Higgs Boson: 10 Years Turning the Possible into the Known

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Abstract

The first decade of $H^0(125)$ measurements has been bountiful, allowing us to explore multiple facets of this unique scalar particle. Most measurements to date have been found to be compatible with expectations derived from the Standard Model of particle physics. Nevertheless, for all the possibilities that have been verified to exist in nature, much remains to be uncovered, different interactions await being measured, and other extensions and possibilities are still to be tested. In this article, we review a few of the experimental measurements of the $H^0(125)$ particle performed in the first decade after its discovery, including its spin-parity characterization, some of its rare and challenging decays, searches for other Higgs bosons, and first strides toward measuring the $H^0(125)$ self-interaction from the study of the production of $H^0(125)$ pairs. The role of improvements in analysis techniques and detector technologies in making these possible is highlighted throughout.

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1. INTRODUCTION

The Standard Model of particle physics (SM) is a self-consistent theory describing elementary particles and their interactions that was developed in the last century and became complete after the discovery of the $H^0(125)$ particle in 2012. Completeness here is to be understood as the fact that all particles predicted by the SM now have experimentally identified candidates in nature. In this sense, the continued use of the word "Model" in "Standard Model" is symptomatic of the decades-long timescale involved in establishing the SM as the standard theory.

The SM has had a phenomenal success in describing a plethora of experimental measurements during the last 60 years, has guided experimental activity in the search for new particles and phenomena in that period. This has established the SM as the theoretical bedrock against which any new theory must also be gauged against. At the same time, the SM predictions are a powerful "null hypothesis" against which measurements can also be equally gauged in the search for phenomena beyond the SM.

For all the SM successes, it remains an incomplete theory given the presence in nature of phenomena for which the SM makes no allowance, such as nonzero neutrino masses or dark matter, should the latter be made of particles. Another aspect of the SM is that as a mathematical construction it can be seen as the marriage of a very elegant structure describing the electroweak interaction, the masses of gauge bosons, and the strong force with a near-arbitrary set of Yukawa interactions related to fermion masses. Of course, as far as one would like to have a single theory of physics that can explain the behavior of matter at both the smallest and largest physical scales, the SM is completely mute as concerns gravitation. In spite of decades of work dedicated to this matter, a quantum description of gravity continues to elude physicists, making it impossible for gravity to join the three fundamental forces described by the quantum field theory framework that underpins the SM.

Many extensions to the SM have been, and continue to be, proposed to address the SM's shortcomings. Some extensions try to achieve simpler descriptions of the interactions present in nature and answer questions opened by the fact that there are three families of fermions, related to there being nine arbitrary masses, and corresponding Yukawa interactions, which must be measured experimentally and account for almost half of the SM's free parameters. Other extensions target specific phenomena directly, like the fact that at least two neutrinos have been measured to have nonzero mass. Both types of extension deserve experimental exploration, even if we have clearly entered an era of data-driven exploration, which contrasts with the theory-driven (SM-driven) exploration of the last century and has some people in the field adapting to this change in gears.

Having $H^0(125)$ accessible to experiments and ready for empirical scrutiny has opened a whole new area of experimental physics. Measurements of the properties of the $H^0(125)$ particle itself and of its interactions with other known particles have been the object of vigorous efforts by experimentalists and theorists alike in the last decade, pushing the boundaries of the possible into the known.

This effort is far from over, and in this article, we will focus on a set of measurements and searches that have challenged experimentalists to improve their detectors and analysis techniques, and pushed theorists to refine their calculations. This contribution complements the companion article [1] in this issue.

2. 2017: "HALF-TIME" EXPECTATIONS

Five years after the 2012 discovery, with the LHC well into Run 2, a few aspects of the $H^0(125)$ particle were known, starting from having established its existence in 2012, elucidating some of its spin-parity properties mostly in interactions with other bosons soon thereafter, and performing quite precise and accurate measurements of its mass. All these were possible thanks to the data taken in the LHC Run 1 with proton-proton collisions at an energy of 7 TeV and 8 TeV.

For Run 2, not only did the LHC increase the collision rate by up to a factor of three, the collision energy was also increased to 13 TeV. These two improvements opened up new frontiers to experimental exploration, and in 2017, the $H^0(125)$ decay to τ leptons was established independently in CMS and in ATLAS. This was the opening salvo of a detailed exploration of the interactions of the $H^0(125)$ particle with fermions, both leptons and quarks.

Moreover, the LHC long shutdown preceding Run 2 provided the experimental collaborations with an opportunity to refresh their detectors, including the installation of new hardware. These upgrades had been in the works since before the $H^0(125)$ discovery and the abilities that they afforded the experiments also played a critical role in the reach of Run 2 analyses.

In the SM, the fermionic sector of Higgs interactions is exceedingly simple [2] and, at the same time, one of the largest sources of arbitrariness in the theory, as each fermion mass contributes one free parameter to the SM. The mass of nine fermions in the SM[1] is predicted to be proportional to the intensity of their interaction with the Higgs boson and make up almost half of the free parameters in the SM.

In 2017, it was clear that the next steps in exploring the nature of the $H^0(125)$ particle were to challenge SM predictions concerning interactions with fermions, and moving in the direction of exploring rarer and rarer decay channels, as discussed in Section 4. At the same time, with the much larger data sets at larger collisions energies and better detectors, the community's eyes were also set in extending searches for other scalar states, discussed in Section 5, and in going after the SM predictions related to the Higgs self-interaction, namely via the production of pairs of $H^0(125)$, the latest results of which are discussed in Section 6. Before looking at those measurements and searches, we discuss one foundational aspect in the characterization of any new particle, the study of its quantum numbers in Section 3.

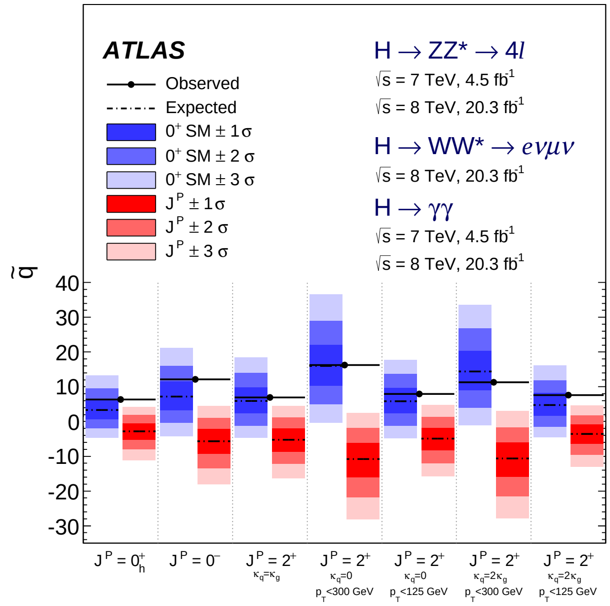


FIGURE 1: Hypothesis tests between the SM $J^P = 0^+$ hypothesis (blue) and alternative J^P assignments (red). The combined analysis of LHC Run 1 data (black) from four-lepton and diphoton decays consistently favors the SM assignment for the $H^0(125)$ particle against multiple alternatives. Figure reproduced from [4]. Similar results were obtained by CMS [5].

3. $H^0(125)$ QUANTUM NUMBERS

The single most distinguishing feature of the SM Higgs boson is that it is predicted to be a $J^{CP} = 0^{++}$ scalar particle with no spin and even parity. All other elementary bosons are vector bosons with $J = 1$ and $H^0(125)$ is the only known fundamental scalar, $J = 0$, particle [3].

Early spin-parity studies of the $H^0(125)$ particle involved interactions with (virtual) bosons and decays to four leptons and two photons. Those studies allowed us to rule out many possibilities soon after the discovery, including ruling out $J = 1$ and $J = 2$.

The determination of the CP characteristics remains a very active field of research, since the observed $H^0(125)$ could be a mixture of CP-even and CP-odd components. Much has been achieved in this front, including recent results in interactions of the $H^0(125)$ with fermions, adding to the knowledge gained from interactions with bosons.

3.1. J^{CP} in Interactions with Bosons

Observing the decay into two photons excluded the spin-one $J = 1$ hypothesis, leaving the possibility of $J = 0$ or $J = 2$ open. To resolve this ambiguity, it was crucial to explore the trove of information that is encoded in events where the $H^0(125)$ decays into four leptons, especially four charged leptons that are all precisely tracked and measured in the detectors. Measuring the four charged leptons allows us to determine the polarization of the virtual particles, like Z^0 bosons, involved in the decay.

Early studies using only the LHC Run 1 dataset strongly disfavored all $J \neq 0$ hypotheses [4, 5]. This is illustrated in Figure 1, where the results of a combined analysis of three decay channels are presented.

Moreover, the CP-even hypothesis was generally favored, especially when considered in alternative to a pure CP-odd pseudoscalar hypothesis, as shown in the second column of Figure 1.

3.2. J^{CP} in Interactions with Fermions

With the seven times larger Run 2 data set, it has become possible to probe the CP properties of the $H^0(125)$ in decays into τ leptons. While the polarization of the τ leptons cannot be easily reconstructed in full, there is enough information available such that angular distributions of the decay products can discriminate between different CP hypotheses and mixtures thereof.

The latest results [6, 7] are shown in Figure 2 and are provided in terms of a mixing angle ϕ_τ, where $\phi_\tau = 0$ corresponds to the pure CP-even (SM) hypothesis, $\phi_\tau = \pi/2$ corresponds to the pure CP-odd hypothesis, and other values correspond to mixtures of the two pure states.

The results show that within the present precision, the data are compatible with the SM prediction of a CP-even particle,

[1] In the SM, neutrinos are massless. This has been refuted experimentally and several extensions to the SM have been proposed to accommodate the extraordinarily small masses of neutrinos.

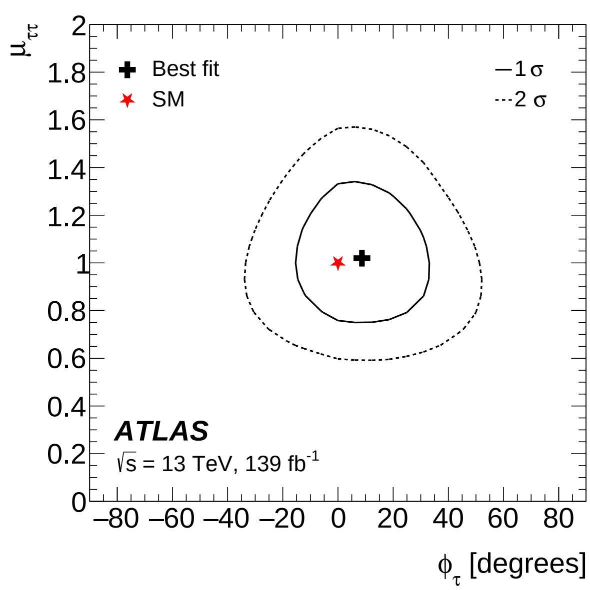


FIGURE 2: Results of the full Run 2 analysis of the CP properties in $H^0(125)$ decays into τ-lepton pairs. The likelihood of the data (black cross and contours) shows that the data is compatible with the SM hypothesis (red star) of a $\phi_\tau = 0$, CP-even, particle. Figure reproduced from [6]. Similar results were obtained by CMS [7].

disfavor the pure CP-odd hypothesis, and leave plenty of room to explore the allowed regions.

4. RARE DECAYS

Using the power of the full LHC Run 2 dataset has allowed us to experimentally probe predictions for some rare Higgs bosons decays such as the direct decays to muons and charm quarks, and loop-mediated decays such as $H^0(125) \to Z\gamma$.

The vastly increased Run 2 dataset also allowed us to substantially extend the range of searches for invisible $H^0(125)$ decays, where the SM predicts a minuscule probability of decay into four neutrinos of about 0.1%. Incidentally, invisible Higgs decays connect to direct searches for dark matter and this $H^0(125) \to 4\nu$ decay can be considered the Higgs physics analog of the “neutrino floor” in direct dark matter searches.

All these searches for rare decays are bolstered by the new and refreshed detectors for the LHC Run 2, and the use of associated production topologies to tease out the $H^0(125)$ decay signals from exceedingly large contributions from other processes. As an example of the use of associated production topologies, Figure 3 shows data from a collision event selected in a search for $H^0(125) \to \mu\mu$ targeting the vector-boson fusion production mode where an associated pair of forward jets of particles is produced together with the Higgs boson.

By requiring additional reconstructed objects in an event, the use of this and other associated production modes, like WH, ZH, and $t\bar{t}H$, drastically improves the relative amount of $H^0(125)$ decay events with respect to all other events passing the selection criteria.

The increase in the signal-over-background ratio afforded by these topologies is crucial to explore rare decay modes

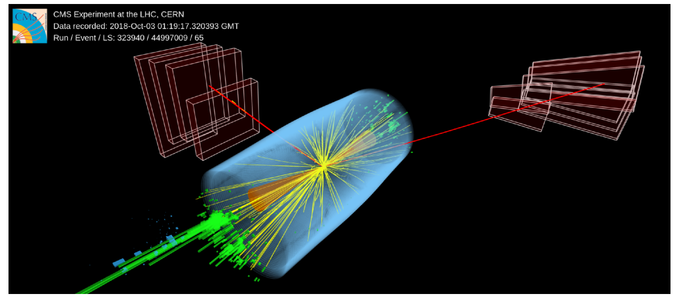


FIGURE 3: An event from the search for the $H^0(125) \to \mu\mu$ decay (muon tracks in red) where the presence of a reconstructed pair of forward jets (golden cones) is required. This requirement rejects many events where the two muons are not from an $H^0(125)$ decay, substantially increasing the signal-to-background ratio. Exploiting this and other associated production modes is crucial to study rare decay modes of the $H^0(125)$ particle. Figure reproduced from [8]. Comparable topologies were explored by ATLAS [9].

and represents a major fraction of the experimental effort in $H^0(125)$ studies since 2017, and in allowing us to exploit the larger datasets at a higher energy that open these rare decays up to experimental access in the first place.

4.1. *Reaching out to the Second Generation*

At the end of 2018, there was direct evidence of the coupling of the $H^0(125)$ particle to top quarks, bottom quarks, and τ leptons. These are all third-generation fermions, with relatively large masses—the top quark is the heaviest elementary particle known to date—and, consequently, large couplings to the Higgs boson according to the SM.

As the next logical step, the focus turned to the second generation that features charm quarks, strange quarks, and muons. Of these three, it is remarkable that there is presently excellent sensitivity to the SM prediction for the interaction of the Higgs boson with charm quarks and muons. Searching for the $H^0(125) \to \mu\mu$ and $H^0(125) \to c\bar{c}$ decays requires very different analyses and several machine learning and data analysis techniques have been invented and employed for the first time, with fantastic results, also making use of the detector upgrades for Run 2.

4.1.1. $H^0(125) \to \mu\mu$

Muons generate very clean signatures in high-energy particle detectors such as CMS or ATLAS, allowing for triggering, identification, and reconstruction with high efficiency and high purity. Because of this, the efficiency to retain $H^0(125) \to \mu\mu$ decay events is very high, and the challenge is foremost to reject the much larger irreducible contribution from Drell-Yan events, $\gamma^\star \to \mu\mu$.

There are two prongs in rejecting background events in this analysis. The first step is to target the associated production of $H^0(125)$ together with other particles. This is achieved by requiring additional reconstructed particles in the event, splitting the full event sample into smaller samples for the different topologies. The second step segregates events within the same topology into different categories with different expected

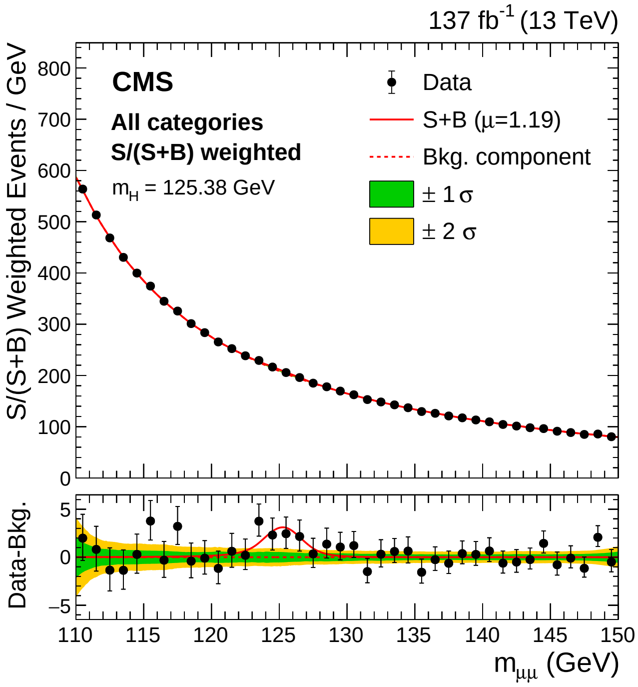


FIGURE 4: Visualization summarizing the data from twenty different event categories used in an $H^0(125) \to \mu\mu$ search where a peaking feature in the $m_{\mu\mu}$ distribution can be glimpsed around the $H^0(125)$ mass value. Each entry in this histogram is weighted by the expected signal-to-background ratio in that event's category. Figure reproduced from [8]. Comparable data were obtained by ATLAS [9].

values of signal-over-background, e.g., by estimating the mass resolution on an event-by-event basis.

In this way, more than a dozen categories can be defined [9, 8], and an invariant mass distribution from the full Run 2 data set is shown in Figure 4. A peaking feature in the data can be seen rising around the $H^0(125)$ mass. The analysis of the data shows that feature to be compatible with the SM prediction within uncertainties that range from 35 % to 50 %, dominated by statistical uncertainties, a present limitation driven by the size of the available data set.

The analysis of these LHC data with muon pairs extends by more than one order of magnitude the range of masses for which the Yukawa coupling mechanism has been probed, as can be appreciated from Figure 5.

4.1.2. $H^0(125) \to c\bar{c}$

Like muons, charm quarks are also second-generation particles. Unlike muons, charm quarks produce jets of particles from their hadronization, including charmed mesons that are relatively long-lived. In this respect, charm quarks are similar to bottom quarks, though the hadronization of the latter leads to hadrons with longer lifetimes.

The challenge in searching for $H^0(125) \to c\bar{c}$ decays is therefore twofold. On the one hand, we are talking about objects harder to experimentally differentiate; harder than the longer-lived b-quark products, and much harder than muons that leave clear-cut signatures in the detector. Adding to that, because the c-quark mass is more than four times smaller than

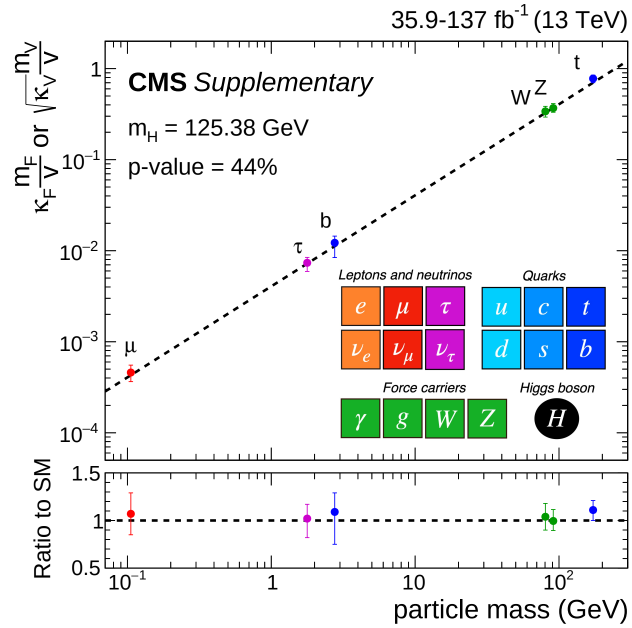


FIGURE 5: Comparison between particle masses and their interaction strength with the $H^0(125)$ particle, where the dashed line represents the prediction for the SM Higgs boson. The $H^0(125) \to \mu\mu$ analysis result extends the range of probed particle masses by one order of magnitude. Figure reproduced from [8]. Comparable results were obtained by ATLAS [9].

the b-quark mass, the SM predicts the $H^0(125) \to c\bar{c}$ branching fraction to be about 3%, some 20 times smaller than the $H^0(125) \to b\bar{b}$ branching fraction.

Rising up to these challenges were the Run 2 detector upgrades that paved the way to employ deep learning algorithms, trained using modern machine learning techniques, and used to discriminate, identify, and select charm-quark decays in collision events. These algorithms were first used to substantially improve the identification of b-quark products and are indissociable from the upgraded pixel detectors installed during the LHC long shutdown ending in 2015. These Run 2 detector upgrades specifically targeted the improvement of b-quark identification abilities and were a major success in that respect.

Another aspect that has come into play concerns developments in the area of boosted-object reconstruction. While in $H^0(125) \to \mu\mu$ decays much of the sensitivity has come from targeting multiple associated production mechanism, in searching for $H^0(125) \to c\bar{c}$ decays, the starting point is WH and ZH production, since the more abundant gluon-fusion and vector-boson fusion mechanisms together with the $H^0(125) \to c\bar{c}$ decay cannot be distinguished from QCD multijet production that is much more abundant and mundane. Originally developed for searches for heavy particles beyond the SM, where the decay products are highly boosted and therefore close-by in a narrow cone, these boosted-object reconstruction techniques quickly found application in top quark and Higgs boson measurements and searches. The main advantage with these techniques is that there is more information to be exploited when identifying a pair of objects because of correlations between the two objects in the pair—that in the $H^0(125) \to c\bar{c}$ case is the

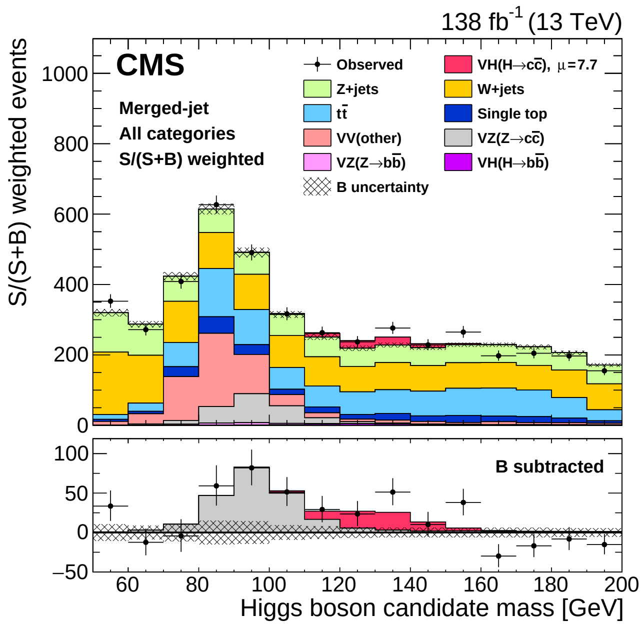


FIGURE 6: Summary visualization of the full Run 2 data used in a $H^0(125) \to c\bar{c}$ search. Peaking features in the candidate mass distribution can be seen around the Z boson mass value and $H^0(125)$ mass values, as expected in the SM. Each entry in this histogram is weighted by the expected signal-to-background ratio of that event. Figure reproduced from [11]. Similar results were obtained by ATLAS [10].

$c\bar{c}$ pair—when compared to the case where one individually treats, and separately identifies, each of the two c-quark jets.

With the performance afforded by these developments, the LHC experiments have been able to reach a sensitivity to the $H^0(125) \to c\bar{c}$ decay under 10 times the SM expectation, setting stringent limits on the possible values for the coupling between the $H^0(125)$ particle and charm quarks [10, 11].

Almost as a by-product, the searches for $H^0(125) \to c\bar{c}$ have enabled the observation of $Z \to c\bar{c}$ decays for the first time at a hadron collider, exploiting WZ and ZZ associated production topologies [11].

The results of this type of search are shown in Figure 6, where the $Z \to c\bar{c}$ and $H^0(125) \to c\bar{c}$ contributions are individuated.

It is a testament to the continued improvement of the detectors and reconstruction software techniques alike that such results are available within 10 years of the $H^0(125)$ discovery, especially when considering the hadron collider environment. These results with charm quarks were certainly not expected by this author to be available within the first decade of experimental exploration of the $H^0(125)$ particle's properties.

4.2. $H^0(125) \to Z\gamma$

In the SM, the $\mu\mu$ and $c\bar{c}$ decays are tree-level direct interactions with the Higgs boson that are rare because of the small mass of those second-generation particles. The decay into $Z\gamma$ is mediated by loops of virtual particles and that is what, in the SM, suppresses the branching fraction for this decay, making it also a rare decay.

Loop-mediated decays, like those into two photons or into $Z\gamma$, are therefore sensitive to the effect of new, heavy, particles that provide virtual contributions to the total decay amplitude, which increase or decrease the $H^0(125) \to Z\gamma$ branching fraction with respect to the SM expectation, depending on whether they interfere constructively or destructively with the SM contributions, respectively.

The search for the $H^0(125) \to Z\gamma$ decay can be framed as part of a "family" of searches and measurements, inaugurated by the diphoton decay analysis, which also includes the $H^0(125) \to \mu\mu$ analysis. This family of analyses shares a few experimental features that are discussed in the following.

The first common feature is that the $H^0(125)$ decays into experimentally clean objects, namely, charged leptons and photons. In the $Z\gamma$ case, the final state is $\ell^+\ell^-\gamma$, where the electron or muon pair is required to be loosely compatible with resulting from the decay of a Z^0 boson, or at least have a large invariant mass. The decay signature also translates to the expected signal having a rather good mass resolution, of the order of 1%. The understanding of the detector and experimental control over the reconstruction of the properties of charged leptons and photons further provides an accurate estimate of the per-object energy resolution. This level of understanding translates to being able, on an event-by-event basis, to estimate the mass resolution of the $H^0(125)$ candidate, allowing us to split the data samples into categories with different signal-to-background ratios, purely on the basis of separating the best resolution events from those with poorer resolution.

The second commonality in this family of analyses is the relatively large and smooth background against which the signal is measured. The smoothness of the background processes all taken together is of critical importance as it allows for a data-driven modelling using sidebands in the mass distributions, $m_{\ell^+\ell^-\gamma}$ in the $H^0(125) \to Z\gamma$ search.

The latest results from the $H^0(125) \to Z\gamma$ searches are very promising with an observed significance in either experiment close to the evidence threshold of 3 standard deviations against there being no such decay [12, 13]. Given this state of affairs, a combined LHC analysis can be expected in the short term. This level of evidence is illustrated in Figure 7, where a peaking feature in data at the expected $H^0(125)$ mass rises above the smooth background.

4.3. *Invisible* $H^0(125)$ *Decays*

Given how different couplings between the $H^0(125)$ particle and other known fermions and bosons have been established, it is conceivable that the $H^0(125)$ particle also interacts with particles that have not yet been discovered. One particular puzzle that new elementary particles could help resolve is that of dark matter, a substance about five times more abundant than the regular matter that all known elementary particles can account for. If part of the mass of dark matter particles is due to interactions with the $H^0(125)$, then the $H^0(125)$ particle would be expected to decay into dark matter particles, depending on the mass of the latter.

Dark matter particles are not expected to leave visible traces in the detectors, leading to so-called "invisible" decay signatures. To search for these, associated production modes are also employed as in the case of rare decays. That said, unlike the search for rare decays, the additional objects are not used to increase the signal-over-background ratio, but rather to provide

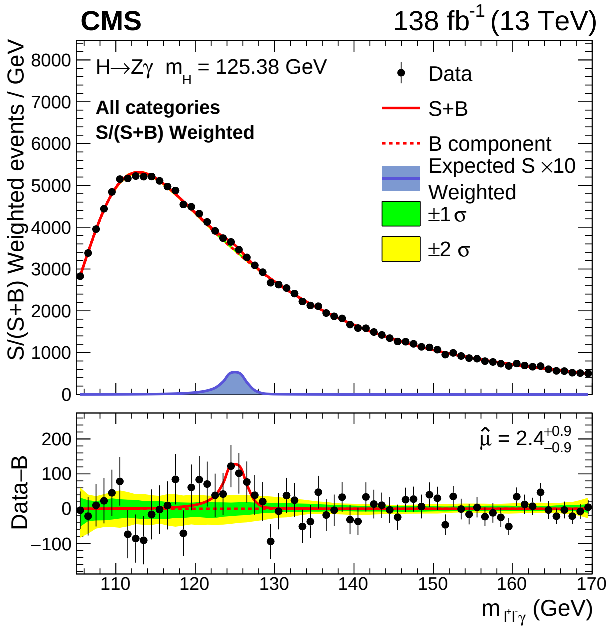


FIGURE 7: Summary visualization of the full Run 2 data used in a $H^0(125) \to Z\gamma$ search across eight different event categories targeting different production processes and expected mass resolutions. A prominent peaking feature in the candidate mass distribution can be seen around the $H^0(125)$ mass value, where it would be expected. Each entry in this histogram is weighted by the expected signal-to-background ratio of that event's category. Figure reproduced from [13]. Comparable results were obtained by ATLAS [12].

a visible signature against which the presence of an invisible decay can be searched for.

Through a series of ever-improving results, the sensitivity of the LHC experiments presently sets upper limits on $B_{H\to\text{inv}}$, the possible invisible branching fraction of the $H^0(125)$ particle, of about 10% [14, 15]. While these limits are still far from 0.1%, the SM prediction for the $H^0(125)$ decay into four neutrinos, a large swathe of dark matter candidate models has been tested, and the results are competitive with the results from experiments dedicated to direct dark matter searches as illustrated in Figure 8.

5. OTHER HIGGS BOSONS

The SM is minimal as far as its Higgs sector goes, with only one doublet and predicting one single scalar neutral particle. It is easy to supplement the SM Higgs sector with more doublets and/or singlets, giving rise to a plethora of models with rich phenomenology. We are not going to list all such models but rather focus on two experimental aspects that have impacted the measurements and searches performed in the area of extended Higgs sectors during the first ten years of Higgs physics at the LHC [16, 17, 18].

The first set of measurements that plays an important role in constraining these models beyond the SM is direct searches, dedicated to specific production and decay signatures. These searches usually target heavy neutral or charged scalar particles and their predicted interactions involving the $H^0(125)$

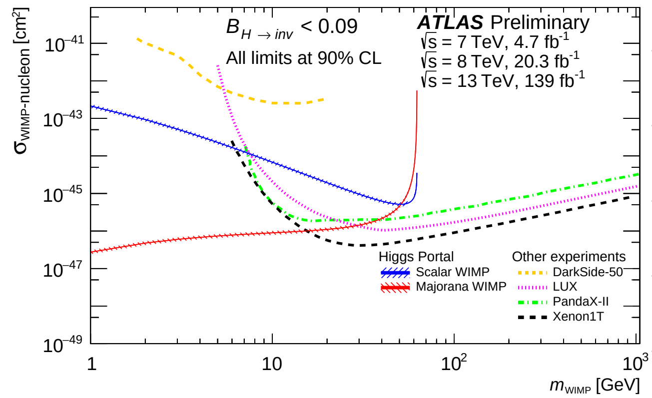


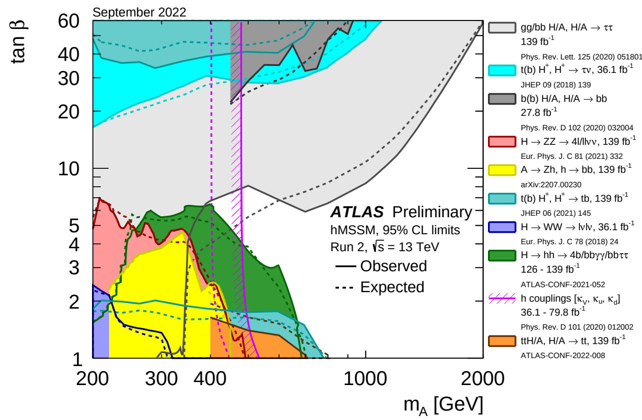
FIGURE 8: Results from interpreting a 90% confidence level upper limit on $B_{H\to\text{inv}}$, the $H^0(125)$ invisible decay fraction, of 9% in the context of two dark matter models (continuous lines). These results can be compared with direct search results from dedicated experiments (broken lines) and show a complementarity of the two types of experiment in terms of the ranges probed for the dark matter particle mass hypothesis, m_{WIMP}. Measurements of the $H^0(125)$ particle provide competitive bounds for dark matter particle values of the order of dozens of GeV, i.e., below half the $H^0(125)$ mass. Figure reproduced from [14]. Similar results were obtained by CMS [15].

or heavy fermions, like the top quark, the tau lepton, or the beauty quark. Other searches for light scalars typically exploit clean dilepton signatures. The phenomenology is very rich, and both aspects of the production and the decay of such additional scalars are considered to provide the best sensitivity to predictions from those models.

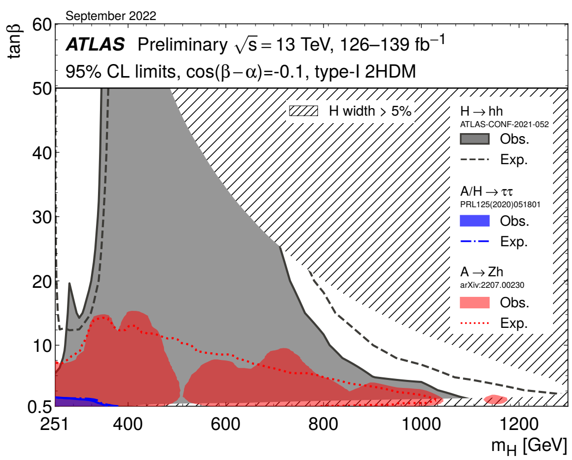
The results of experimental searches in two particular models with extended Higgs sectors are presented in Figure 9. These two models are to be taken purely as examples, a small sample of the experimental searches for light and heavy elementary scalars.

For the hMSSM model, we can see in Figure 9(a) how an array of nine dedicated searches (filled areas) provides extensive and complementary sensitivity and coverage in terms of that model's parameters. The second set of measurements are those of the $H^0(125)$ particle. Since the $H^0(125)$ particle must be part of the Higgs sector that those models extend beyond the SM, measurements of $H^0(125)$ properties also place limits on the parameters of many of those models. For the same example hMSSM model, the constraints on that model's parameters from $H^0(125)$ measurements are represented by the purple lines in Figure 9(a). Given how the $H^0(125)$ properties have been, to date and within uncertainties, compatible with the SM predictions, models predicting large deviations from the SM are strongly constrained by $H^0(125)$ measurements.

For a different example model, a type-I 2HDM, Figure 9(b) shows the results from three direct searches. In these searches, the $H^0(125)$ particle is assumed to be the lightest neutral scalar in the 2HDM and H represents the heavy neutral scalar predicted in 2HDM models. The hatched region in Figure 9(b) denotes the set of parameter values for which the 2HDM predicts that the H boson does not have a narrow width, an assumption used in this set of experimental searches. Therefore, no conclusions can be drawn concerning the parameters in the hatched



(a)



(b)

FIGURE 9: Summary of parameter regions excluded for two proposed extensions of the Standard Model Higgs sector, the hMSSM model (a) and a type-I 2HDM model (b). These extensions are used only for illustration as multiple other SM extensions have been scrutinized. The ability to exclude different regions comes from executing a broad array of dedicated searches for additional Higgs particles (solid areas) and from interpreting $H^0(125)$ measurements (purple lines in (a)) within that model. Figures reproduced from [16]. Comparable results were obtained by CMS [17, 18].

region until such a time as when new analyses independent of that assumption are devised.

Even after vigorous efforts, large regions of many models remain compatible with the data and future measurements and searches are needed to understand if the Higgs sector in nature is as parsimonious as the minimal solution predicted by the SM. While in principle there is no theoretical reason for it, in the end nature reigns supreme.

6. $H^0(125)$ PAIR PRODUCTION

The measurement of the production of pairs of $H^0(125)$ boson opens a direct window to study the $H^0(125)$ self-coupling. In the SM, this kind of coupling is a unique feature of the Higgs boson because while gluons interact with each other, each carries a different $SU(3)$ color charge such that a gluon does not interact with itself, but rather with other gluons. For a scalar particle like the Higgs boson, there is no charge involved and its trilinear and quartic interactions genuinely involve the same particle at the corresponding vertices.

The SM Higgs sector is minimalist including only one scalar doublet. The corresponding scalar field potential is equally frugal, $V(H) = -m^2 H^\dagger H + \lambda(H^\dagger H)^2$. This potential leads to clear-cut predictions for the couplings of the physical Higgs particle trilinear (h^3) and quartic (h^4) interactions:

$$V(h) = \frac{1}{2}m_h^2 h^2 + \sqrt{\frac{\lambda}{2}}m_h h^3 + \frac{\lambda}{4}h^4, \tag{1}$$

where $\lambda = m_h^2/(2v^2)$ is the self-interaction strength, m_h is the Higgs boson mass, and v is the vacuum expectation value. Since both m_h and v have been experimentally measured to be about 125 GeV and 246 GeV, respectively, it follows that within the SM framework, all the measurements needed to fully predict the shape of the potential and the self-interaction strength are already in place. In particular, in the SM, the trilinear and quartic couplings are also fully determined from the measurements of m_h and v.

While the SM is spartan, the scalar field potential in nature can assume a number of different shapes [19]. Both the fact that the SM provides an exquisitely simple and predictive framework, where both the trilinear and quartic couplings are fully determined by m_h and v, as well as the fact that alternatives abound provide strong motivation to experimentally scrutinize processes sensitive to the self-interaction, be it direct measurements of processes with multiple $H^0(125)$ bosons in the final state, or precision measurements of processes to which $H^0(125)$-boson loops contribute substantially.

Important efforts have been aimed at the direct study of the self-coupling from measuring $H^0(125)$ pair production. The main production processes being targeted are illustrated in Figure 10 and include gluon-fusion (Figures 10(a) and 10(b)) and vector-boson fusion (VBF, Figures 10(c) to 10(e)). It can be seen that the different (interfering) diagrams are sensitive to different combinations of Higgs boson couplings, as denoted by the coupling modifiers κ_i of SM interaction vertices i. In the κ-framework, these modifiers are multiplicative, such that $\kappa_i = 1$ corresponds to the SM.

At the LHC, the gluon-fusion production cross-section is predicted to be about 20 times larger than that of VBF production. Even that being the case, the development of dedicated VBF searches has played a crucial qualitative role in the search for the production of $H^0(125)$ pairs, and the latest results from the LHC experiments for these searches are nothing short of spectacular [21, 20].

Similar to what happened with the 2012 results for single $H^0(125)$ production, the searches of 2022 for $H^0(125)$ pairs focus on the two largest production processes and make use of the power of exploring multiple decay channels.

Given that the largest $H^0(125)$ branching fraction is into $b\bar{b}$ pairs, the most sensitive channels with the LHC Run 2 dataset are in the searches for $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, and $b\bar{b}b\bar{b}$, each contributing similar fractions of the sensitivity to $H^0(125)$ pair production as depicted in Figure 11.

The widespread use of b-quark tagging highlights how detector upgrades, like the pixel tracker detector upgrade for Run

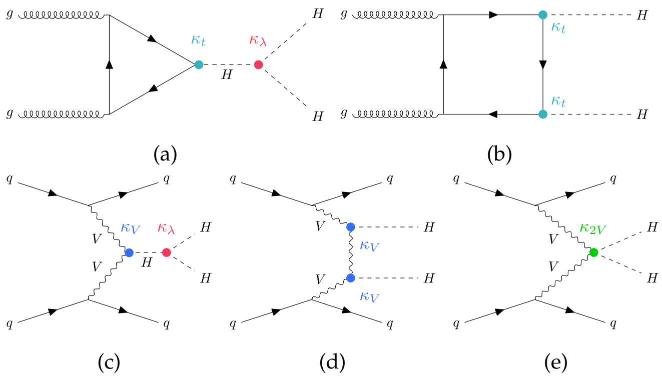


FIGURE 10: Leading-order Feynman diagrams for the production of $H^0(125)$ boson pairs at the LHC via gluon-fusion ((a) and (b)) and vector-boson fusion ((c) to (e)). Each diagram highlights the Higgs boson interactions involved and the corresponding κ_i coupling modifiers that the diagram is sensitive to, where $\kappa_i = 1$ corresponds to the SM prediction and λ refers to the Higgs trilinear coupling. As a consequence, we can see that gluon-fusion yields sensitivity to κ_t and κ_λ, while vector-boson fusion provides sensitivity to κ_V, κ_λ, and κ_{2V}, the last of which refers to the SM 4-point $WWHH$ and $ZZHH$ interactions between two vector bosons and two Higgs bosons. Illustrations reproduced from [20].

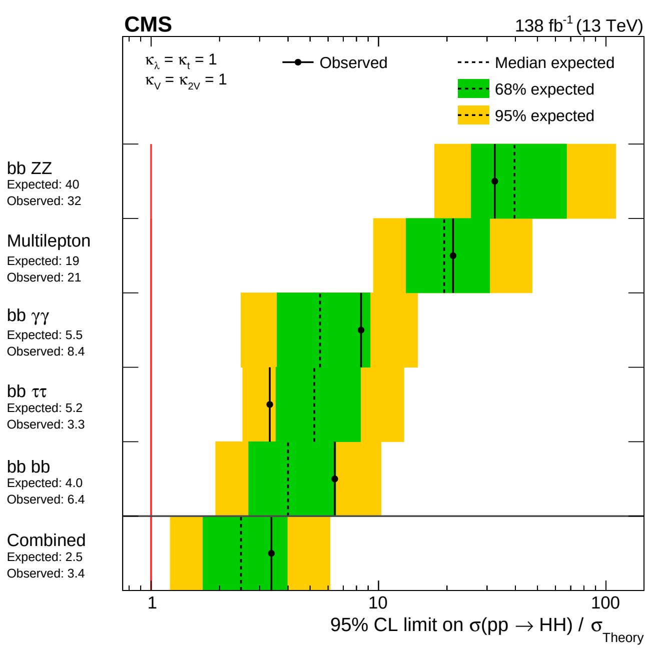


FIGURE 11: Results from searches for $H^0(125)$ pair production in individual channels and their combined analysis. The $b\bar{b}\,b\bar{b}$, $b\bar{b}\,\tau\tau$, and $b\bar{b}\,\gamma\gamma$ analyses have similar sensitivities and all strongly contribute to the combined analysis results that set limits on $H^0(125)$ pair production of a few times the SM expectation. These results can be translated to limits on κ_λ, the $H^0(125)$ boson self-coupling modifier, of $-1 < \kappa_\lambda < 6$ at the 95% confidence level. Figure reproduced from [21]. Comparable results were obtained by ATLAS [20].

2, are of seminal importance. In the pixel detector case it directly improves the efficiency with which the experiments can identify b-quarks, ϵ_b. Considering the impact on the analyses shown in Figure 11, $b\bar{b}\,\tau\tau$ and $b\bar{b}\,\gamma\gamma$ are affected by a factor proportional to ϵ_b^2, and $b\bar{b}\,b\bar{b}$ is affected by a factor proportional to ϵ_b^4. Therefore, even small improvements to ϵ_b can have large consequences on the experimental sensitivity and the reach of the analyses.

While $b\bar{b}\,b\bar{b}$, $b\bar{b}\,\tau\tau$, and $b\bar{b}\,\gamma\gamma$ are widely different topologies, the similar power of rather different channels is not dissimilar to what happened in the Run 2 search for, and eventual discovery of, associated production of the $H^0(125)$ particle and a pair of top quarks. In a nutshell, there is a natural balance between mass resolution (with implications on signalover-background ratio), statistical uncertainty, and systematic uncertainty. These factors conspire in such a way that the different analyses end up having similar discriminating power. In particular, the $b\bar{b}\,\gamma\gamma$ analysis has good mass resolution but lower statistics, while the $b\bar{b}\,b\bar{b}$ analysis has larger statistics but poorer mass resolution and more difficult background-related systematic uncertainties; $b\bar{b}\,\tau\tau$ tends to fall somewhere in between the other two channels in most respects.

Just 10 years after the $H^0(125)$ discovery, the LHC experiments have reached a sensitivity to the trilinear coupling of the same order of magnitude of the SM prediction and were able to set limits on $H^0(125)$ pair production of a few times the SM expectation. This is a major achievement that has resulted in some surprises and excellent future prospects as discussed in the following.

6.1. *A 4-Point Vertex Appears*

A particularly interesting result coming out of the Run 2 study of $H^0(125)$ pair production is the conclusion that $\kappa_{2V} \neq 0$ in nature, as illustrated in Figure 12, a clear milestone on the way to measuring the $H^0(125)$ self-interaction strength. The result is presently in agreement with the SM prediction and, within the allowed region, much remains to be explored.

The strong conclusion that a $VVHH$ interaction, as that depicted in Figure 10(e), exists in nature is the consequence of dedicated searches targeting the VBF topology and making use of the latest advances in machine-learned algorithms to identify boosted $H^0(125)$ bosons, where the decay products are collimated together. These techniques are similar to those discussed in Section 4.1.2, and both benefit from the same detector and software improvements.

While the VBF searches have only modest sensitivity to κ_λ, they provide complementary physics reach and, in this case, yielded, for the first time, direct evidence for a 4-point vertex involving the $H^0(125)$ boson.

Similar to the discussion on direct and indirect searches of Section 5, this highlights the importance of developing complementary analyses, since it is in the combined constraining power of a variety of channels that one can find the most accurate and precise answers about nature.

6.2. *Looking Back, Looking Forward*

At present, none of the analyses used to search for the production of $H^0(125)$ pairs is statistically limited, and it is informative to consider how results have evolved until now and how they can be expected to evolve with additional data [21].

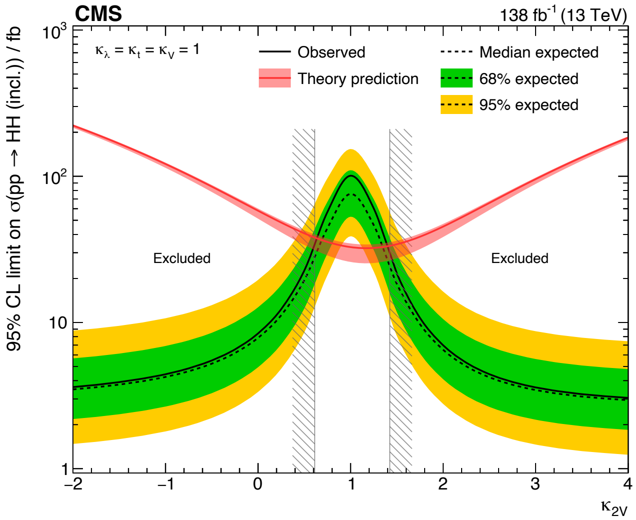


FIGURE 12: Results from searches for $H^0(125)$ pair production interpreted in terms of the κ_{2V} coupling modifier, associated with the $VVHH$ interaction vertex shown in Figure 10(e). Under the assumption that other couplings are as predicted by the SM ($\kappa_t = \kappa_V = \kappa_\lambda = 1$), the $\kappa_{2V} = 0$ hypothesis is excluded with a significance beyond 5σ, establishing that a $VVHH$ interaction exists in nature, the first 4-point vertex discovered involving the $H^0(125)$ boson. The sensitivity to this interaction is a direct consequence of the development of dedicated searches for the VBF topology that use boosted-jet machine-learned reconstruction techniques. Figure reproduced from [21]. Related results were obtained by ATLAS [20].

This evolution can be appreciated from Figure 13 and deserves discussion. Comparing early Run 2 results and 2022 results, which are set about 5 years apart, one can see a large improvement in the upper limits, and for the combined analysis, the result improves by a factor of about 7. Naively, the fourfold increase of the data set affords an improvement by a factor of about 2. The additional factor of about 3.5 represents an acceleration that is due to two main factors.

Firstly, the underlying ingredients used in these searches, which include the trigger, identification, and reconstruction algorithms, had time to be improved and targeted, following a matured and better understanding of the Run 2 detector. As a consequence, experiments are able to better use the recorded information and employ new algorithms that are developed by some of the brightest minds in the field, who dedicate their time to improve the performance of physics "objects" with cross-cutting impact across the physics reach of the collaborations.

Secondly, as larger data samples are made available, rarer and cleaner final states can be individuated for experimental scrutiny, opening new niches of sensitivity. This is an important qualitative aspect, analogous to the opening of new channels when taking a theory perturbative calculation to a higher order. The decision to create new analyses dedicated to specific phase spaces that have improved sensitivity can be due to two main reasons: the possibility to avoid experimental limitations (such as separating events into those with better or worse mass resolution) or the possibility of covering phenomenology hitherto not individuated (such as the searches for VBF $H^0(125)$ pair production). While the first class follows exclusively from experimental considerations, the latter can be the result of theory-experiment discussions that motivate new kinds of measurements.

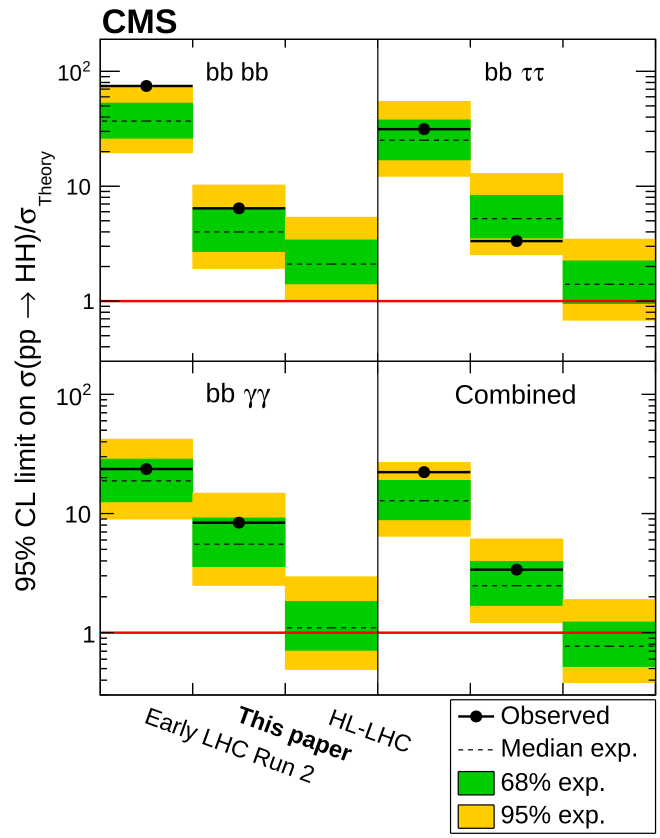


FIGURE 13: Evolution of upper limits on the $H^0(125)$ pair production cross-section. The expected sensitivity for one experiment at the end of the HL-LHC is such that it will be possible to strongly challenge the SM prediction (red line) as the result of a combined analysis of multiple final states. The faster-than-luminosity improvement between the early LHC Run 2 results and the 2022 results should be contrasted with the purely statistical extrapolation of the 2022 results to the full HL-LHC data set, especially under the light that future analyses can only be better than present ones. Figure reproduced from [21].

The main point is that when comparing early Run 2 results and 2022 results as done in Figure 13, all the foregoing effects are present and are responsible for the factor of 3.5 acceleration in performance. These factors must be considered when evaluating projections to the future.

The exercise of statistically extrapolating the performance of the 2022 analyses to the full HL-LHC data set is also shown in Figure 13. The combined analysis of a single experiment will clearly challenge the SM, with an expected median upper limit below the SM prediction. When considering this extrapolation, one must add the power of a second experiment, and the foregoing considerations of what only becomes possible with larger data sets and improved detectors.

All in all, this bodes well for the experimental collaborations at the LHC to be able to make important statements about the self-coupling of the $H^0(125)$ boson in the coming decades.

7. CLOSING REMARKS

After the discovery of the $H^0(125)$ particle, the first ten years of experimental measurements of this particle and searches for other such scalar particles has revolutionized the field of particle physics.

Regardless of theory, the $H^0(125)$ remains a singular particle that exhibits couplings to both fermions and bosons as long as they have mass. To date, all its properties remain compatible with those predicted by the Standard Model of particle physics. This does not mean that the $H^0(125)$ particle is the SM Higgs boson; it only reflects the fact that more precise measurements of the $H^0(125)$ and new, different, $H^0(125)$ measurements are needed, as it is a promising gateway to phenomena beyond the Standard Model.

The great strides made in one decade of experimental physics with the $H^0(125)$ particle would not have been possible without continued improvements and upgrades to the detectors, be it their tracking systems, their trigger systems, or the calibration and reconstruction software algorithms. These have enabled us to peer into the interaction of the $H^0(125)$ particle with second generation particles and produce spectacular results coming from the study of the production of $H^0(125)$ boson pairs.

The $H^0(125)$ particle is a new tool in the toolbox of fundamental physics. While it remains the sole representative of what could be a host of scalar particles, the $H^0(125)$ particle has been seen to have a broad reach and the coming decades and future accelerators are needed to understand its role in nature and whether it can provide hints for a theory that overcomes the shortcoming of the Standard Model, perhaps through a global interpretation in the framework of an effective field theory that can capture deviations from large classes of concrete alternatives to the Standard Model.

Experimentalists and theorists alike stand ready to take on the challenge. They only require the resources to produce large numbers of $H^0(125)$ bosons, detect them, and analyze and interpret those data.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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