jets or other hadronic activities, can obscure or mimic the signals physicists are trying to study. For example, in the search for HB decays into two photons, there are significant background processes that produce photon pairs, making it difficult to isolate the Higgs signal. In 2012, during the discovery of the HB, both the ATLAS and CMS experiments had to carefully separate the signal from background noise by using advanced statistical techniques. The signal corresponding to the HB was identified as an excess of events around a specific mass (approximately 125 GeV) compared to the expected background.

To mitigate background noise, experimenters employ various techniques. One method is using strict event selection criteria based on the characteristics of the detected particles. For instance, requiring that photons in the diphoton channel have high transverse momentum and that their trajectories point back to the interaction point helps to reduce the influence of background processes. Machine learning algorithms have also been increasingly used to enhance the sensitivity of searches by classifying events based on complex patterns that distinguish signal from background.

Another approach to improving detection sensitivity is through detector upgrades. As particle collisions at the LHC produce massive amounts of data, detector components like calorimeters, muon chambers, and tracking systems must be continuously improved to handle the higher collision rates and more complex events anticipated in future runs, such as those of the High Luminosity LHC (HL-LHC). These upgrades allow for better spatial and temporal resolution, ensuring that faint signals like the HB can be accurately identified amidst background events.

3.3 Event Reconstruction Techniques

Event reconstruction is a critical part of the experimental process, enabling physicists to deduce the properties of particles like the HB from the data gathered in high-energy collisions. The primary goal of reconstruction is to identify the trajectories, momenta, and types of particles produced in a collision. For HB studies, this is especially important because the Higgs decays almost instantaneously into other particles, and the only evidence of its existence comes from these decay products. For example, in the case of HZZ*4l, (the HB decays into two Z bosons and then decay into four charged leptons) the reconstruction of the lepton tracks and their momenta allows physicists to calculate the invariant mass of the system, which peaks about 125 GeV if a HB was involved in the interaction.

ATLAS and CMS use sophisticated reconstruction algorithms to process the raw data collected from their detectors. For charged particles, the inner tracking system records the curvature of their trajectories in the magnetic field, which provides information about their momentum. For neutral particles, calorimeters measure the energy deposits, and these energy deposits are then associated with particle trajectories using complex pattern recognition algorithms. This multi-layered reconstruction process ensures that even the most elusive decay products of the HB can be identified.

A significant challenge in event reconstruction, particularly in the HL environment of the HL-LHC, is dealing with pile-up, where multiple proton-proton collisions take place in the same bunch crossing. This creates additional particle tracks and energy deposits that can complicate the reconstruction of the event of interest. To address this, advanced pile-up mitigation techniques are used, such as vertex reconstruction algorithms that separate particle tracks originating from different collisions and improved timing measurements to isolate particles from different bunch crossings.

3.4 Luminosity and Data Acquisition Rates

A collider’s luminosity is a measure of its ability to produce particle collisions. Higher luminosity means more collisions per second, which increases the chances of producing rare particles like the HB. For the LHC, achieving high luminosity is crucial for producing enough HBs to study their properties with precision. During Run 2 of the LHC, which operated at 13 TeV, the luminosity reached a peak of around 2×10^{34} $cm^{-2}s^{-1}$, enabling the collection of approximately 150 fb^{-1} of data, a substantial increase over the previous run. This allowed for improved measurements of the HB’s couplings and branching ratios. However, high luminosity also presents challenges. As the number of proton-proton collisions increases, so does the amount of data that needs to be dealt with and stored. The ATLAS and CMS experiments produce massive plenty of data, with each collision producing around 1 MB of raw data, and the LHC produces 40 million collisions per second. Data acquisition systems need to be fast and efficient, capable of selecting the most interesting events in real-time through a process known as triggering. Both ATLAS and CMS employ multi-level trigger systems that quickly analyze collision data to decide whether to record or discard an event. Only a tiny fraction of events, typically a few hundred per second, are saved for further analysis, which requires balancing the need for recording rare signals like those from HB decays with the overwhelming amount of background events.

The HL-LHC will push the limits of these data acquisition systems even further, as it aims to deliver an integrated luminosity of 3000 fb^{-1} over its operational lifetime. This will require significant upgrades to the trigger systems to cope with the higher collision rates while maintaining high efficiency in detecting HB events. The ongoing development of new algorithms and hardware, such as field-programmable gate arrays (FPGAs) and machine learning techniques, will be essential in ensuring that future experiments can handle the increased data load.

3.5 Importance of Precision in Collision Energy and Timing

Precision in both collision energy and timing is crucial for the success of experiments at the LHC and future colliders. The energy of the proton beams determines the types of particles that can be produced, with higher energy levels enabling the creation of more massive particles. For the LHC, operating at 13 TeV allows for the production of HBs through multiple mechanisms, such as GGF and vbf. Achieving and maintaining this energy with high precision is vital to ensure that the collider operates at its maximum potential, and any deviations in energy could affect the accuracy of experimental results. In addition to energy precision, timing plays a significant role in classifying particles and their interactions. The timing of particle collisions, along with the time at which decay products reach the detectors, is critical for reconstructing events and distinguishing between particles produced in different collisions. For example, in detecting the HB through its decay into two photons, precise timing helps in reducing background noise from other photon-producing processes. Upgrades to the timing systems in ATLAS and CMS will allow for time resolutions on the order of tens of picoseconds, providing better separation of events in HL environments, like those expected at the HL-LHC.

In conclusion, precision in both energy and timing is essential for the success of HB experiments. Ensuring that the LHC and its detectors operate at optimal levels of precision will allow for more accurate measurements of HB properties, improving our understanding of this fundamental particle and its role in the universe.

4. Higgs Production Cross Sections

In particle physics, the production cross section is a measure of the probability that a particular process will emerge when particles collide. For the HB, the production cross section refers to the likelihood that it will be created in a high-energy collision, such as those occurring at the LHC. The cross section is typically expressed in terms of barns (b), where 1 barn is equivalent to 10^{24} cm^2. In the context of Higgs production, picobarns (pb) and femtobarns (fb) are commonly used to describe the cross-section values. Understanding the production cross sections for various Higgs production mechanisms is crucial for testing the predictions of the SM and for exploring potential new physics beyond the SM. The main generation mechanisms for the HB at the LHC are GGF (GGF), vbf, and associated production with a W or Z boson (Higgs-strahlung). Additionally, associated production with top quarks (ttH) plays a critical role in probing the Higgs-top quark interaction. Each of these production mechanisms has its own unique cross section, which depends on the center-of-mass energy of the proton-proton collisions and the mass of the HB.

The GGF (GGF) mechanism is the dominant production mode for the HB at the LHC. In this process, two gluons (the force carriers of the strong interaction) interact via a loop of virtual heavy quarks (predominantly top quarks) to produce a HB. Despite the fact that gluons are massless and do not couple directly to the HB, the interaction is mediated by the presence of virtual top quarks, which couple strongly to both gluons and the HB. This makes GGF the most probable generation mode for the HB, contributing to about 87% of all HB production events at the LHC. At a center-of-mass energy of 13 TeV, which was the energy used in Run 2 of the LHC, the total Higgs production cross section via GGF for a Higgs mass of 125 GeV is approximately 48.6 pb. This cross-section value is derived from next-to-next-to-leading order quantum chromodynamics calculations, which take into account the complex nature of the strong force interactions at high energies. These theoretical predictions are based on the work of researchers in quantum field theory who have developed increasingly sophisticated models to describe the interactions between gluons, quarks, and the HB.

Experimental data from the ATLAS and CMS experiments have confirmed the dominance of the GGF mechanism in Higgs production. For example, in the 2018 analysis of data collected during Run 2, both ATLAS and CMS measured the GGF production cross section with an uncertainty of around 10%, consistent with the theoretical predictions. This agreement between experiment and theory is a strong validation of the SM's description of the Higgs mechanism and its interaction with the strong force.

The VBF process is the second-generation mechanism for the HB at the LHC, accounting for around 7% of the total Higgs production cross section. In this process, two quarks from the colliding protons exchange virtual W or Z bosons, which then fuse to produce a HB. The two quarks typically remain in the final state and are detected as two high-energy jets in the forward regions of the detector, providing a distinctive signature for VBF events.

In the Higgs-strahlung process, the HB is generated in association with a W or Z boson. This process, also known as associated vector boson production (WH or ZH production), accounts for about 5% of the total Higgs production at the LHC. The final state of this process is characterized by the presence of a W or Z boson decaying into leptons, along with the decay products of the HB. This makes the process particularly useful for studying the HB's interactions with weak gauge bosons. The associated production of the HB with a pair of top quarks (ttH production) is one of the most important production modes for probing the HB's interaction with the top quark, the heaviest known particle in the SM. This process has a much smaller cross section than GGF or VBF, accounting for less than 1% of the total Higgs production at the LHC. However, it provides direct access to the Higgs-top quark coupling, which is crucial for understanding the role of the HB in mass generation. The results are listed in Table 1 [10].

Table 1. Summary of different decay channels.

HB Decay Channel	Significance in CMS Experiment	Significance in ATLAS Experiment	Expected Rate (%)
γγ (Photon-Photon)	4.9σ	4.5σ	0.2%
ZZ (Electron and Muon Pairs)	6.0σ	6.1σ	2.7%
WW (Lepton and Neutrino)	2.8σ	2.9σ	21%
$b\bar{b}$ (Bottom Quark Pairs)	2.1σ	2.3σ	56%
ττ (Lepton Pairs)	2.3σ	2.1σ	6.3%

5. Conclusion

In summary, the measurement of HB generation cross sections at the LHC is a vital part of testing the predictions of the SM and exploring new physics beyond the SM. The dominant production mechanism, GGF, has been studied extensively and is well understood, while the observation of other production mechanisms, such as vbf, Higgs-strahlung, and ttH production, provides important insights into the HB's interactions with other particles. Future upgrades to the LHC, such as the High Luminosity LHC (HL-LHC), will allow for even more precise measurements of these cross sections, helping to further refine our comprehension of the HB and its role in the universe. The production of HBs in particle collisions is governed by the energy available in the system, which must exceed a certain threshold to generate the particle. The HB's mass is approximately 125 GeV (giga-electron volts), meaning that the center-of-mass energy of the colliding particles must be sufficiently high to create a HB in the final state. In practice, however, the actual energy required is much higher, since the production mechanism typically involves intermediate particles or complex processes that require substantial energy beyond just the HB's mass. The LHC is currently the most powerful particle accelerator in the world and has been instrumental in advancing our comprehension of the HB. The LHC's ability to accelerate protons to nearly the speed of light and collide them at unprecedented energy levels has made it possible to observe rare processes such as HB production. However, collider efficiency is not just a matter of energy levels—it also depends on other factors such as luminosity, data collection rates, and the ability to reduce background noise. Luminosity is a measure of how many particles can be collided per second in a given area, and higher luminosity corresponds to more collision events, increasing the chances of observing rare phenomena like HB production. Since its upgrade, the LHC has achieved a peak luminosity of around 2×10^{34} $cm^{-2}s^{-1}$, which has greatly improved the precision of Higgs measurements. The High Luminosity LHC (HL-LHC), scheduled to come online in the 2030s, aims to increase this luminosity by a factor of 10, making it possible to collect far more data on HB interactions and improve the statistical significance of measurements.

One of the key challenges for collider efficiency is background noise, which refers to all the particles and events generated in collisions that are not of interest but can obscure or mimic the signals physicists are trying to study. In HB production, background noise from processes such as top quark pair production or other SM processes can interfere with the clean identification of Higgs decay channels. Sophisticated event reconstruction techniques are employed by the ATLAS and CMS collaborations to distinguish genuine Higgs events from background, using machine learning algorithms, advanced calorimetry, and precise timing detectors. These techniques have enabled the successful observation of Higgs decays into bottom quark pair, w boson pair, and other channels, despite the challenging environment of high-energy collisions. The efficiency of data acquisition and analysis is another critical component of collider operations. During a collision event, the detectors at the LHC record vast amounts of data in real time, much of which is irrelevant to the specific physics questions being investigated. To cope with this, ATLAS and CMS use a trigger system that automatically selects the most interesting events for further analysis, discarding the majority of the data to focus computational resources on potentially significant collisions. The efficiency of this trigger system is vital for maximizing the amount of usable data collected per run.

While the LHC has proven to be an extraordinarily successful machine, it is not without limitations. One of the major challenges faced by current collider technology is the difficulty in reaching even higher energy scales. The LHC's energy is limited by the strength of its superconducting magnets, which guide the protons around its 27-kilometer ring. To achieve significantly higher energies, stronger magnetic fields are required, which

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will necessitate the development of new superconducting materials and technologies. Moreover, the LHC's design is optimized for proton-proton collisions, which are useful for studying a wide range of particle physics phenomena but are less suited for certain precision measurements, such as those involving the HB's couplings to fermions. Future colliders, such as the International Linear Collider (ILC), which would collide electrons and positrons, are expected to provide cleaner environments for these precision studies. Electron-positron collisions are free from the proton structure complications (such as parton distribution functions) that affect the interpretation of proton-proton collisions, making it easier to isolate and study specific processes involving the HB. Additionally, the cost and complexity of building and operating high-energy colliders present significant practical limitations. The LHC, for example, took several decades to design, construct, and bring online, with costs running into the billions of dollars. Future colliders will require even larger investments in both time and money, as well as international collaboration on an unprecedented scale.

References

[1] Bezrukov F, Shaposhnikov M. The Standard Model Higgs boson as the inflaton. Physics Letters B, 2008, 659(3): 703-706.

[2] Bezrukov F L, Magnin A, Shaposhnikov M. Standard Model Higgs boson mass from inflation. Physics Letters B, 2009, 675(1): 88-92.

[3] Schmaltz M. Physics beyond the standard model (theory): Introducing the little Higgs. Nuclear Physics B-Proceedings Supplements, 2003, 117: 40-49.

[4] Cms Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. arXiv preprint arXiv:1207.7235, 2012.

[5] CERN's HB Discovery Portal. Retrieved from: https://home.cern/science/physics/higgs-boson.

[6] Duffell D. Making Music with Samples: Tips, Techniques & 600+ Ready-to-use Samples. Hal Leonard Corporation, 2005.

[7] Okamura K. Atlas of Science Collaboration, 1971–2020. SN Computer Science, 2024, 5(5): 640.

[8] CMS Collaboration on HB:CMS Portal. Retrieved from: https://cms.cern/higgs.

[9] Aad G, Abajyan T, Abbott B, et al. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Physics Letters B, 2012, 716(1): 1-29.

[10] Atlas C, Rossi E. Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at$\sqrt{}$ S= 7 and 8 TeV in the ATLAS experiment. THE EUROPEAN PHYSICAL JOURNAL. C, PARTICLES AND FIELDS, 2016, 76(1): 1-51.