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Review article for God Particle

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Abstract:

The Higgs boson, a fundamental scalar boson with mass 125 GeV, was discovered at the Large Hadron Collider (LHC) at CERN in 2012. So far, experiments at the LHC have focused on testing the Higgs boson's couplings to other elementary particles, precision measurements of the Higgs boson's properties and an initial investigation of the Higgs boson's self-interaction and shape of the Higgs potential. The Higgs boson mass of 125 GeV is a remarkable value, meaning that the underlying state of the Universe, the vacuum, sits very close to the border between stable and metastable, which may hint at deeper physics beyond the standard model. The Higgs potential also influences ideas about the cosmological constant, the dark energy that drives the accelerating expansion of the Universe, the mysterious dark matter that comprises about 80% of the matter component in the Universe and a possible phase transition in the early Universe that might be responsible for baryogenesis. A detailed study of the Higgs boson is at the centre of the European Strategy for Particle Physics update. Here we review the current understanding of the Higgs boson and discuss the insights expected from present and future experiments.

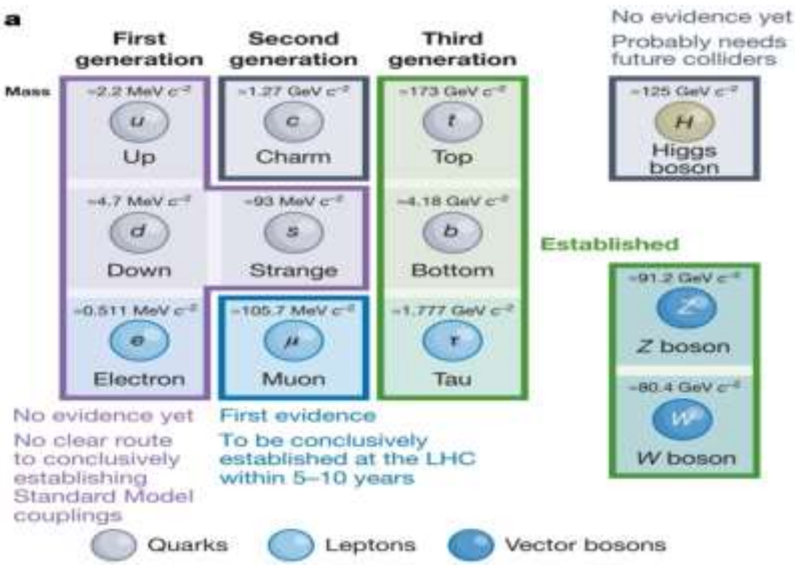
Key points: Higgs boson, confirming the standard model.

Introduction:

The leptons (not shown in the figure), confirm that the Higgs boson carries no intrinsic angular momentum, that is, it is a spin-0 particle; (4) the number of events in the peak is sensitive to the interaction strength of the Higgs boson both with top quarks and with Z bosons. This last point is crucial because the Standard Model Higgs mechanism predicts a very specific interaction strength of each particle with the Higgs boson. Point (4) provides us with a first test of this hypothesis. There are several potential concerns about the robustness of these kinds of test. For instance, in the process shown in Fig. 2 there is an assumption that there was a quantum fluctuation producing a top–anti-top pair. Even if that assumption is correct, the number of events in the peak tells us about the product of the top and Z interactions, not the top and Z interactions separately. For this reason, the LHC experiments look for the Higgs boson in a multitude of production and decay processes, each one with complementary sensitivity. For example, it is possible to observe Higgs-boson decays in events in which top quarks are not simply an evanescent quantum fluctuation, but are instead produced as short-lived real particles that emerge in their own right from the collision together with the Higgs boson and can be experimentally detected. Doing so15,16, in 2018, was a major milestone in particle physics, as were the highly challenging observations of the Higgs boson decaying to bottom quarks17,18 and τ leptons19,20. Together, these measurements conclusively established that the Higgs mechanism is responsible for the mass of the full third generation of charged fermions. Overall, by assembling information from different production and decay channels, a picture has emerged of Higgs interactions for the heaviest particles—both vector bosons and fermions—that is consistent with the Standard Model hypothesis to within the current measurement accuracies that range from 5% to 20%, as summarized in Fig. 3. On the other hand, interactions with very light particles, such as the electron and up and down quarks of which we are made of, are too rare for current methods to observe. Although the discovery of the Standard Model Higgs boson was highly anticipated at the LHC, the ability to explore so many of its features was a surprise. To have established even part of the broad picture of Higgs-boson interactions in just ten years is a major achievement, especially when one considers that, at the time when the LHC was being commissioned, many of the production and decay channels that are central to today's measurements were believed to be beyond the reach of the LHC21,22. There are many reasons why this progress has been possible. One of them is that nature happens to have chosen a value for the Higgs mass that is particularly fortunate for experimental studies. Had the Higgs boson been 50 GeV heavier, it would have been almost impossible to detect more than just two basic decay channels (to a pair of W bosons or a pair of Z bosons). Had it been just 10 GeV lighter, the decays to W bosons and Z bosons would probably have been impossible to see so far. It was not just a question of good fortune, however. The excellent performance of the LHC accelerator and of the ATLAS and CMS detectors, each of them a highly complex system, has been crucial. Furthermore, in the past ten years, there have been major advances in techniques for analysing collider data. One facet has been to learn how to reliably extract information about individual proton–proton collisions when detectors contain not just one proton–proton collision at a time, but dozens filling the detector simultaneously, 40 million times per second23,24. Another reflects the fact that the beautifully clear peak in Fig. 2b is the exception rather than the rule: for most other Higgs-boson studies (for example, Higgs decay to two bottom quarks or two W bosons), experimenters and theorists have had to develop a wide range of technology for differentiating Higgs-boson signals from the many processes with signatures similar to that of a Higgs boson, but that do not involve a Higgs boson. These studies are increasingly benefiting from a combination of new ideas for how to perform the analyses (for example, ref. 25) and the power of machine learning26. The quantitative interpretation of observed signal rates in terms of Higgs interaction strengths would also not have been possible without several decades of progress in the prediction and modelling of the rich array of effects that occur when protons collide, often associated with the strong interaction. It is crucial, for example, to have excellent theoretical control over the rate of quark and gluon collisions given a certain number of proton collisions27,28. Another facet is that collisions often involve not just one quantum fluctuation, as in Fig. 2, but multiple additional quantum fluctuations, each one of which modifies the probability of Higgs-boson production. The greater the number of quantum fluctuations that one can account for in theoretical predictions (today up to three additional fluctuations29), the more accurately one can relate experimental observations to the Standard Model30,31. Finally, Fig. 2 is a vastly simplified picture and the experiments rely profoundly on accurate simulation32,33 of the full structure of proton–proton collisions, involving the production of hundreds of particles per collision.

What is still to be established?

In many respects, the experimental exploration of the Higgs sector is only in its infancy. There are two broad directions of ongoing.



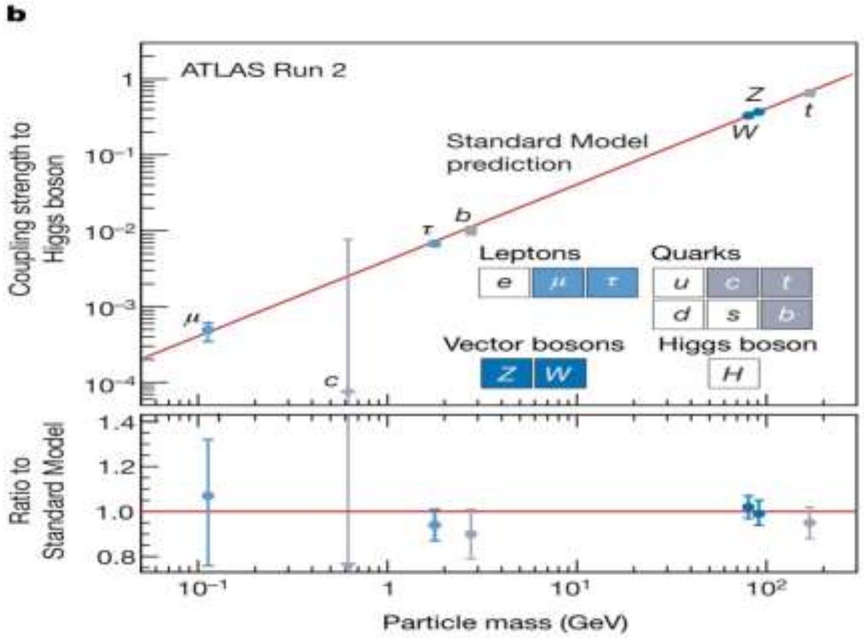


Fig. 3, Status of our knowledge of Higgs interactions with known particles. Summary of which Higgs interactions have been conclusively established and future prospects. Photons and gluons are omitted because they are massless and do not interact directly with the Higgs field. Neutrinos are also omitted: their masses are very small relative to those of the other leptons shown, and not individually known. b, Plot of measured strength of interaction of particles with the Higgs boson versus particle mass, as determined by the ATLAS Collaboration (adapted from ref. 96). The straight line shows the expected Standard Model behaviour, in which the interaction strength is proportional to the mass of the fermions (squared mass for W and Z bosons). The CMS Collaboration has similar results97. Higgs-boson production mechanisms at an electron–positron collider are largely free of complications associated with strong interactions. Such a collider could improve the precision of our knowledge of the Higgs interactions by a further factor of about ten41. Let us now turn to a discussion of interactions that are yet to be observed. Notwithstanding the good prospects for dramatically improving the precision of Higgs measurements connected with the vector bosons and third-generation (heaviest) quarks and leptons, recall that the relevance of the Higgs sector for our everyday life is that it is believed to generate masses for the first (lightest) generation of fundamental particles, the electron and up and down quarks. Even though experimentally testing our theoretical expectations for the interactions between first-generation fermions and the Higgs boson is highly challenging, there are prospects for the second generation, and in particular the interactions of the Higgs boson with the muon, which can be observed through the Hμ μ→ +− decay. So far the data is suggestive of such decays42,43, and definitive observation of Hμ μ→ +− , if it occurs at a rate that is compatible with the Standard Model, is expected to come in the next decade. Measurements involving the rest of the second generation are more difficult. The LHC can exclude anomalously large interactions of the Higgs boson with charm quarks34 (for example, using ideas such as those in refs. 44,45).

It has long been thought that to definitively observe Hc c→ decays would require a future e e+− collider (or alternatively an electron– proton collider46). Significant recent improvements in sensitivity to this decay channel at the LHC47,48 raise the question of whether future developments can bring its observation within reach of the high-luminosity LHC. For other Yukawa interactions, the path is less clear. Investigations are ongoing to establish the potential sensitivity of a future e e+− collider to electron and strange-quark Yukawa interactions (see, for example, ref. 49), although currently it seems that it will be challenging to obtain a statistically conclusive signal. For the coupling of up and down quarks to the Higgs boson, there are currently no concrete possibilities in sight unless those couplings are very strongly enhanced relative to the Standard Model expectation. There has been discussion of whether precise atomic physics measurements could be sensitive to the Higgs forces involving light quarks50; however, this seems challenging51. Central to all of Higgs physics is the Higgs potential. Recall that the Higgs field is non-zero everywhere in the Universe, and so produces non-zero masses for fermions and electroweak bosons, because the minimum of the Higgs potential, equation (1) and Fig. 1, lies at a non-zero value of the Higgs field ϕ. One of the most important open questions in Higgs physics is whether the potential written in that equation is the one chosen by nature. We cannot directly explore the potential across different values of the Higgs field. However, it turns out that the specific shape of the potential in the immediate vicinity of the minimum determines the probability of an important process—the splitting of a Higgs boson into two (or even three) Higgs bosons; this kind of process is referred to as a Higgs-boson self-interaction. Accurate observation of such a process is widely considered to be the best (but not the only52) way of experimentally establishing whether the world we live in is consistent with that simple potential. By the end of the high-luminosity LHC's operation in 15–20 years, the ATLAS and CMS experiments are expected to see first indications of the simultaneous production of two Higgs bosons. However, gathering conclusive evidence for a contribution to Higgs-pair production from the splitting of a first Higgs boson almost certainly requires a more powerful collider and several options are under discussion36,53–56.These are but some of the questions that are being explored. Other important ones that the LHC experiments are starting to be sensitive to include the lifetime of the Higgs boson57–60 and the nature of Higgs interactions at energies well above the electroweak energy scale 61,62

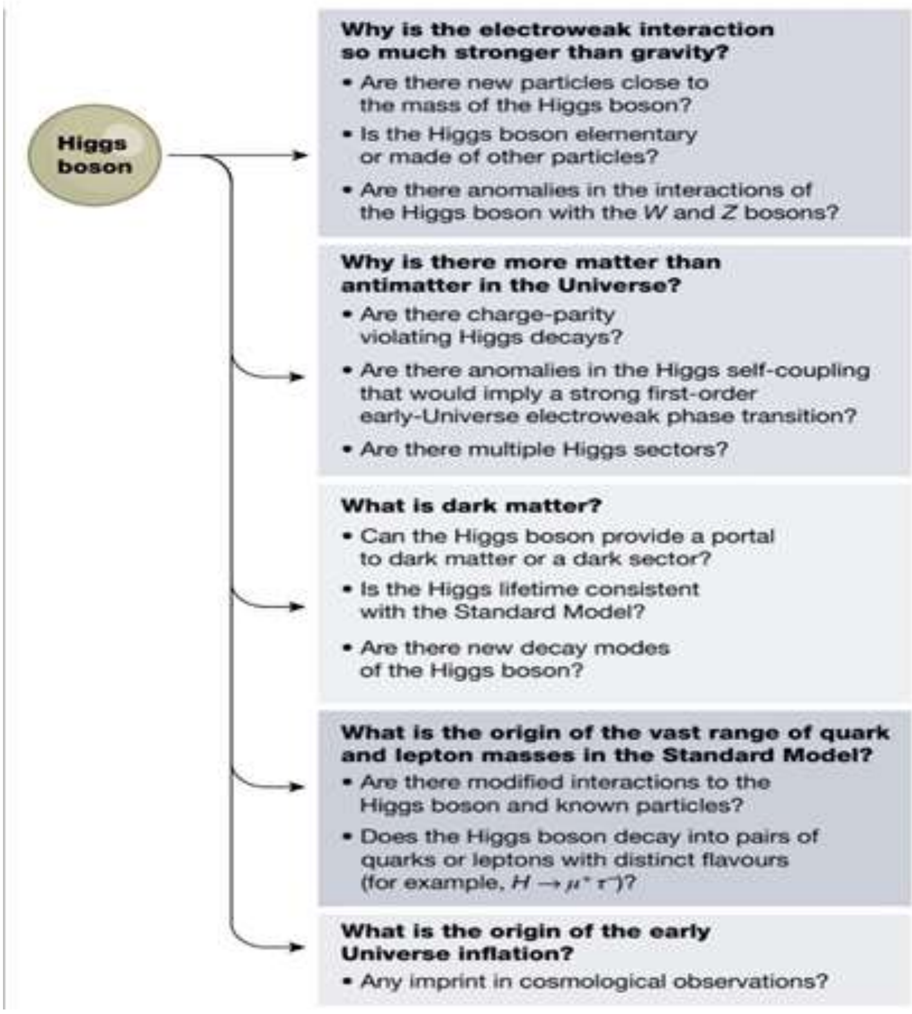
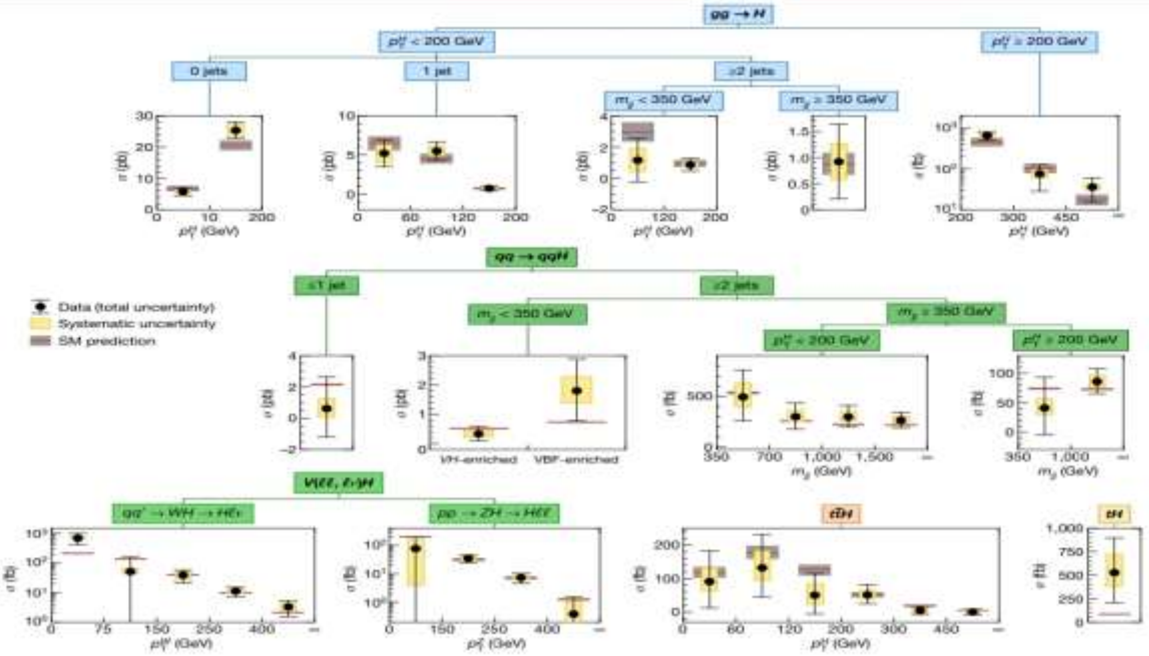


Fig. 4 | Possible connections of Higgs physics with major open questions of particle physics and cosmology.

There are several major open questions in particle physics that are motivated by experimental observations or theoretical arguments. The Higgs boson could be the key to unravelling some of these problems Higgs and major open questions of particle physics and cosmology.



Many of the above measurements are of interest not just owing to the fundamental nature of the Higgs sector within the Standard Model, but because they are also sensitive to scenarios that extend the role of the Higgs sector beyond that in the Standard Model. Even though the Standard Model has successfully passed all the numerous experimental tests so far, it leaves open several major questions. To various degrees, the Higgs boson is tied to potential solutions to these puzzles. We close our discussion with an overview of some of these possible connections, illustrated in Fig. 4, as they play an important role in guiding ongoing experimental and theoretical research directions in particle physics. There is a lot of ground to cover, so we will begin with and give more emphasis to aspects closely related to the Higgs boson, and only briefly mention later some of the more speculative ideas. One major puzzle is that the weak and Higgs interactions are much stronger, by a factor of about 1032, than the gravitational interaction. This is especially challenging if one harbours the hope—as do many physicists—that all the known interactions might come from a unifying and simpler framework. Over the past decades, the desire to explain the origin of this large difference, the so-called ‘hierarchy problem’, has motivated a range of theoretical proposals. One possibility is for the Higgs boson not to be an elementary particle, but rather a composite object made of other, as yet undiscovered particles63. Examples of other well studied proposals are new (approximate) space–time symmetries64–66 and new space dimensions67–70. More recently, some more speculative ideas suggested possible connections between the weak scale and cosmological evolution71–73 or the amount of dark energy in the Universe74,75. Without one of these proposals, or a new mechanism yet to be thought of, the hierarchy between the weak and the gravitational interaction can only arise if distinct parameters in some ultimate fundamental theory cancel to within 1 part in 1032. This is known as the fine-tuning problem of the Higgs sector. The discovery of the Higgs boson brought such questions unavoidably to the fore. The mere existence of the Higgs boson, and the (still approximate) picture of its properties, already exclude many theoretical ideas. In comparison with the decades before its discovery, we now have a much clearer target and sharper questions to answer with our theoretical models. Another important question is why there is more matter than antimatter in the Universe. This so-called baryonic asymmetry cannot be explained within the Standard Model. Such an asymmetry can be generated if a suitable set of conditions is met76. One promising avenue that is being explored follows the history of the Universe as it cooled down after the Big Bang. When the Universe was very hot, the minimum of the Higgs potential at a non-zero value of the Higgs field was largely irrelevant because temperature fluctuations were much larger than the depth of the potential. As the Universe cooled, the situation changed. Within the Standard Model that change is smooth.

Other promising scenarios, which involve new particles interacting with the Higgs boson, would generate a sharper transition, which sets the stage for generating the observed baryon asymmetry77, although further ingredients are also needed. These scenarios involve more complex structures for the Higgs potential, and at least one new particle at the electroweak energy scale, which can be searched for at the LHC either through its direct production or through its indirect impact on the Higgs couplings, in particular the Higgs self-interaction. A measurement of the latter is therefore essential to shed light on this question. Early-Universe phase transitions could also produce gravitational signatures that can be detected by future gravitational wave experiments78,79. In addition to the questions directly related to the Higgs boson mentioned above, there are also other contexts in which the Higgs boson can play an important role. One example of this is the question of dark matter. Astrophysical and cosmological observations show that the majority of the matter in the Universe is dark and not made of any particle we know of. Such observations rely on the gravitational effects of the dark matter on ordinary, Standard Model matter. At the same time, we know very little about the non-gravitational properties of dark matter. New particles with masses around the electroweak and Higgs mass scales can be promising dark-matter candidates. As the Higgs mechanism is responsible for generating similar masses of the Standard Model particles, it is possible that it plays some role in generating the dark-matter mass as well80–82. There are also scenarios in which the dark-matter sector involves more than one kind of particle. Similar to particles in the Standard Model, they could have their own interactions, and a whole set of other closely related particles. In this case, the Higgs boson would provide a portal to a new 'dark world'83. The origin of the pattern of masses and interactions among different generations of the Standard Model particles is an intriguing puzzle. For example, first-generation quarks are much lighter than third-generation quarks, which in the Standard Model needs to be arranged manually by setting correspondingly disparate values of the Yukawa couplings. Understanding the origin of this pattern has also been the focus of decades of efforts. As the Higgs sector is responsible for generating the masses of these particles, it is tempting to think that the actual Higgs sector may be structurally different from the Standard Model, in a way that causes the observed pattern to emerge naturally84–86. The models that explore such ideas often lead to predictions of modified interactions between the Higgs boson and the quarks (and/ or leptons). One signature of such models is that the Higgs boson could decay into a pair of quarks or leptons with different flavour. Similarly, one may also ask whether the Higgs mechanism has a role in generating the extremely small masses for neutrinos and various models have been envisaged in this respect87. The questions above relate the Higgs boson with known or unknown elementary particles. However, there are also mysteries in fundamental physics that go beyond such types of questions and speculative, yet intriguing, links have been proposed with the Higgs sector. For example, it has been noted that the Standard Model self-interaction of the Higgs boson becomes very close to zero if it is measured88–90 at energies nine orders of magnitude beyond the Higgs mass91,92. A curious and connected fact is that it seems likely that the Standard Model Higgs sector has a ground state with lower energy than the state we live in. Hence, quantum mechanics would allow a 'tunnelling' process through which our whole Universe can decay, even though the probability of such an event happening within the 14-billion year age of the Universe is tiny. The final possibility that we mention for new dynamics of the Higgs field at high energies is a possible link to inflation, which is a period of exponential expansion in the early niverse that is essential to explain the striking long-distance uniformity of the cosmic microwave background. The Higgs boson, having spin 0, may be responsible for driving inflation93. The Higgs boson is an invaluable tool in the search for answers to several of the above questions. Many of the proposed solutions predict the existence of new particles that generally interact directly with the Higgs boson. These particles are actively searched for at high-energy colliders. Still, even if the direct production of these particles lies outside our reach, for instance because the LHC is not energetic enough, their involvement in quantum fluctuations may affect Higgs-boson production and decay, in the same way that top-quark quantum fluctuations mediate Higgs production in Fig. 2. The expected future advances in precision measurements of the Higgs boson, as mentioned above, will bring considerably improved sensitivity to such scenarios. The discovery of the Higgs boson at the LHC marked the beginning of a new era of particle physics. In the ten years since, the exploration of the Higgs sector has progressed far beyond original expectations, owing to ingenious advances both experimental and theoretical. Every Higgs-related measurement so far has been consistent with the Standard Model, the simplest of all current models of particle physics: a remarkable win for Occam's razor. Today, it is clear that the Higgs mechanism, first proposed in the 1960s, is responsible not only for the masses of the W and Z bosons and but also for those of the three heaviest fermions. This directly implies the existence of a fifth force, mediated by the Higgs boson. Still, much remains to be probed. Whatever is found in the coming decades, we will be wiser: either with solid evidence for parts of the Standard Model that remain crucially to be established, such as the nature of the Higgs potential, or by opening a window to new horizons and the major mysteries of the Universe.

The standard model of particle physics1–4 describes the known fundamental particles and forces that make up our Universe, with the exception of gravity. One of the central features of the standard model is a field that permeates all of space and interacts with fundamental particles5–9. The quantum excitation of this field, known as the Higgs field, manifests itself as the Higgs boson, the only fundamental particle with no spin. In 2012, a particle with properties consistent with the Higgs boson of the standard model was observed by the ATLAS and CMS experiments at the Large Hadron Collider at CERN10,11. Since then, more than 30 times as many Higgs bosons have been recorded by the ATLAS experiment, enabling much more precise measurements and new tests of the theory. Here, on the basis of this larger dataset, we combine an unprecedented number of production and decay processes of the Higgs boson to scrutinize its interactions with elementary particles. Interactions with gluons, photons, and W and Z bosons—the carriers of the strong, electromagnetic and weak forces—are studied in detail. Interactions with three third-generation matter particles (bottom (b) and top (t) quarks, and tau leptons (τ)) are well measured and indications of interactions with a second-generation particle (muons, μ) are emerging. These tests reveal that the Higgs boson discovered ten years ago is remarkably consistent with the predictions of the theory and provide stringent constraints on many models of new phenomena beyond the standard model. The standard model of particle physics has been tested by many experiments since its formulation1–4 and, after accounting for the neutrino masses, no discrepancies between experimental observations and its predictions have been established so far. A central feature of the standard model is the existence of a spinless quantum field that permeates the Universe and gives mass to massive elementary particles. Testing the existence and properties of this field and its associated particle, the Higgs boson, has been one of the main goals of particle physics for several decades. In the standard model, the strength of the interaction, or 'coupling', between the Higgs boson and a given particle is fully defined by the particle's mass and type. There is no direct coupling to the massless standard model force mediators, the photons and gluons, whereas there are three types of couplings to massive particles in the theory. The first is the 'gauge' coupling of the Higgs boson to the mediators of the weak force, the W and Z vector bosons. Demonstrating the existence of gauge couplings is an essential test of the spontaneous electroweak symmetry-breaking mechanism5–9. The second type of coupling involves another fundamental interaction, the Yukawa interaction, between the Higgs boson and matter particles, or fermions. The third type of coupling is the 'self-coupling' of the Higgs boson to itself. A central prediction of the theory is that the couplings scale with the particle masses and they are all precisely predicted once all the particle masses are known. The experimental determination ofthe couplings of the Higgs boson to each individual particle therefore provides important and independent tests of the standard model. It also provides stringent constraints on theories beyond the standard model, which generally predict different patterns of coupling values. In 2012, the ATLAS12 and CMS13 experiments at the Large Hadron Collider (LHC)14 at CERN announced the discovery of a new particle with properties consistent with those predicted for the Higgs boson of the standard model10,11. More precise measurements that used all of the proton–proton collision data taken during the first data-taking period from 2011 to 2012 at the LHC (Run 1) showed evidence that, in contrast to all other known fundamental particles, the properties of the discovered particle were consistent with the hypothesis that it has no spin15,16. Alternate spin-1 and spin-2 hypotheses were also tested and were excluded at a high level of confidence. Investigations of the charge conjugation and parity (CP) properties of the new particle were also performed, demonstrating consistency with the CP-even quantum state predicted by the standard model, while still allowing for small admixtures of non-standard model CP-even or CP-odd states15,16. Limits on the particle's lifetime were obtained through indirect measurements of its natural width15–19. In addition, more precise measurements of the new particle's interactions with other elementary particles were achieved20. The results of all these investigations demonstrated that its properties were compatible with those of the standard model Higgs boson. However, the statistical uncertainties associated with these early measurements allowed considerable room for possible interpretations of the data in terms of new phenomena beyond the standard model and left many predictions of the standard model untested. The characterization of the Higgs boson continued during the Run 2 data-taking period between 2015 and 2018. About 9 million Higgs bosons are predicted to have been produced in the ATLAS detector during this period, of which only about 0.3% are experimentally accessible. This is 30 times more events than at the time of its discovery, owing to the higher rate of collisions and the increase of the collision energy from 8 teraelectronvolts (TeV) to 13 TeV, which raises the production rate.

In this Article, the full Run 2 dataset, corresponding to an integrated luminosity of 139 inverse femtobarns (fb^{-1}), is used for the measurements of Higgs boson production and decay rates, which are used to study the couplings between the Higgs boson and the particles involved. This improves on the previous measurements obtained with partial Run 2 datasets21,22. The corresponding predictions depend on the value of the Higgs boson mass, which has now been measured by the ATLAS and CMS experiments23–25 with an uncertainty of approximately 0.1%. The predictions employed in this article use the combined central value of 125.09 GeV23. The dominant production process at the LHC, which accounts for about 87% of Higgs boson production, is the heavy-quark loop-mediated gluon–gluon fusion process (ggF). The second most copious process is vector boson fusion (VBF), in which two weak bosons, either Z or W bosons, fuse to produce a Higgs boson (7%). Next in rate is production of a Higgs boson in association with a weak (V = W, Z) boson (4%). Production of a Higgs boson in association with a pair of top quarks ttH() or bottom quarks bbH() each account for about 1% of the total rate. The contribution of other qqH processes is much smaller and experimentally not accessible. Only about 0.05% of Higgs bosons are produced in association with a single top quark (tH). Representative Feynman diagrams of these processes are shown in Fig. 1a–e. After it is produced, the Higgs boson is predicted to decay almost instantly, with a lifetime of 1.6×10^{-22} seconds. More than 90% of these decays are via eight decay modes (Fig. 1f–i): decays into gauge boson pairs, that is, W bosons with a probability, or branching fraction, of 22%, Z bosons 3%, photons (γ) 0.2%, Z boson and photon 0.2%, as well as decays into fermion pairs, that is, b quarks 58%, c quarks 3%, τ leptons 6%, and muons (μ) 0.02%. There may also be decays of the Higgs boson into invisible particles, above the standard model prediction of 0.1%, which are also searched for. Such decays are possible in theories beyond the standard model, postulating, for example, the existence of dark matter particles that do not interact with the detector. In this Article, the mutually exclusive measurements of Higgs boson production and decays probing all processes listed above are combined taking into account the correlations among their uncertainties. In a single measurement, different couplings generally contribute in the production and decay. The combination of all measurements is therefore necessary to constrain these couplings individually. This enables key tests of the Higgs sector of the standard model to be performed, including the determination of the coupling strengths of the Higgs boson to various fundamental particles and a comprehensive study of the kinematic properties of Higgs boson production. The latter could reveal new phenomena beyond the standard model that are not observable through measurements of the coupling strengths.

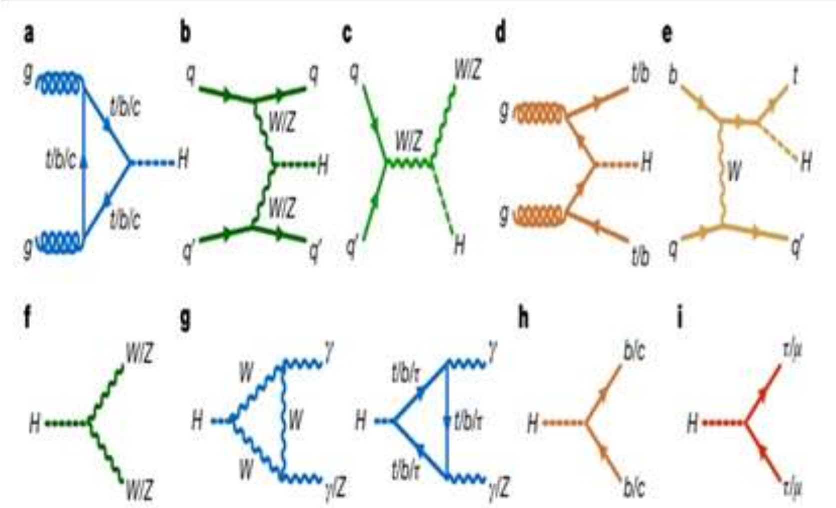


Fig. 1 | Examples of Feynman diagrams for Higgs boson production and decay. a–e, The Higgs boson is produced via gluon–gluon fusion (a), vector boson fusion (VBF; b) and associated production with vector bosons (c), top or b quark pairs (d), or a single top quark (e). f–i, The Higgs boson decays into a pair of vector bosons (f), a pair of photons or a Z boson and a photon (g), a pair of quarks (h), and a pair of charged leptons (i). Loop-induced Higgs boson interactions with gluons or photons are shown in blue, and processes involving couplings to W or Z bosons in green, to quarks in orange, and to leptons in red. Two different shades of green (orange) are used to separate the VBF and VH (ttH and tH) production processes.

ATLAS detector at the LHC:

The ATLAS experiment12 at the LHC is a multipurpose particle detector with a forward–backward symmetric, cylindrical geometry and a near 4π coverage in solid angle. The detector records digitized signals produced by the products of LHC’s proton bunch collisions, hereafter termed collision ‘events’. It is designed to identify a wide variety of particles and measure their momenta and energies. These particles include electrons, muons, τ leptons and photons, as well as gluons and quarks, which produce collimated jets of particles in the detector. Because the jets from b quarks and c quarks contain hadrons with relatively long lifetimes, they can be identified by observing a decay vertex, which typically occurs at a measurable distance from the collision point. The presence of particles that do not interact with the detector, such as neutrinos, can be inferred by summing the vector momenta of the visible particles in the plane transverse to the beam and imposing conservation of transverse momenta. The detector components closest to the collision point measure charged-particle trajectories and momenta. This inner spectrometer is surrounded by calorimeters that are used in the identification of particles and in the measurement of their energies. The calorimeters are in turn surrounded by an outer spectrometer dedicated to measuring the trajectories and momenta of muons, the only charged particle to travel through the calorimeters. A two-level trigger system was optimized for Run 2 data-taking26 to select events of interest at a rate of about 1 kHz from the proton bunch collisions occurring at a rate of 40 MHz. An extensive software suite27 is used in the simulation, reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data-acquisition systems of the experiment.

Input measurements and combination procedure

Physics analyses typically focus on particular production and decay processes and measure the number of Higgs boson candidates observed after accounting for non-Higgs background processes. To determine the strengths of the interactions of the Higgs boson, simultaneous fits with different physically motivated assumptions are performed on a combined set of complementary measurements. The relative weights of the input measurements in the combination depend on the analysis selection efficiencies, on the signal rates associated with the Higgs processes studied by the analysis, on the signal-to-background ratios, and on the associated systematic uncertainties. For each decay mode entering the combination, the production process is assessed via event classification based on the properties of particles produced in association with the Higgs boson, mostly via dedicated machine-learning approaches. Unless stated otherwise, studies of each decay mode consider all individual or combined contributions from six production processes: ggF, VBF, WH, ZH, ttH and tH. Higgs boson interactions are further explored via additional event classification of each production process based on the kinematic properties of the produced Higgs boson and the associated particles. The input to the combined measurement includes the latest results from the decay modes that initially led to the Higgs boson discovery: $H \rightarrow ZZ \rightarrow \ell+\ell-\ell+\ell-$ decays28 with two Z bosons that subsequently decay into a pair of oppositely charged electrons or muons; $H \rightarrow W \pm W\mp \rightarrow \ell\pm\nu\ell\ell\mp\nu\ell$ decays targeting separately the ggF and VBF29, and WH and ZH30 production processes; and $H \rightarrow \gamma\gamma$ decays31 with two high-energy photons. The latter is the only measurement used to discriminate between the ttH and tH processes.

These diboson decay modes are for the first time complemented by a search for the rare $H \rightarrow Z\gamma \rightarrow \ell+\ell-\gamma$ decay32. The decays of Higgs bosons to fermions are also extensively explored. The measurement of the dominant Hb b→ decay mode is particularly challenging owing to a very large multi-jet background, which can be suppressed by requiring the presence of additional particles characteristic of the WH or ZH33,34, VBF35 and ttH36 production processes. As a new input, the fully hadronic Hb b→ signal events with large Higgs boson transverse momentum are also considered37, providing for the first time sensitivity to the ggF production process in this decay mode. The sensitivity of the latest measurement in the $H \rightarrow \tau+\tau-$ decay mode38 is now extended to the VH and combined ttH and tH production processes. In addition to the ttH measurements obtained in the γγ, τ+τ− and ZZ decay modes, a complementary analysis that is sensitive to τ+τ−, WW ± ∓ and ZZ decays is performed using events with multiple leptons in the final state39. The considerably more challenging measurements of Higgs boson couplings to second-generation fermions are explored via searches for the $H \rightarrow \mu+\mu-$ decay40 and, included in the combination for the first time, Hc c→ decay41. Owing to the large multi-jet background, the latter decay mode is currently accessed only via WH and ZH production. Finally, the inputs to the combination are complemented by the latest direct searches in the VBF and ZH production processes for Higgs boson decays into invisible particles that escape the detector42,43. A summary of these input measurements used in the combination is available in Extended Data Table 1. All input measurements are performed with the full set of Run 2 data, except for the measurements of previous works30,39, which use a partial Run 2 dataset collected during 2015 and 2016. The direct searches for invisible Higgs boson decays and the Hc c→ measurements are employed only for measurements of the relevant Higgs boson coupling strengths, and the Hb b→ measurements at high Higgs boson transverse momenta37 are considered only when probing the kinematic properties of Higgs boson production. All other inputs are used for the measurements of production cross-sections, branching fractions and coupling strengths. The measurement of kinematic properties of Higgs boson production excludes input measurements from previous works 30, 32, 39–41, owing to their limited sensitivity. Analyses performed with the Run 2 data introduce a number of improvements, often resulting in up to 50% better signal sensitivities compared to those expected from just the increase in the analysed amount of data. These improvements include better particle reconstruction (optimized to cope with an increased number of proton interactions per bunch crossing), dedicated reconstruction of highly Lorentz-boosted Hb b→ decays, a greater number of simulated events, higher granularity of the kinematic regions that are probed in each production process, and improved signal and background theory predictions. The standard model is tested by comparing the observed signal rates to theory predictions that require state-of-the-art calculations of Higgs boson production cross-sections and branching fractions 44–50.

All signal reconstruction efficiencies and most background rates are predicted from the simulation. The simulation is complemented by the use of dedicated signal-depleted control data for measurements of selected background processes and to constrain signal-selection efficiencies. A common set of event generators were used in all analyses to describe the gluon and quark interactions in the proton–proton collisions. The generated particles were passed through a detailed simulation of the ATLAS detector response prior to their reconstruction and identification. The statistical analysis of the data is described in more detail in Methods. It relies on a likelihood formalism, where the product of the likelihood functions describing each of the input measurements is calculated in order to obtain a combined likelihood51. The effects of experimental and theoretical systematic uncertainties on the predicted signal and background yields are implemented by including nuisance parameters in the likelihood function. The values of those additional parameters are either fully determined by the included data, or constrained by Gaussian terms that multiply the likelihood. The effects of uncertainties that affect multiple measurements are propagated coherently through the fit by using common nuisance parameters. The statistical test of a given signal hypothesis, used for the measurement of the parameters of interest, is performed with a test statistic that is based on the profile likelihood ratio52. The confidence intervals of the measured parameters and the p value used to test the compatibility of the results and the standard model predictions are constructed from the test statistic distribution, which is obtained using asymptotic formulae52. The total uncertainty in the measurement of a given parameter of interest can be decomposed into different components. The statistical uncertainty is obtained from a fit with all externally constrained nuisance parameters set to their best-fit values. The systematic uncertainty, the squared value of which is evaluated as the difference between the squares of the total uncertainty and the statistical uncertainty, can be decomposed into categories by setting all relevant subsets of nuisance parameters to their best-fit values. Combined measurement with ATLAS Run 2 data. The Higgs boson production rates are probed by the likelihood fit to observed signal yields described earlier. Because the production cross-section σi and the branching fraction Bf for a specific production process i and decay mode f cannot be measured separately without further assumptions, the observed signal yield for a given process is expressed in terms of a single signal strength modifier μ σσ BB = (/) (/)if ii ff SM SM , where the superscript 'SM' denotes the corresponding standard model prediction. Assuming that all production and decay processes scale with the same global signal strength μ = μif, the inclusive Higgs boson production rate relative to the standard model prediction is measured to be μ=1.05±0.06=1.05±0.03 (stat.) ±0.03 (exp.) ±0.04 (sig.th.) ±0.02 (bkg.th.). The total measurement uncertainty is decomposed into components for statistical uncertainties, experimental systematic uncertainties, and theory uncertainties in both sign.

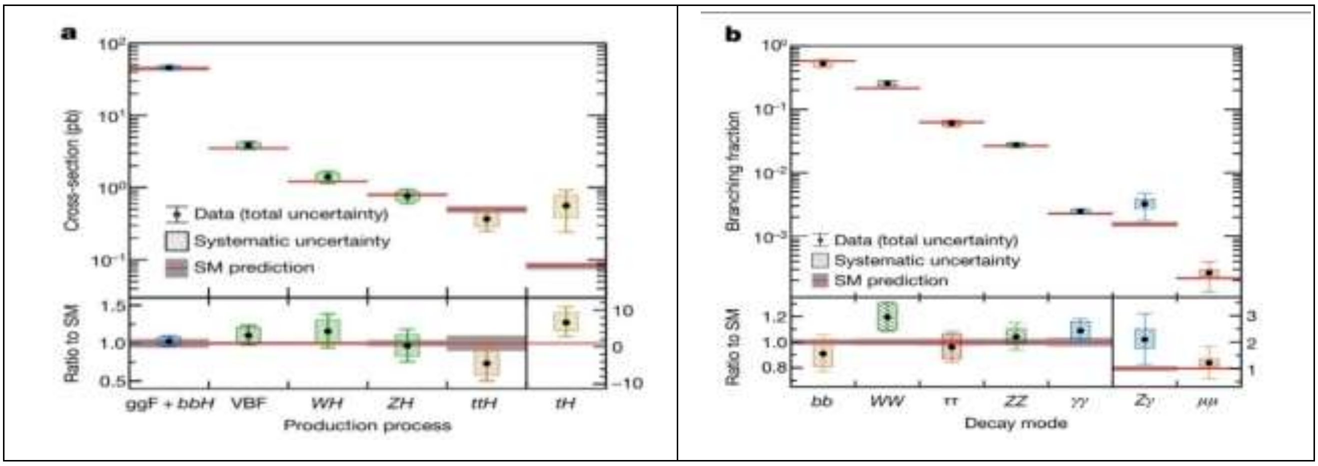


Fig. 2, Observed and predicted Higgs boson production cross-sections and branching fractions. a, Cross-sections for different Higgs boson production processes are measured assuming standard model (SM) values for the decay branching fractions. b, Branching fractions for different Higgs boson decay modes are measured assuming SM values for the production cross-sections. The lower panels show the ratios of the measured values to their SM predictions. The vertical bar on each point denotes the 68% confidence interval. The p value for compatibility of the measurement and the SM prediction is 65% for a and 56% for b. Data are from ATLAS Run 2. A factor of two lower than in the Run 1 result 20. The presented measurement supersedes the previous ATLAS combination with a partial Run 2 dataset22, decreasing the latest total measurement uncertainty by about 30%. Higgs boson production is also studied per individual process.

As opposed to the top quark decay products from ttH production, the identification efficiency of b jets from the bbH production is low, making the bbH process experimentally indistinguishable from ggF production. The bbH and ggF processes are therefore grouped together, with bbH contributing a relatively small amount: of the order of 1% to the total bbH ggF+ ¯ production. In cases where several processes are combined, the combination assumes the relative fractions of the components to be those from the standard model within corresponding theory uncertainties. Results are obtained from the fit to the data, where the cross-section of each production process is a free parameter of the fit. Higgs boson decay branching fractions are set to their standard model values, within the uncertainties specified previously44. The results are shown in Fig. 2a. All measurement results are compatible with the standard model predictions. For the ggF and VBF production processes, which were previously observed in Run 1 data, the cross-sections are measured with a precision of 7% and 12%, respectively. The following production processes are now also observed: WH with an observed (expected) signal significance of 5.8 (5.1) standard deviations (σ), ZH with 5.0σ (5.5σ) and the combined ttH and tH production processes with 6.4σ(6.6σ), where the expected signal significances are obtained under the standard model hypothesis. The separate ttH and tH measurements lead to an observed (expected) upper limit on tH production of 15 (7) times the standard model prediction at the 95% confidence level (CL), with a relatively large negative correlation coefficient of 56% between the two measurements. This is due to cross-contamination between the ttH and tH processes in the set of reconstructed events that provide the highest sensitivity to these production processes. Branching fractions of individual Higgs boson decay modes are measured by setting the cross-sections for Higgs boson production processes to their respective standard model values.

The results are shown in Fig. 2b. The branching fractions of the γγ, ZZ, WW ± ∓ and τ+τ− decays, which were already observed in the Run 1 data, are measured with a precision ranging from 10% to 12%. The bb decay mode is observed with a signal significance of 7.0σ (expected 7.7σ), and the observed (expected) signal significances for the H → μ+μ− and H → Zγ decays are 2.0σ (1.7σ) and 2.3σ (1.1σ), respectively. The assumptions about the relative contributions of different decay or production processes in the above measurements are relaxed by directly measuring the product of production cross-section and branching fraction for different combinations of production and decay processes. The corresponding results are shown in Fig. 3. The measurements are in agreement with the standard model prediction. To determine the value of a particular Higgs boson coupling strength, a simultaneous fit of many individual production times branching fraction measurements is required. The coupling fit presented here is performed within the κ framework53 with a set of parameters κ that affect the Higgs boson coupling strengths without altering any kinematic distributions of a given process.

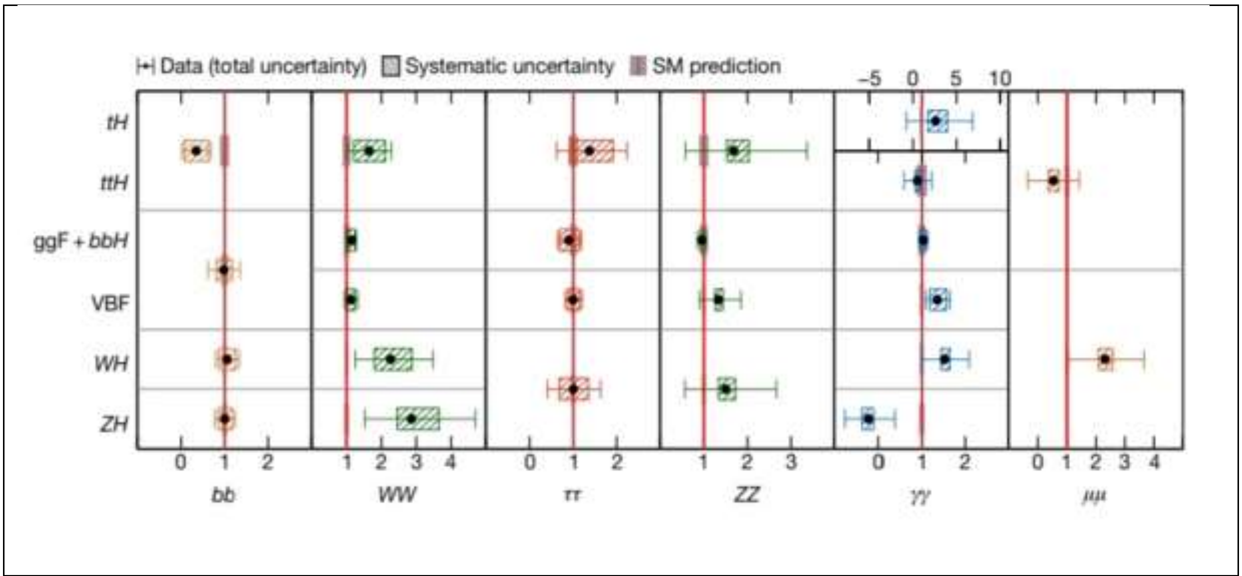


Fig. 3, Ratio of observed rate to predicted standard model event rate for different combinations of Higgs boson production and decay processes. The horizontal bar on each point denotes the 68% confidence interval. The narrow grey bands indicate the theory uncertainties in the standard model(SM) cross-section multiplied by the branching fraction predictions. The p value for compatibility of the measurement and the SM prediction is 72%. σi Bf is normalized to the SM prediction. Data are from ATLAS Run 2.

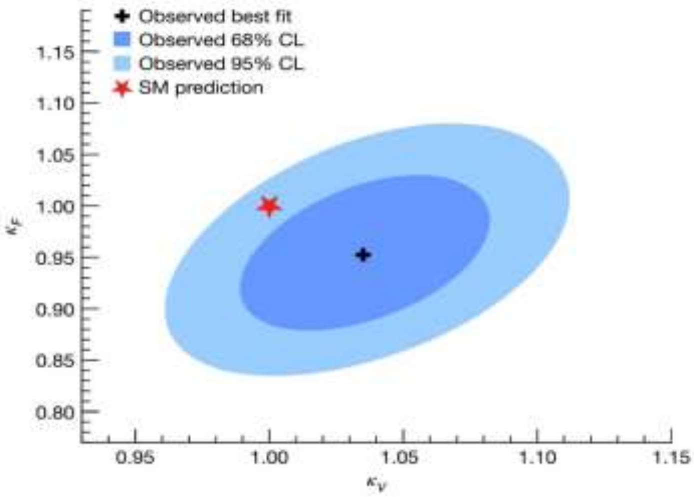


Fig. 4, Negative log-likelihood contours corresponding to 68% and 95% CL in the (κV, κF) plane. The data are obtained from a combined fit assuming no contributions from invisible or undetected non-standard model Higgs boson decays. The p value for compatibility of the combined measurement and the standard model (SM) prediction is 14%. Data are from ATLAS Run 2. Within this framework, the cross-section times the branching fraction for an individual measurement is parameterized in terms of the multiplicative coupling strength modifiers κ. A coupling strength modifier κp for a production or decay process via the coupling to a given particle p is defined as κσ σ =/ pp p 2S M or κΓ Γ =/ pp p 2S M, respectively, where Γp is the partial decay width into a pair of particles p. The parameterization takes into account that the total decay width depends on all decay modes included in the present measurements, as well as currently undetected or invisible, direct or indirect decays predicted by the standard model (such as those to gluons, light quarks or neutrinos) and the hypothetical decays into non-standard model particles. The decays to non-standard model particles are divided into decays to invisible particles and other decays that would be undetected owing to large backgrounds. The corresponding branching fractions for the two are denoted by Binv. and Bu., respectively. In the following, three classes of models with progressively fewer assumptions about coupling strength modifiers are considered. Standard model values are assumed for the coupling strength modifiers of first-generation fermions, and the modifiers of the second-generation quarks are set to those of the third generation, except where κc is left free-floating in the fit. Owing to their small sizes, these couplings are not expected to noticeably affect any of the results. The ggF production and the $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ decays are loop-induced processes. They are either expressed in terms of the more fundamental coupling strength scale factors corresponding to the particles that contribute to the loop-induced processes in the standard model, or treated using effective coupling strength modifiers κg, κγ and κZγ, respectively. The latter scenario accounts for possible loop contributions from particles beyond the standard model. The small contribution from the loop-induced $gg \rightarrow ZH$ process is always parameterized in terms of the couplings to the corresponding standard model particles. The first model tests one scale factor for the vector bosons, κV = κW = κZ, and a second, κF, which applies to all fermions. In general, the standard model prediction of κV = κF = 1 does not hold in extensions of the standard model.

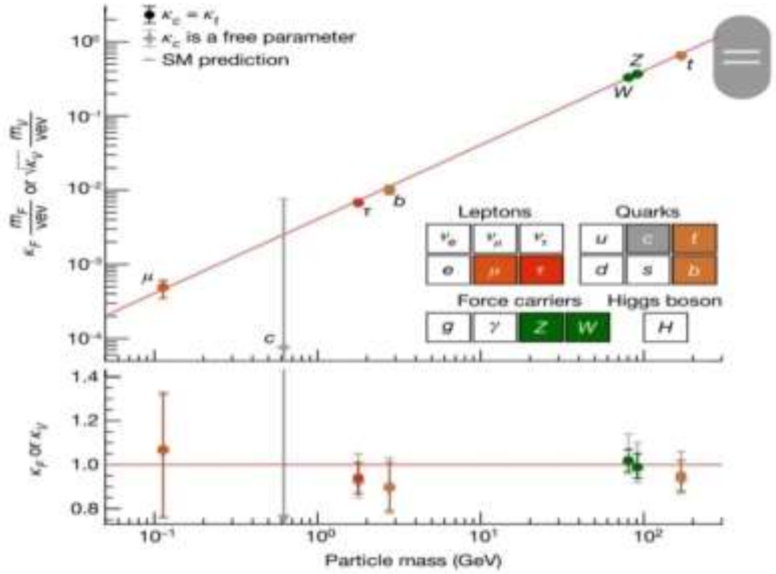


Fig. 5, Reduced Higgs boson coupling strength modifiers and their uncertainties. They are defined as κFmF/vev for fermions (F = t, b, τ, μ) and κm/vev VV for vector bosons as a function of their masses mF and mV. Two fit scenarios with κc = κt (coloured circle markers), or κc left free-floating in the fit (grey cross markers) are shown. Loop-induced processes are assumed to have the standard model (SM) structure, and Higgs boson decays to non-SM particles are not allowed. The vertical bar on each point denotes the 68% confidence interval. The p values for compatibility of the combined measurement and the SM prediction are 56% and 65% for the respective scenarios. The lower panel shows the values of the coupling strength modifiers. The grey arrow points in the direction of the best-fit value and the corresponding grey uncertainty bar extends beyond the lower panel range. Data are from ATLAS Run 2 less than 1 in models in which the Higgs boson is a composite particle. The effective couplings corresponding to the ggF, H → γγ and H → Zγ loop-induced processes are parameterized in terms of the fundamental standard model couplings. It is assumed that there are no invisible or undetected Higgs boson decays beyond the standard model, that is, Binv. = Bu. = 0. As only the relative sign between κV and κF is physical and a negative relative sign has been excluded with a high level of confidence20, κV ≥ 0 and κF ≥ 0 are assumed. Figure 4 shows the results of a combined fit in the (κV, κF) plane. The best-fit values and their uncertainties from the combined fit are κV = 1.035 ± 0.031 and κF = 0.95 ± 0.05, compatible with the standard model predictions. A relatively large positive correlation of 39% is observed between the two fit parameters, because some of the most sensitive input measurements involve the ggF production process (that is, via couplings to fermions) with subsequent Higgs boson decays into vector bosons. In the second class of models, the coupling strength modifiers for W, Z, t, b, c, τ and μ are treated independently. All modifiers are assumed to be positive. It is assumed that only standard model particles contribute to the loop-induced processes, and modifications of the fermion and vector boson couplings are propagated through the loop calculations. Invisible or undetected non-standard model Higgs boson decays are not considered. These models enable testing of the predicted scaling of the couplings of the Higgs boson to the standard model particles as a function of their mass using the reduced coupling strength modifiers κg κm /2vev= (/ vev)V V VV for weak bosons with a mass mV and κFgF = κFmF/vev for fermions with a mass mF, where gV and gF are the corresponding absolute coupling strengths and 'vev' is the vacuum expectation value of the Higgs field. Figure 5 shows the results for two scenarios: one with the coupling to c quarks constrained by κc = κt in order to cope with the low sensitivity to this coupling; and the other with κc left as a free parameter in the fit. All measured coupling strength modifiers are found to be compatible with their standard model prediction. When the coupling strength modifier κc is left unconstrained in the fit, an upper limit of κc < 5.7 (7.6) times the standard model prediction is observed (expected) at 95% CL and the uncertainty in each of the other parameters increases because of the resulting weaker constraint on the total decay width. This improves the current observed (expected) limit of κc < 8.5 (12.4) at 95% CL from the individual measurement of Hc c→ decays41 despite the relaxed assumptions on other coupling strength modifiers, through constraints coming from the parameterization of the total Higgs boson decay width that impacts all measurements. The third class of models in the κ framework closely follows the previous one, but allows for the presence of non-standard model particles in the loop-induced processes. These processes are parameterized by the effective coupling strength modifiers κg, κγ and κZγ instead of propagating modifications of the standard model particle couplings through the loop calculations. It is also assumed that any potential effect beyond the standard model does not substantially affect the kinematic properties of the Higgs boson decay products. The fit results for the scenario in which invisible or undetected non-standard model Higgs boson decays are assumed not to contribute to the total Higgs decay width, that is, Binv. = Bu. = 0, are shown in Fig. 6 together with theresults for the scenario allowing such decays. To avoid degenerate solutions, the latter constrains Bu. ≥ 0 and imposes the additional constraint κV ≤ 1 that naturally arises in various scenarios of physics beyond the standard model54,55. All measured coupling strength modifiers are compatible with their standard model predictions. When allowing invisible or undetected non-standard model Higgs boson decays to contribute to the total Higgs boson decay width, the previously measured coupling strength modifiers do not change significantly, and upper limits of Bu. < 0.12 (expected 0.21) and Binv. < 0.13 (expected 0.08) are set at 95% CL on the corresponding branching fraction. The latter improves on the current best limit of Binv. < 0.145 (expected 0.103) from direct ATLAS searches42. In all tested scenarios, the statistical and the systematic uncertainty contribute almost equally to the total uncertainty in most of the κ parameter measurements. The exceptions are the κμ, κZγ, κc and Bu. measurements, for which the statistical uncertainty still dominates. Kinematic properties of Higgs boson production probing the internal structure of its couplings are studied in the framework of simplified template cross-sections44,56–58. The framework partitions the phase space of standard model Higgs boson production processes into a set of regions defined by the specific kinematic properties of the Higgs boson and, where relevant, of the associated jets, W bosons, or Z bosons, as described in Methods. The regions are defined so as to provide experimental sensitivity to deviations from the standard model predictions, to avoid large theory uncertainties in these predictions, and to minimize the model-dependence of their extrapolations to the experimentally accessible signal regions. Signal cross-sections measured in each of the introduced kinematic regions are compared with those predicted when assuming that the branching fractions and kinematic properties of the Higgs boson decay are described by the standard model. The results of the simultaneous measurement in 36 kinematic regions are presented in Fig. 7. Compared to previous results with a smaller dataset22, a much larger number of regions are probed, particularly at high Higgs boson transverse momenta, where in many cases the sensitivity to new phenomena beyond the standard model is expected to be enhanced. All measurements are consistent with the standard model predictions.

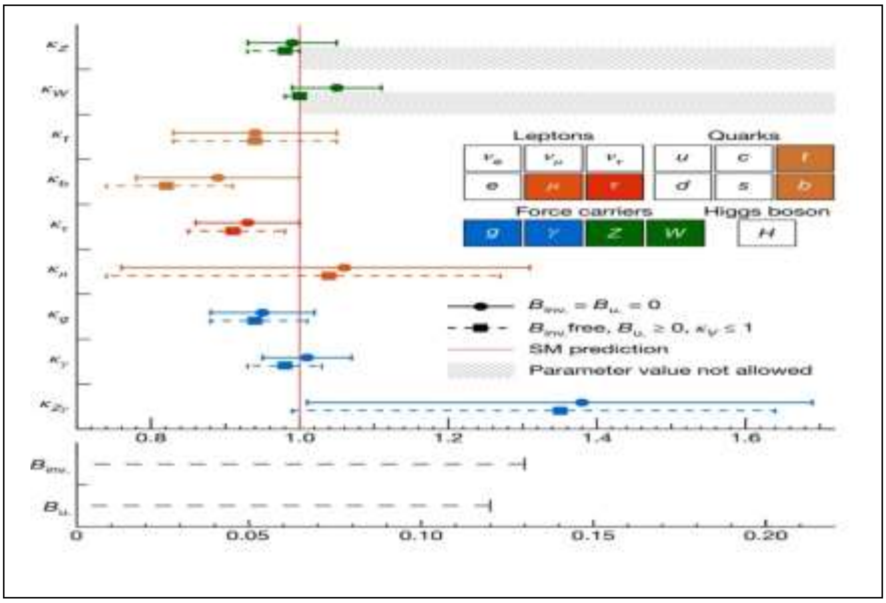


Fig. 6, Reduced coupling strength modifiers and their uncertainties per particle type with effective photon, Zγ and gluon couplings. The horizontal bars on each point denote the 68% confidence interval. The scenario in which Binv. = Bu. = 0 is assumed is shown as solid lines with circle markers. The p value for compatibility with the standard model (SM) prediction is 61% in this case. The scenario in which Binv. and Bu. are allowed to contribute to the total Higgs boson decay width while assuming that κV ≤ 1 and Bu. ≥ 0 is shown as dashed lines with square markers. The lower panel shows the 95% CL upper limits on Binv. and Bu.. Data are from ATLAS Run 2.

Conclusion:

In summary, the production and decay rates of the Higgs boson were measured using the dataset collected by the ATLAS experiment during Run 2 of the LHC from 2015 to 2018. The measurement results were found to be in excellent agreement with the predictions of the standard model. In different scenarios, the couplings to the three heaviest fermions, the top quark, the b quark and the τ lepton, were measured with uncertainties ranging from about 7% to 12% and the couplings to the weak bosons (Z and W) were measured with uncertainties of about 5%. In addition, indications are emerging of the presence of very rare Higgs boson decays into second-generation fermions and into a Z boson and a photon. Finally, a comprehensive study of Higgs boson production kinematics was performed and the results were also found to be compatible with standard model predictions. In the ten years since its discovery, the Higgs boson has undergone many experimental tests that have demonstrated that, so far, its nature is remarkably consistent with the predictions of the standard model. However, some of its key properties—such as the coupling of the Higgs boson to itself—remain to be measured. In addition, some of its rare decay modes have not yet been observed and there is ample room for new phenomena beyond the standard model to be discovered. Substantial progress on these fronts is expected in the future, given that detector upgrades are planned for the coming years, that systematic uncertainties are expected to be reduced considerably 59, and that the size of the LHC's dataset is projected to increase by a factor of 20.

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