

# The Higgs boson turns ten

<https://doi.org/10.1038/s41586-022-04899-4>

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Received: 22 March 2022

Accepted: 24 May 2022

Published online: 4 July 2022



The discovery of the Higgs boson, ten years ago, was a milestone that opened the door to the study of a new sector of fundamental physical interactions. We review the role of the Higgs field in the Standard Model of particle physics and explain its impact on the world around us. We summarize the insights into Higgs physics revealed so far by ten years of work, discuss what remains to be determined and outline potential connections of the Higgs sector with unsolved mysteries of particle physics.

Ten years ago, on 4 July 2012, scientists and journalists gathered at CERN, and remotely around the world, for the announcement of the discovery of a new fundamental particle, the Higgs boson. The discovery, by the ATLAS<sup>1</sup> and CMS<sup>2</sup> collaborations at the Large Hadron Collider (LHC), came almost 50 years after theorists had postulated the existence of such a particle. The significance of the discovery was not only that a new, long-awaited particle had been found, but that the existence of this particle provides first direct evidence that surrounding us there is a new kind of fundamental ‘field’, known as the Higgs field.

Fields in physics are familiar in everyday life, for example in the form of the earth’s magnetic field, and its impact on the needle of a compass. The most important difference between the Higgs field and a magnetic field is that if one removes the magnetic source, the magnetic field disappears. By contrast, the Higgs field is non-zero everywhere, all the time, independently of whether anything else is present in the Universe. In a way, it is reminiscent of the ancient Greek concept of Aether with the crucial difference that it is consistent with Einstein’s theory of special relativity.

Physicists’ current theory of fundamental particles and forces is known as the Standard Model, a theoretical framework that provides a description of elementary particles and the forces that make them interact with one another, with the exception of gravity. Within the Standard Model, the Higgs field is essential to describe the world as we know it.

As we shall see below, the strength of the interaction between any particle and the Higgs field directly affects a fundamental property of that particle: its mass. As such<sup>3</sup>, it ultimately determines the size of atoms, makes the proton stable and sets the timescale of radioactive ( $\beta$ ) decays, which for example impact the lifetime of stars (Table 1). Yet, in everyday life, we do not notice that the Higgs field is all around us. The only way we have of revealing the Higgs field is to perturb it, a little like throwing a stone into water and seeing the ripples. The particle known as the Higgs boson is the manifestation of such a perturbation.

The significance of its discovery in 2012 was such that the Nobel prize was awarded one year later to François Englert and Peter Higgs who, with the late Robert Brout, were the first to discuss the potential importance of such a field for fundamental physics<sup>4–6</sup>. Since then, the Higgs boson has become a powerful tool to study the ways in which the underlying Higgs field affects the fundamental particles of the Standard Model. Furthermore, the ubiquity of the Higgs field means that the Higgs boson is, today, widely used in the search for signatures of particles or effects that are hitherto unknown and lie outside the Standard Model.

## The Higgs boson in the Standard Model

In the Standard Model, aside from the Higgs boson, there are two kinds of particles. There are fermions, such as the up and down quarks and the electron, which make up ordinary matter. These specific particles (together with one of the three neutrinos) are called first-generation fermions. Two further sets of fermions (second and third generations) involve heavier particles, not normally present in the world around us. Additionally, there are the force carriers: the photon, the  $W$  and  $Z$  bosons and the gluon, collectively called vector bosons. When these are exchanged between two fermions, they create an attractive or repulsive force between those fermions: photons carry the electromagnetic force,  $W$  and  $Z$  bosons the weak force and gluons the strong force.

In the 1960s, as physicists were taking the first steps towards assembling this picture, it remained unclear whether a self-consistent theory that included massive force carriers could be constructed. This question was being posed in the context of nuclear physics and also superconductivity in condensed matter physics. Researchers found that such a theory was ultimately possible if one introduced an interaction of the force carriers with a ‘Higgs’ field, and if one could also engineer a non-zero value for that field<sup>4–9</sup>.

As the electroweak part of the Standard Model was being developed<sup>10–12</sup>, interactions of particles with a Higgs field were to become a central part of its formulation, especially in order to generate masses for the  $W$  and  $Z$  bosons, as required for consistency with experimental observations, while photons and gluons remain massless.

Remarkably, interactions with the Higgs field also provided a consistent theoretical mechanism for producing fermion masses: each fermion interacts with the Higgs field with a different strength (or ‘coupling’), and the stronger the interaction, the larger the resulting mass for the particle. Within the Standard Model the interaction is known as a ‘Yukawa’ interaction<sup>13</sup>. Thus any question about the origin of the masses of fermions reduces to a question about the origin of the interactions of fermions with the Higgs field.

Why is the Higgs field non-zero in the first place? According to the Standard Model there is a potential energy density associated with the value of the Higgs field and the lowest potential energy corresponds to a non-zero value of the Higgs field. The Standard Model potential has a form dictated by internal consistency conditions. With some simplifications, labelling the magnitude of the Higgs field as  $\phi$ , the potential has the form

$$V(\phi) \propto -\phi^2 + \frac{1}{2}\phi^4. \quad (1)$$

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**Table 1 | Ways in which the Higgs boson affects the world around us**

Particle whose mass is set by the interaction with the Higgs field	Role of the particle masses	Impact on everyday life	Has the Higgs-particle interaction been experimentally confirmed?
Up quark ( $m_{\text{up}} \approx 2.2 \text{ MeV } c^{-2}$ ) Down quark ( $m_{\text{down}} \approx 4.7 \text{ MeV } c^{-2}$ )	Affects the mass of the proton and neutron	Differences in quark masses ( $m_{\text{up}} < m_{\text{down}}$ ) contribute to protons (made of two up and one down quarks) being lighter than neutrons (made of one up and two down quarks). As a result, protons are stable, as required for the existence of hydrogen.	No
Electron	Atomic radius $\propto 1/m_e$	A different value of the electron mass would modify the energy levels and chemical reactions of all known elements.	No
W boson	Radioactive beta decay rate $\propto 1/m_W^4$	Many radioactive decays, and the fusion reactions that power the Sun, involve the W boson. The W mass affects the rate of all of these reactions.	Yes

Three examples of how particle masses<sup>34</sup> play a crucial role in determining the physical nature of the world in which we live. In all three cases, the Standard Model suggests that the corresponding particle masses arise from interactions of those particles with the Higgs field. The last column indicates whether or not we have clear experimental indications that confirm that hypothesis.

This is illustrated by the red line in Fig. 1. The minimum of the potential, that is, the energetically most favourable choice for  $\phi$ , lies at a value of  $\phi$  that is non-zero,  $\phi = 1$ . An important implication of the non-zero constant value of the Higgs field is the impossibility to carry angular momentum, or more technically having ‘spin 0’. A non-zero value for the spin would break at least one of the well-tested space–time symmetries. Hence, the excitation of the Higgs field, the Higgs boson, must be a spin-0 particle and it is in fact the only known fundamental particle with this property.

One of the reasons for the central importance of the discovery of the Higgs boson was that it finally made it possible to start testing the remarkable theoretical picture outlined above. It is not possible to probe the interactions of a given particle with the Higgs field. However, one can instead measure a particle’s interaction with the excitations of the Higgs field, that is, with a Higgs boson. If the Standard Model provides the correct picture for the generation of mass, the strength of any particle’s interaction with the Higgs boson has to be directly related to that particle’s mass.

Aside from providing a powerful way of testing the Higgs mechanism, the interaction of the Higgs boson with other particles is intriguing because it implies the existence of a ‘fifth force’, mediated by the exchange of Higgs bosons. The fact that such a force is stronger for heavier particles makes it qualitatively different from all other interactions in the Standard Model, whose interaction strengths come in multiples of some basic unit of charge, like the electron charge for the electric force. The pattern is, if anything, more reminiscent of gravity, but with

important differences. One is that the force mediated by the Higgs boson is active only at very short distances, whereas Einstein’s gravity acts over all distance scales. Another is that the Higgs boson couples directly only to elementary Standard Model particles. By contrast, gravity couples to the total mass. In ordinary matter, that total mass is much larger than the sum of the elementary particle masses, because the strong force contributes substantially to the proton and neutron masses<sup>44</sup>.

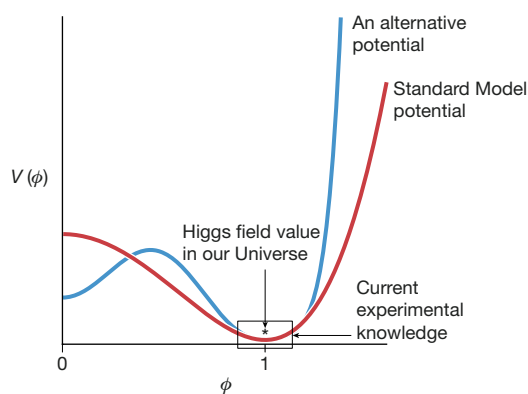
### What we know so far and how

The Higgs mechanism provides the simplest model to explain particle masses in a way that is consistent with the electroweak interactions. As physicists we should seek to establish whether it is the model chosen by nature.

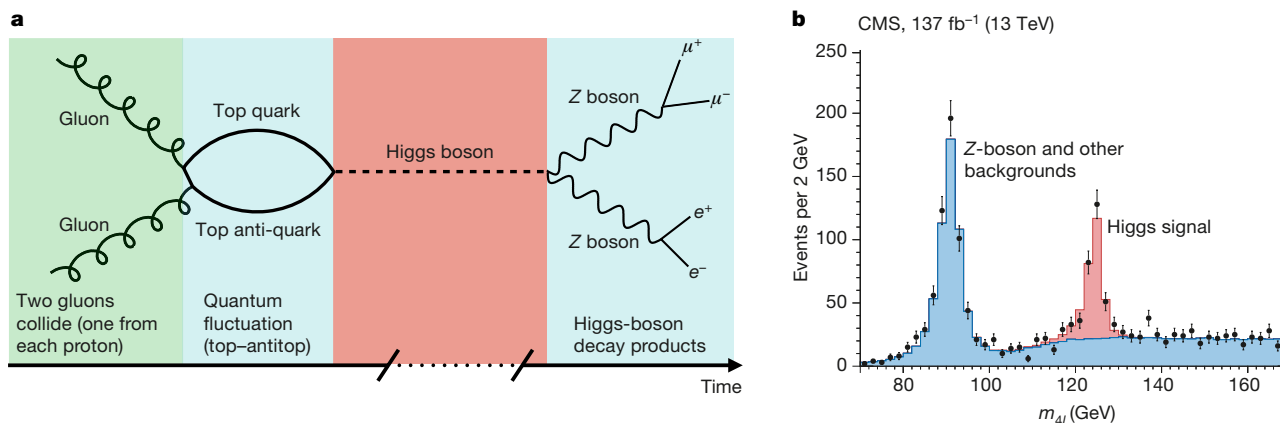
Experimental studies of the Higgs boson take place at particle colliders. The likelihood of producing a Higgs boson in a collision becomes larger when the particles that collide interact strongly with the Higgs field, that is, when they are heavy. At the high centre-of-mass energies that are required, particle physicists know how to collide just two things: protons and electrons, as well as their antiparticles. That poses an issue, because electrons and the particles that make up protons are light, that is, they interact only very weakly with the Higgs boson.

The approach of particle physicists is to exploit the occasional production of heavy particles in the high-energy collision of light particles, and to then have those heavy particles produce a Higgs boson. CERN’s LHC collides protons, which are mostly made of up and down quarks and gluons. The most frequent way of producing a Higgs boson is for a pair of gluons, one from each proton, to collide and create a top quark and a top anti-quark as a very short-lived quantum fluctuation. The top quark is the heaviest known particle (about 184 times the proton mass) and so the top and anti-top quarks interact strongly with the Higgs field, thereby occasionally producing a Higgs boson. A short while later (about  $10^{-22}$  s), the Higgs boson decays. About 2.6% of decays are to a pair of Z bosons, which themselves also decay almost immediately, for example each to an electron–positron or muon–anti-muon pair (so-called charged leptons), which gives a distinctive experimental signature. This sequence is illustrated in Fig. 2a.

The ATLAS and CMS experiments at the LHC select events with four such leptons and record the total of the energy of the leptons (in their centre-of-mass frame). There are a variety of ways in which four leptons can be produced, but for those events in which they come from a Higgs-boson decay, the total energy is expected to cluster around the Higgs mass—the red peak in Fig. 2b. That red peak provides considerable information: (1) the existence of the peak near 125 GeV tells us that there is a new particle, the Higgs boson; (2) the position of the peak indicates the mass of the Higgs boson; (3) other features of the events in the peak, for example the relative angular distributions of



**Fig. 1 | Higgs potential.** The potential energy density  $V(\phi)$  associated with the Higgs field  $\phi$ , as a function of the value of  $\phi$ . The red curve shows the potential within the Standard Model. The Higgs field has a value corresponding to a minimum of the potential and the region highlighted in black represents our current experimental knowledge of the potential. Alternative potentials (for example, the blue curve) would be equally consistent with current data.



**Fig. 2 | Higgs production at the LHC.** **a**, Illustration of one process for the production and decay of a Higgs boson at the LHC. **b**, Total centre-of-mass energy of four leptons ( $4l$ ; electrons and/or muons and their antiparticles) from the CMS experiment; the peak around 125 GeV corresponds to decays of Higgs bosons, whereas the peak near 91.2 GeV corresponds to decays of single

Z bosons (not Higgs-induced), adapted from ref. <sup>95</sup>. The decay to Z bosons was one of the channels used for the discovery of the Higgs boson, with the other important discovery channels being the decay to two  $W$  bosons and that to two photons (the latter proceeds through a quantum fluctuation with top quarks and  $W$  bosons).

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 so<sup>15,16</sup>, in 2018, was a major milestone in particle physics, as were the highly challenging observations of the Higgs boson decaying to bottom quarks<sup>17,18</sup> and  $\tau$  leptons<sup>19,20</sup>. 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 LHC<sup>21,22</sup>.

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

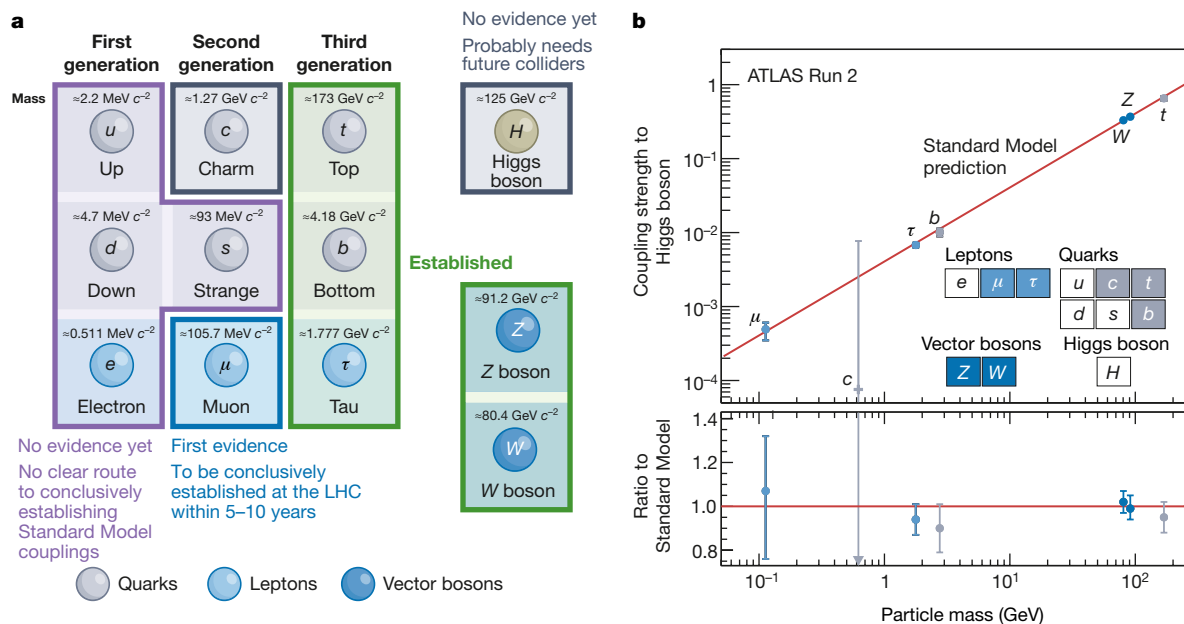
boson been 50 GeV heavier, it would have been almost impossible to detect more than just two basic decay channels (to a pair of  $W$  bosons or a pair of Z bosons). Had it been just 10 GeV lighter, the decays to  $W$  bosons and Z bosons would probably have been impossible to see so far. It was not just 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 second<sup>23,24</sup>. 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. <sup>25</sup>) and the power of machine learning<sup>26</sup>.

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 collisions<sup>27,28</sup>. 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 fluctuations<sup>29</sup>), the more accurately one can relate experimental observations to the Standard Model<sup>30,31</sup>. Finally, Fig. 2 is a vastly simplified picture and the experiments rely profoundly on accurate simulation<sup>32,33</sup> 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.** **a**, 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. <sup>96</sup>). 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 results <sup>97</sup>.

investigation: obtaining higher precision in studies of interactions that have already been observed and detecting further kinds of interactions that are, so far, yet to be seen.

We start with the question of precision. Examining Fig. 3b, one sees that the interactions of the Higgs boson with *W* and *Z* bosons and the third-generation charged leptons and quarks are currently known to a precision of about 5–20%. We would not consider the theory of electromagnetism established if we had only verified the strength of electromagnetic forces to within 10% accuracy.

One of the reasons for aiming for higher precision is that even though the Standard Model Higgs mechanism outlined above is the simplest model that is consistent with data, it is far from being the only viable one. Indeed, as we shall elaborate on below, it is widely believed that the Standard Model as it stands cannot be a complete description of nature. For example, it is conceivable that the Higgs boson is not an elementary particle, but rather is composed of other, yet-to-be-discovered particles. High-precision measurements of Higgs-related processes can be very sensitive to such extensions of the Standard Model. In particular, the rates of Higgs-related processes could be affected by quantum fluctuations involving any new particles. Such effects might be visible even in scenarios where the new particles are too heavy to be directly produced and observed at a given collider. In general, increasing the precision by a factor of four effectively doubles the mass scale that can be indirectly probed for those new particles.

The path for improvement is conceptually straightforward: with 20 times more data to come in the next 15–20 years from the approved high-luminosity upgrade of the LHC, and foreseeable improvements in analysis techniques and theoretical calculations, the ATLAS and CMS experiments expect to determine the currently observed set of interactions to within a couple of percent <sup>34</sup>. Reaching beyond that requires a different kind of collider. An electron–positron collider with centre-of-mass energies of around 250 GeV (a ‘Higgs factory’) <sup>35–39</sup> is widely considered to be a promising option (see the European Strategy for Particle Physics <sup>40</sup>). Advantages are that electrons and positrons, in contrast to protons, are simple fundamental particles, and that the main

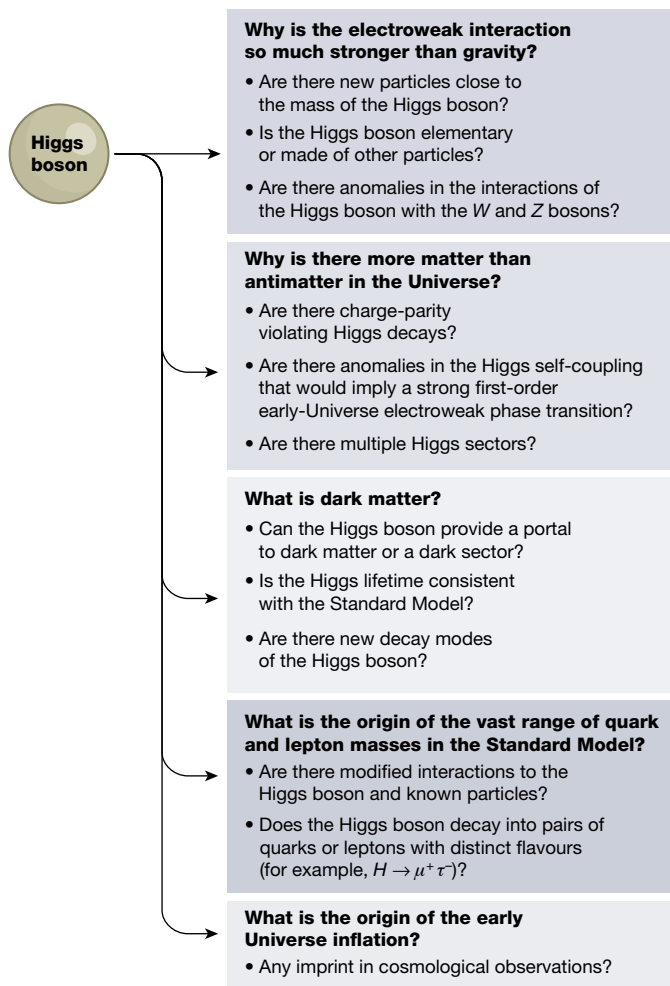
Higgs-boson production mechanisms at an electron–positron collider are largely free of complications associated with strong interactions. Such a collider could improve the precision of our knowledge of the Higgs interactions by a further factor of about ten <sup>41</sup>.

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  $H \rightarrow \mu^+ \mu^-$  decay. So far the data is suggestive of such decays <sup>42,43</sup>, and definitive observation of  $H \rightarrow \mu^+ \mu^-$ , 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 quarks <sup>34</sup> (for example, using ideas such as those in refs. <sup>44,45</sup>). It has long been thought that to definitively observe  $H \rightarrow c\bar{c}$  decays would require a future  $e^+e^-$  collider (or alternatively an electron–proton collider <sup>46</sup>). Significant recent improvements in sensitivity to this decay channel at the LHC <sup>47,48</sup> 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. <sup>49</sup>), 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





**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.

whether precise atomic physics measurements could be sensitive to the Higgs forces involving light quarks<sup>50</sup>; however, this seems challenging<sup>51</sup>.

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  $\phi$ . 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 only<sup>52</sup>) 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 discussion<sup>36,53–56</sup>.

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 boson<sup>57–60</sup> and the nature of Higgs interactions at energies well above the electroweak energy scale<sup>61,62</sup>.

## 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  $10^{32}$ , 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 particles<sup>63</sup>. Examples of other well studied proposals are new (approximate) space–time symmetries<sup>64–66</sup> and new space dimensions<sup>67–70</sup>. More recently, some more speculative ideas suggested possible connections between the weak scale and cosmological evolution<sup>71–73</sup> or the amount of dark energy in the Universe<sup>74,75</sup>.

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  $10^{32}$ . 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 met<sup>76</sup>. 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 asymmetry<sup>77</sup>, 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 experiments<sup>78,79</sup>.

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 well<sup>80–82</sup>. 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’<sup>83</sup>.

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 naturally<sup>84–86</sup>.

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 respect<sup>87</sup>.

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 measured<sup>88–90</sup> at energies nine orders of magnitude beyond the Higgs mass<sup>91,92</sup>. 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 universe 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 inflation<sup>93</sup>.

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.

## Conclusions

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.

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**This article describes the current status of our knowledge of Higgs boson interactions, as measured by the CMS Collaboration.**

**Acknowledgements** Our Perspective on the Higgs sector has been shaped by exchanges with many of our colleagues. In this regard, we especially acknowledge conversations with N. Arkani-Hamed, F. Caola, G. Giudice, C. Grojean, U. Haisch, M. Kado, G. Landsberg, M. Mangano, M. McCullough, P. Nason, M. Reece, G. Servant, R. Sundrum and C. Wagner, and thank a number of them also for valuable comments on this manuscript. G.P.S. is supported by a Royal Society Research Professorship (RP/R1180112) and by the United Kingdom’s Science and Technology Facilities Council (grant no. ST/T000864/1). L.-T.W. is supported by the US Department of Energy (grant no. DE-SC0009924).

**Author contributions** The authors declare that they contributed equally to the manuscript.

**Competing interests** The authors declare no competing interests.

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**Peer review information** Nature thanks Francesco Riva and Shufang Su for their contribution to the peer review of this work.

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