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Dark Matter in the Higgs Decay Channel: A Review of Past Experiments and Future Prospects

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Abstract. The Higgs boson provides an important opportunity to investigate possible connections between the Standard Model and the dark sector. In particular, Higgs-portal models propose that dark matter may interact with ordinary matter through the Higgs field, motivating experimental searches for invisible and exotic Higgs decays. This review examines the theoretical foundations and experimental progress of these searches, with emphasis on results from the ATLAS and CMS collaborations at the Large Hadron Collider (LHC). Existing measurements have placed increasingly stringent constraints on the invisible branching fraction of the Higgs boson, restricting parts of the parameter space of several Higgs-portal dark matter models. The review also discusses effective field theory descriptions, theoretical constraints from unitarity and positivity, and exotic decay signatures involving hidden-sector particles and displaced vertices. In addition, it evaluates the prospects of future electron–positron colliders, including the Circular Electron Positron Collider (CEPC) and the Future Circular Collider in its electron–positron configuration (FCC-ee). Techniques such as recoil-mass reconstruction may enable more precise measurements of invisible Higgs decays, while improved detector capabilities could extend searches for long-lived particles. These developments will help test Higgs-portal scenarios and further constrain possible interactions between the visible and dark sectors.

Keywords: dark matter, Higgs boson, Higgs portal, invisible decay, collider physics

1. Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012 provided important confirmation of the Higgs mechanism. Since the Higgs field is responsible for generating the masses of fundamental particles, the Higgs boson has also attracted considerable interest in dark matter research. Its possible connection to particles outside the Standard Model makes it a promising way to investigate the largely unknown dark sector.

One of the main approaches is to search for invisible Higgs decays. In these processes, the Higgs boson decays into particles that do not leave a direct signal in the detector and could, in some models, be dark matter particles. Recent combined results from the Compact Muon Solenoid (CMS) experiment place an upper limit of about 15% on the Higgs branching fraction to invisible final states at 95% confidence level [1]. Such limits provide constraints on Higgs-portal models, in which

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dark matter interacts with the Higgs field. Collider measurements can therefore be considered alongside astrophysical observations and experiments when testing possible scenarios.

This paper reviews the experimental searches that have been carried out so far, discusses the main theoretical developments, and considers how future experiments could improve the sensitivity to Higgs-portal dark matter. Particular attention is given to proposed lepton colliders, including the Circular Electron Positron Collider (CEPC) and the Future Circular Collider in its electron-positron configuration (FCC-ee). The relatively clean collision environment at these machines, together with methods such as recoil-mass reconstruction, could provide a sensitive probe of invisible Higgs decays. Other possibilities, including exotic signatures such as displaced vertices, are also relevant when considering future detector capabilities and searches for physics beyond the Standard Model.

In doing so, the purpose of this review is to bring together the current experimental and theoretical picture of Higgs-portal dark matter, while also identifying the main limitations of existing searches. It further examines how future collider experiments may extend these studies and improve our ability to explore the dark sector through Higgs boson decays.

2. Literature review

Higgs-portal models are one possible way of connecting dark matter with the Standard Model. In this type of model, the Higgs boson mediates the interaction between the visible and dark sectors. The dark matter particle is not necessarily the same in every model. It can be a scalar, fermion, or vector particle, depending on the assumptions made about the dark sector [2].

EFT is useful for describing these interactions without specifying the full high-energy theory. It has been compared with several UV models, including singlet-doublet fermions and dark SU(2)/SU(3) gauge extensions. The comparisons in [2] show that the EFT description remains reasonable for a relatively broad range of masses and couplings. This is one reason why EFT is useful for interpreting LHC searches for invisible Higgs decays [2].

The allowed parameter space is not completely unrestricted. Unitarity gives one of the important theoretical constraints. In Walker's study, partial-wave unitarity leads to scales between roughly 2.4 and 14.2 TeV, depending on which annihilation channel is considered [3]. Positivity bounds give another restriction. For dimension-8 derivative interactions, Kim, Lee, and Yamashita found that these bounds become more restrictive when combined with collider and dark matter detection results [4].

Another possibility is to formulate the Higgs portal with nonlinear electroweak symmetry breaking. The interaction terms are different from those in the linear case, and this can affect several predictions. The expected dark matter density, collider production rate, and detection signals can all change depending on the form of the interactions [5].

Invisible decays are not the only Higgs signatures worth considering. The Higgs could also decay into particles from a hidden sector. Some of these particles may be long-lived and decay at a measurable distance from the original collision point. A displaced vertex can then appear in the detector. Finding these events is more complicated than a standard invisible-decay search and requires dedicated reconstruction techniques [6].

The Higgs portal can also be involved in non-thermal dark matter production. In some cases, the dark matter abundance can be generated without the standard thermal freeze-out picture. The same models can allow an invisible Higgs branching ratio of roughly 10%, particularly for MeV-scale dark matter. This makes them relevant to future Higgs-factory experiments [7].

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3. Main body

3.1. General techniques for invisible Higgs detection

Detecting invisible decays of the Higgs boson, such as into dark matter particles, critically relies on the clean experimental environment provided by future electron–positron colliders, which is contrasted with the more complex backgrounds of hadron colliders.

3.1.1. Role of hadron colliders

Hadron colliders, like the Large Hadron Collider (LHC), have been crucial in Higgs physics and initial searches for invisible Higgs decays. However, their complex environment, characterized by high backgrounds from jets and pile-up, limits the precision of these searches. Although techniques such as vector-boson fusion are employed, the hadronic environment makes achieving clean signal identification challenging [8].

3.1.2. Recoil mass method at e^+e^- colliders

The recoil mass method is a powerful technique in particle physics for detecting particles that escape direct observation. Its efficacy was first successfully demonstrated at the Large Electron–Positron (LEP) collider. During LEP operations, the method was crucial in studying the Z boson through the process $e^+e^- \rightarrow Z\gamma$. By precisely measuring the four-momentum of the photon, researchers could reconstruct the invariant mass of the recoiling Z boson system. This allowed high-precision measurements of the Z boson's properties, including its mass and width, and was particularly effective in studying Z decays into invisible neutrinos ($Z \rightarrow \nu\bar{\nu}$) [9].

The method is now planned to play a central role in Higgs physics and is based on conservation of four-momentum. In the case of the Higgsstrahlung process ($e^+e^- \rightarrow ZH$), an electron and a positron annihilate to produce a Z boson and a Higgs boson. The four-momentum of each particle is a vector containing its energy and three-dimensional momentum.

The key to the method is that the total four-momentum of the system is conserved before and after the collision. Since the initial four-momentum of the electron–positron pair is precisely known, the four-momentum of the Higgs boson can be determined by subtracting the measured four-momentum of the Z boson from the total initial four-momentum. The invariant mass of the Higgs boson is then calculated from its reconstructed four-momentum. This value, known as the recoil mass, is independent of how the Higgs boson subsequently decays [10].

The recoil mass is defined as

$$M_{recoil}^2 = s + M_Z^2 - 2\sqrt{s}E_Z \tag{1}$$

where M_{recoil} is the reconstructed mass of the Higgs boson, s is the square of the center-of-mass energy of the e^+e^- collision, M_Z is the known mass of the Z boson, and E_Z is the measured energy of the Z boson.

This method can be used to search for invisible Higgs decays predicted in several extensions of the Standard Model. One of its main advantages is that the Higgs production rate can be measured without knowing how the Higgs decays. In practice, the accuracy of the recoil-mass measurement depends mainly on how well the detector measures the energy and momentum of the particles produced in the Z decay.

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3.1.3. Precision at CEPC and FCC-ee

The CEPC and FCC-ee are planned to operate at energies around 250 GeV, close to the point where Higgs production through $e^+e^- \rightarrow ZH$ is largest [11]. This makes them particularly suitable for recoil-mass studies. For CEPC, simulations indicate that an invisible Higgs branching ratio of about 0.3% could be reached [12]. This would provide much better sensitivity than current searches at the LHC.

3.1.4. Advantages over hadron machines

There is a practical difference between e^+e^- and hadron colliders in this type of search. At the LHC, the large amount of activity from proton collisions makes it harder to identify events with missing particles. Electron–positron collisions are much cleaner, so the recoil against the Z boson can be reconstructed with less background. This is particularly useful when looking for a small invisible Higgs decay rate [13].

The main differences between hadron and lepton colliders, particularly their experimental environments and suitability for invisible Higgs decay searches, are summarized in Table 1.

Table 1. Comparison of hadron colliders and lepton colliders

Hadron collider	Lepton collider
Collides hadrons, such as protons, at very high energies.	Collides leptons, specifically electrons and positrons, at high energies.
Features a complex environment with high backgrounds from jets and pile-up.	Offers a cleaner experimental environment, allowing more precise measurements.
Can reach higher collision energies, crucial for discovery of new heavy particles.	A clean environment and precise measurements allow greater sensitivity to rare and invisible decay channels.
Instrumental in the discovery of the Higgs boson and initial searches for invisible Higgs decays.	Expected to serve as a Higgs factory, providing high precision in Higgs branching-ratio measurements.

3.2. Advantages over hadron machines

After the Higgs boson was discovered in 2012, both ATLAS and CMS began searching for possible invisible decays. Different Higgs production processes have been used for this purpose, including vector-boson fusion, ZH production, gluon–gluon fusion with initial-state radiation, and off-shell Higgs production.

In the Standard Model, invisible decays are dominated by $H \rightarrow ZZ^* \rightarrow 4\nu$ with a predicted branching ratio of approximately 0.1%. Hence, a substantial invisible signal would indicate the presence of novel physics, for instance, Higgs-portal dark matter [14].

One of the most sensitive ATLAS analyses targeted VBF production using the full Run 2 dataset (139 fb^{-1} at $\sqrt{s}$ = 13 TeV). This search set an observed upper limit of 14.5% (expected 10.3%) on the invisible Higgs branching fraction at a 95% confidence level, as documented in the ATLAS report on invisible Higgs searches [15].

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CMS obtained a similar constraint using 2016 data (observed limit approximately 33%), and a combination of all LHC data (Runs 1 and 2) reduced this to approximately 19% (expected 15%). ATLAS later combined results from VBF, ZH, and other production modes, achieving an observed upper limit of 10.7% (expected 7.7%) on BR(H → invisible) [14, 15]. These constraints, consistent across both experiments, already exclude wide regions of simple Higgs-portal dark-matter models for dark-matter masses below approximately 60 GeV.

The principal differences between Standard Model Higgs boson decays and exotic Higgs decays are summarized in Table 2, including their possible final states and experimental signatures.

Table 2. Comparison of Standard Model Higgs boson decays and exotic Higgs decays

Standard Model Higgs boson decays	Exotic Higgs decays
Decays into Standard Model particles, such as bottom quarks, W and Z bosons, gluons, and tau leptons.	Decays into non-Standard-Model or hidden-sector particles, potentially producing invisible, displaced, or semi-visible signatures.
Decay modes and branching fractions are predicted by the Standard Model.	Possible decay modes and branching fractions depend on the new particles and their interactions.
Searches test whether measured decay rates agree with Standard Model predictions.	Searches may require dedicated techniques, including missing-momentum analysis or displaced-vertex reconstruction.

3.3. Rare and exotic Higgs decays

Invisible Higgs decays are mainly discussed in connection with dark matter, but they are not the only possibility. The Higgs could also decay into particles from a hidden sector. Depending on their properties, these particles may produce prompt, displaced, or semi-visible signals.

One example is the decay $h \to aa$, where a is a lighter pseudoscalar particle. The pseudoscalars can then decay into Standard Model particles. Experimental searches have considered several final states, including $\ell\,\ell\,bb$ and $\tau\tau bb$. The full Run 2 dataset has been used to set limits on the corresponding branching fractions, including the μμbb channel [16].

Long-lived particles are another important case. If the Higgs decays to an LLP, the particle can travel some distance before it decays. This can result in a displaced vertex rather than a decay occurring close to the primary interaction point. The sensitivity of these searches depends on the LLP mass and lifetime, but they cover regions of parameter space that are not necessarily accessible through invisible-decay searches. In searches for Higgs decays into lightweight scalar particles, no significant deviation from the expected background was observed, and upper limits were set on the possible decay rate [17].

So far, the different experimental searches have not found a statistically significant signal of an exotic Higgs decay. They have nevertheless placed limits on many BSM models. Further data from the High-Luminosity LHC will improve these limits and allow some of the less explored regions of parameter space to be tested.

3.4. Future prospects and experimental directions

Future collider experiments will provide better sensitivity to both invisible and exotic Higgs decays. The main improvement will come from larger datasets and, in the case of lepton colliders, a cleaner

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collision environment. These measurements can be used to look for small Higgs branching fractions that are difficult to study at the LHC.

3.4.1. Lepton Higgs factories

At future e^+e^- Higgs factories, the recoil-mass technique in $e^+e^- \rightarrow ZH$ events can be used to measure invisible Higgs decays without reconstructing the Higgs decay itself. The same machines could also search for other exotic signatures, including semi-visible decays and long-lived particles. Depending on the final state and detector performance, studies have estimated sensitivities between about 10^{-3} and 10^{-5} in branching fraction [18].

3.4.2. Detector and machine design

Detector performance will be important for reaching these sensitivities. Good lepton momentum resolution and calorimetry are needed for recoil-mass measurements and for reducing backgrounds that can look like missing energy. Searches for displaced particles have additional requirements. Precise vertex detectors, sufficient tracker coverage, and timing information can help determine where and when a long-lived particle decays [5, 18].

3.4.3. Beam polarization

Beam polarization is another option for future linear colliders such as the International Linear Collider (ILC). The spins of the incoming electrons and positrons can be controlled to some extent, which changes the rates of different processes. Choosing suitable beam polarizations can increase the signal relative to some backgrounds and can also provide more information for precision measurements. At a center-of-mass energy of 250 GeV, studies indicate that polarization can give Higgs-coupling precision comparable to an unpolarized machine with substantially higher luminosity.

3.4.4. Theoretical–experimental synergy

Theory and experiment are closely connected in Higgs-portal searches. EFTs and other theoretical models give possible descriptions of invisible and exotic Higgs decays. Constraints such as unitarity and positivity can then be used to remove parts of the parameter space that are not theoretically consistent.

Experimental results provide another constraint. As the limits on the invisible Higgs branching ratio become stronger, some Higgs-portal models become increasingly restricted. If a deviation from the Standard Model is eventually observed, the measurements can also be used to determine which types of models are consistent with the result [2].

Model-reinterpretation tools are useful for this purpose. They allow experimental measurements, such as production cross sections and decay limits, to be compared with the parameters of specific Higgs-portal models. In this way, a limit on an observable quantity can be translated into limits on couplings, masses, or mediator properties.

Theory can also affect experimental design. For example, studies of long-lived particles have motivated improvements in detector timing and proposals for dedicated LLP detectors [6]. Work on nonlinear Higgs portals also motivates accurate Higgs-coupling measurements, which are one of the main reasons for developing high-precision lepton colliders [11].

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The relationship works in both directions. Theoretical models suggest which signatures may be worth searching for, while experimental results show which parts of those models remain possible. Future measurements will therefore help narrow down the range of viable Higgs-portal scenarios.

3.4.5. Practical outlook

Short Term (approximately 5 Years): The HL-LHC is expected to improve the limits on invisible Higgs decays to the few-percent level. The upgraded detectors will also improve searches for displaced and long-lived particles.

Medium Term (approximately 5–15 Years): Future machines such as FCC-ee and CEPC could reach per-mille sensitivity to invisible Higgs decays. Depending on the final state, exotic decay searches could reach branching fractions in the range of 10^{-3} to 10^{-5} [18].

Long Term: Results from the HL-LHC and future lepton colliders can be combined to test Higgs-portal models over a wider range of parameters. If no signal is found, the allowed parameter space will become smaller. If an excess is observed, measurements from both types of collider will help determine whether it is consistent with a Higgs connection to the dark or hidden sector.

4. Conclusion

The searches for invisible and exotic Higgs decays have placed strong limits on possible connections between the Higgs boson and the dark sector. ATLAS and CMS have improved the limits on invisible Higgs decays considerably over the past decade, which rules out parts of the simplest Higgs-portal models. Other searches, including those for displaced vertices and semi-visible final states, cover additional possibilities. So far, however, none of these searches has produced a statistically significant deviation from the Standard Model.

Future colliders should improve the situation further. CEPC, FCC-ee, and the ILC are expected to measure invisible Higgs decays with much higher precision than the LHC. Some studies predict sensitivity at the per-mille level for invisible decays, while searches for particular exotic final states could reach branching fractions of about 10^{-3} to 10^{-5} [18]. Detector improvements and new analysis methods, including machine-learning techniques, may also help with these searches.

There is also a theoretical side to the problem. Unitarity and positivity bounds restrict the parameters that can be used in Higgs-portal models, while different dark matter production mechanisms lead to additional constraints. These results are useful when interpreting collider limits and deciding which parts of the parameter space are still worth studying.

Overall, Higgs decays remain a useful way of looking for physics connected to the dark sector. A future observation of an invisible or exotic decay would provide direct evidence for physics beyond the Standard Model. If no such signal is found, more precise measurements will continue to reduce the range of possible Higgs-portal models. Both outcomes will provide useful information about possible connections between the Higgs sector and dark matter.

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