The Higgs adventure: five years in

Five years since the ATLAS and CMS collaborations discovered the Higgs boson, much has been learnt about this most fascinating scalar object. But we are still only at the beginning of our journey of understanding.

Where were you on 4 July 2012, the day the Higgs boson discovery was announced? Many people will be able to answer without referring to their diary. Perhaps you were among the few who had managed to secure a seat in CERN's main auditorium, or who joined colleagues in universities and laboratories around the world to watch the webcast. For me, the memory is indelible: 3.00 a.m. in Watertown, Massachusetts, huddled over my laptop at the kitchen table. It was well worth the tired eyes to witness remotely an event that will happen once in a lifetime.

"I think we have it, no?" was the question posed in the CERN auditorium on 4 July 2012 by Rolf Heuer, CERN's Director-General at the time. The answer was as obvious as the emotion on faces in the crowd. The then ATLAS and CMS spokespersons, Fabiola Gianotti and Joe Incandela, had just presented the latest Higgs search results based on roughly two years of LHC operations at energies of 7 and 8 TeV. Given the hints for the Higgs presented a few months earlier in December 2011, the frenzy of rumours on blogs and intense media interest during the preceding weeks, and a title for the CERN seminar that left little to the imagination, the outcome was anticipated. This did not temper excitement.

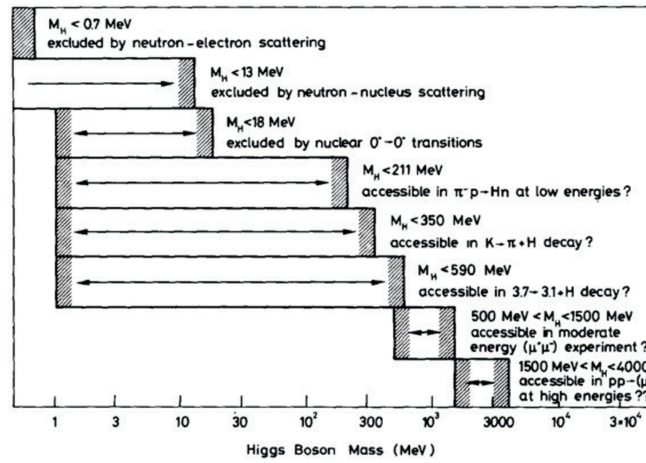
Since then, we have learnt much about the properties of this new scalar particle, yet we are still at the beginning of our understanding. It is the final and most interesting particle of the Standard Model of particle physics (SM), and its connections to many of the deepest current mysteries in physics mean the Higgs will remain a focus of activities for experimentalists and theorists for the foreseeable future.

Speculative theories

The Higgs story began in the 1960s with speculative ideas. Theoretical physicists understood how the symmetries of materials can spontaneously break down, such as the spontaneous alignment of atoms when a magnet is cooled from high temperatures, but it was not yet understood how this might happen for the symmetries present in the fundamental laws of physics. Then, in three separate publications by Brout and Englert, by Higgs, and by Guralnik, Hagen and Kibble in 1964, the broad particle-physics structures for spontaneous symmetry breaking were fleshed out. In this and subsequent work it became clear that a scalar field was a cornerstone of the general symmetry-breaking mechanism. This field may be excited and oscillate, much like the ripples that appear on a disturbed pond, and the excitation of the Higgs field is known as the Higgs boson.

As the detailed theoretical structure of symmetry breaking in nature was later developed, in particular by Weinberg, Glashow, Salam, 't Hooft and Veltman, the precise role of the Higgs in the SM evolved to its modern form. In addition to explaining what we see in modern particle detectors, the Higgs plays a leading role in the evolution of the universe. In the hot early epoch an infinitesimally small fraction of a second after the Big Bang, the Higgs field spontaneously "slipped" from having zero average value everywhere in space to having an average value equivalent to about 246 GeV. When this happened, any field that was previously kept massless by the SU(2) × U(1) gauge symmetries of the SM instantly became massive.

Before delving further into the vital role of the Higgs, it is worth revisiting a couple of common misconceptions. One is that the Higgs boson gives mass to all particles. Although all of the *known* massive fundamental particles obtain their mass by interacting with the pervasive Higgs field, there are non-elementary particles, such as the proton, whose mass is dominated by the binding energy of the strong force that holds its constituent gluons and quarks together. So very little of the mass we see in nature comes directly from the Higgs field. Another misconception is that the Higgs boson gives mass to everything it interacts with. On the contrary, the Higgs has very important interactions with two massless fundamental fields: the photon and the gluon. The Higgs is not charged under the forces associated with the photon and the gluon (quantum electrodynamics and quantum chromodynamics), and therefore cannot give them mass, but it can still interact with them. Indeed, somewhat ironically, it was precisely its interactions with massless gluons and photons that revealed the existence of the Higgs boson in the summer of 2012.



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(Top) In Search of the Higgs Boson, *a series of works produced by artist Xavier Cortada and physicist Pete Markowitz. (Image credit: X Cortada.) Fig. 1. (Above) Possible Higgs boson mass and the relevant method for discovery, as considered in the landmark 1975 paper by Ellis, Gaillard and Nanopoulos.*

The one remaining unmeasured free parameter of the SM at that time, which governs which production and decay modes the particle can have, was the Higgs boson mass. In the early days it was not at all clear what the mass of the Higgs boson would be, since in ▷

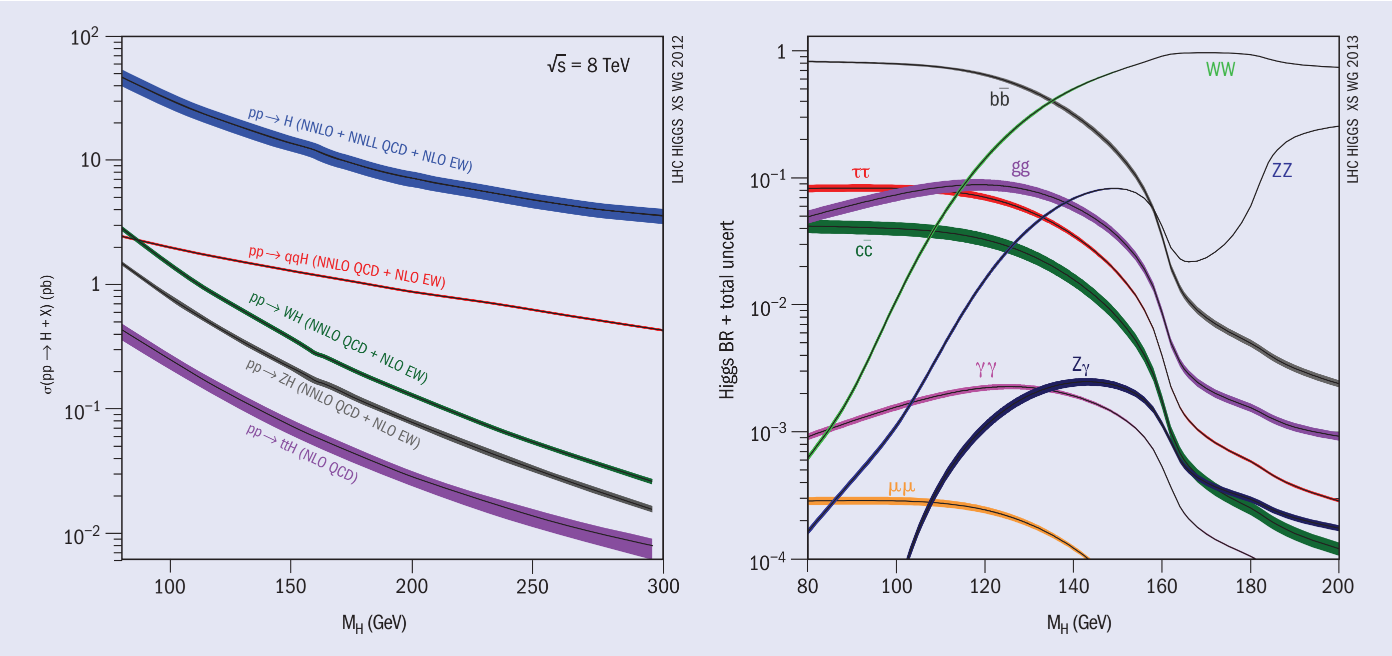

Fig. 2. Possibilities for the Higgs boson discovery at the LHC before 2012. (Left) Different Higgs cross-sections as a function of mass, with lower lines showing scenarios where a Higgs boson is produced in association with another particle and the top line showing the single-Higgs production cross-section, which is dominated by gluon fusion. (Right) The relative rates for the Higgs boson to decay into different particles for different Higgs boson mass values. Lighter Higgs bosons can observably decay to a variety of final states.

the SM this is an input parameter of the theory. Indeed, in 1975, in the seminal paper about its experimental phenomenology by Ellis, Gaillard and Nanopoulos, it is notable that the allowed Higgs mass range at that time spanned four orders of magnitude, from 18 MeV to over 100 GeV, with experimental prospects in the latter energy range opaque at best (figure 1, previous page).

How the Higgs was found

By 4 July 2012 the picture was radically different. The Higgs no-show at previous colliders, including LEP at CERN and the Tevatron at Fermilab, had cornered its mass to be greater than 114 GeV and not to lie between 147–180 GeV, while theoretical limits on the allowed properties of W- and Z-boson scattering required it to be below around 800 GeV. If nature used the SM version of the Higgs mechanism, there was nowhere left to hide once CERN's LHC switched on. In the end, the Higgs weighed in at the relatively light mass of 125 GeV. How the different Higgs cross-sections, which are related to the production rate for various processes, depend on the mass are shown in figure 2, left.

Producing the Higgs would alone not be sufficient for discovery. It would also have to be observed, which depends on the different fractional ways in which the Higgs boson will decay (figure 2, right). If heavy, one would have to search for decays to the weak gauge bosons, W and Z; if lighter, a cocktail of decays would light up detectors. Going further, if thousands of Higgs bosons could be produced, then decays to pairs of photons may show up. Thus, by the time of the LHC operation, the basic theoretical recipe was relatively simple: pick a Higgs mass, calculate the SM predictions and search.

On the other hand, the experimental recipe was far from simple. The LHC, a particle accelerator capable of colliding protons at energies far beyond anything previously achieved, was a necessity. But energy alone was not enough, as sufficient numbers of Higgs bosons also had to be produced. Although occurring at a low rate, Higgs decays into pairs of massless photons would prove to be experimentally clean and furnish the best opportunity for discovery. Once detection efficiencies, backgrounds, and requirements of statistical significance are folded into the mix, on the order of 100,000 Higgs bosons would be required for discovery. This is no short order, yet that is what the accelerator teams delivered to the detectors.

With the accelerator running, it remained to observe the thing. This would push ingenuity to its limits. Physicists on the ATLAS and CMS detectors would need to work night and day to filter through the particle detritus from innumerable proton–proton collisions to select data sets of interest. The search set tremendous challenges for the energy-resolution and particle-identification capabilities of the detectors, not to mention dealing with enormous volumes of data. In the end, the result of this labour reduced to a couple of plots (figure 3). The discovery was clear for each collaboration: a significance pushing the 5σ "discovery" threshold. In further irony for the mass-giving Higgs, the discovery was driven primarily by the rare but powerful diphoton decays, followed closely by Higgs decays to Z bosons. Global media erupted in a science-fuelled frenzy. It turns out that everyone gets excited when a fundamental building block of nature is discovered.

The hard work begins

The joy in the experimental and theoretical communities in the summer of 2012 was palpable. If we were to liken early studies of the electroweak forces to listening to a crackling radio, LEP had given us black and white TV and the LHC was about to show us the world in full cinematic colour. Particle physicists now had the work they had waited a lifetime to do. Is it the SM Higgs boson, or something else, something exotic? All we knew at the time was that there was a new boson, with mass of roughly 125 GeV, that decayed to photons and Z bosons.

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Higgs physics

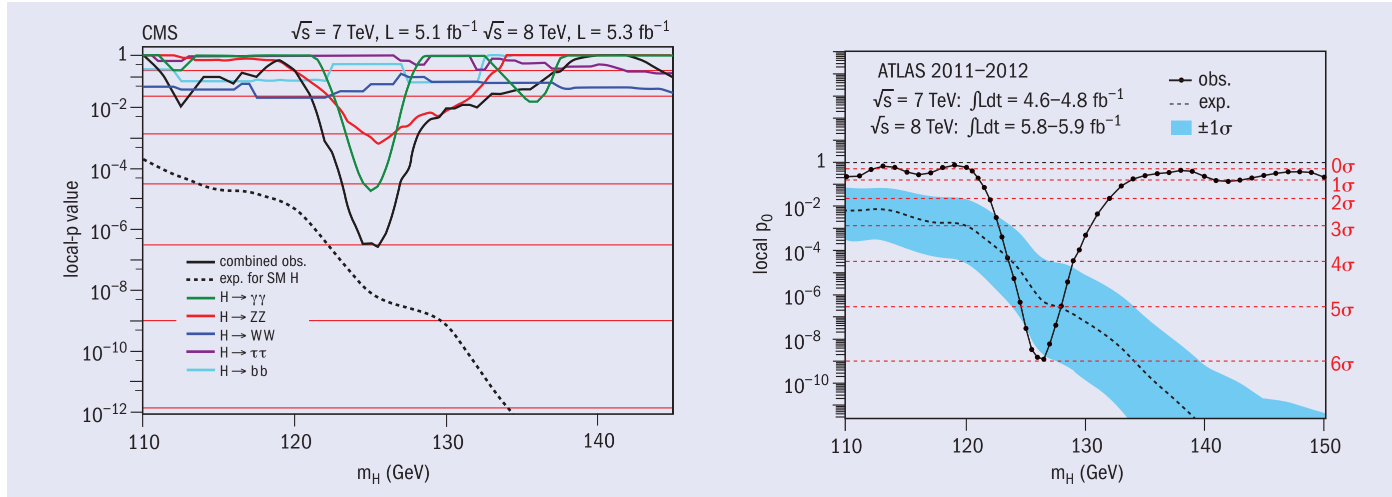

Fig. 3. The discovery of the Higgs boson at ATLAS and CMS, as reported in two papers (arXiv:1207.7214 and arXiv:1207.7235) published after the 4 July announcement. Black lines show the local "p-value", which is the probability that the observation is a statistical fluctuation and not the Higgs boson. This p-value is less than one part in a million, similar to the probability of flipping a coin 21 times and it coming up heads on every occasion, and the significance is peaked at the same mass for both experiments.

Despite the huge success of the SM, there was every reason to hope that the new boson would not be of the common variety. The Higgs brings us face-to-face with questions that the SM cannot answer, such as what constitutes dark matter (observed to make up 80% of all the matter in the universe). Unlike the other SM particles, it is uncharged and without spin, and can therefore interact easily with any other neutral scalar particles. This makes it a formidable tool in the hunt for dark matter – a possibility we often call the "Higgs portal". The ATLAS and CMS collaborations have been busy exploring the Higgs portal and we now know that the Higgs decay rate into invisible new dark particles must be less than 34% of its total rate into known particles. This is an incredible thing to know for a particle that is itself so elusive, and a significant early step for dark-sector physics.

Another deep puzzle, even more esoteric than dark matter and which has driven the theoretical community to distraction for decades, is called the hierarchy problem. We know that at higher energies (smaller sizes) there must be more structure to the laws of nature: the scale of quantum gravity, the Planck scale, is one example, but there are hints of others. For any other SM particle, this new physics at high energies has no dramatic effect, since fundamental particles with nonzero spin possess special protective symmetries that shield them from large quantum corrections. But the Higgs possesses no such symmetry, and is thus a sensitive creature: quantum-mechanical effects will give large corrections to its mass, pulling it all the way up to the masses of the new particles it is interacting with. That has clearly not happened, given the mass we measure in experiments, so what is going on?

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Thus the discovery of the Higgs brings the hierarchy problem to the fore. If the Higgs is composite, being made up of other particles, in a similar fashion to the ubiquitous QCD pion, then the problem simply goes away because there is no fundamental scalar in the first place. Another popular theory, supersymmetry, postulates new space–time symmetries, which protect the Higgs boson from these quantum corrections and could modify its properties. Measurements of the Higgs interactions thus indirectly probe this deepest of questions in modern particle physics. For example, we now know the interaction between the Higgs boson and the Z boson to an accuracy at the level of 10%, a significant constraint on these theories.

It is also crucial that we understand the way the Higgs interacts with fermions. Anyone who has ever looked up the masses of the quarks and leptons will see that they follow cryptic hierarchical patterns, while families of fermions can also mix into one another through the emission of a W boson in peculiar patterns that we do not yet understand. By playing a star role in generating particle masses, and as a supporting actor by also generating the mixings, the Higgs could shed light on these mysteries.

At the time of the Higgs discovery in 2012, the only interactions we were certain of concerned bosons: photons, W and Z bosons, and, to a certain degree, gluons. There was emerging evidence for interactions with top quarks, but it was circumstantial, coming from the role of the top quark in the quantum-mechanical process that generates Higgs interactions with gluons and photons. After a four-year wait, in 2016 ATLAS and CMS combined forces to reach the first 5σ direct discovery of Higgs interactions with a fermion: the τ lepton, to be precise. This was a significant milestone, not least because it also happened to give the first ▷

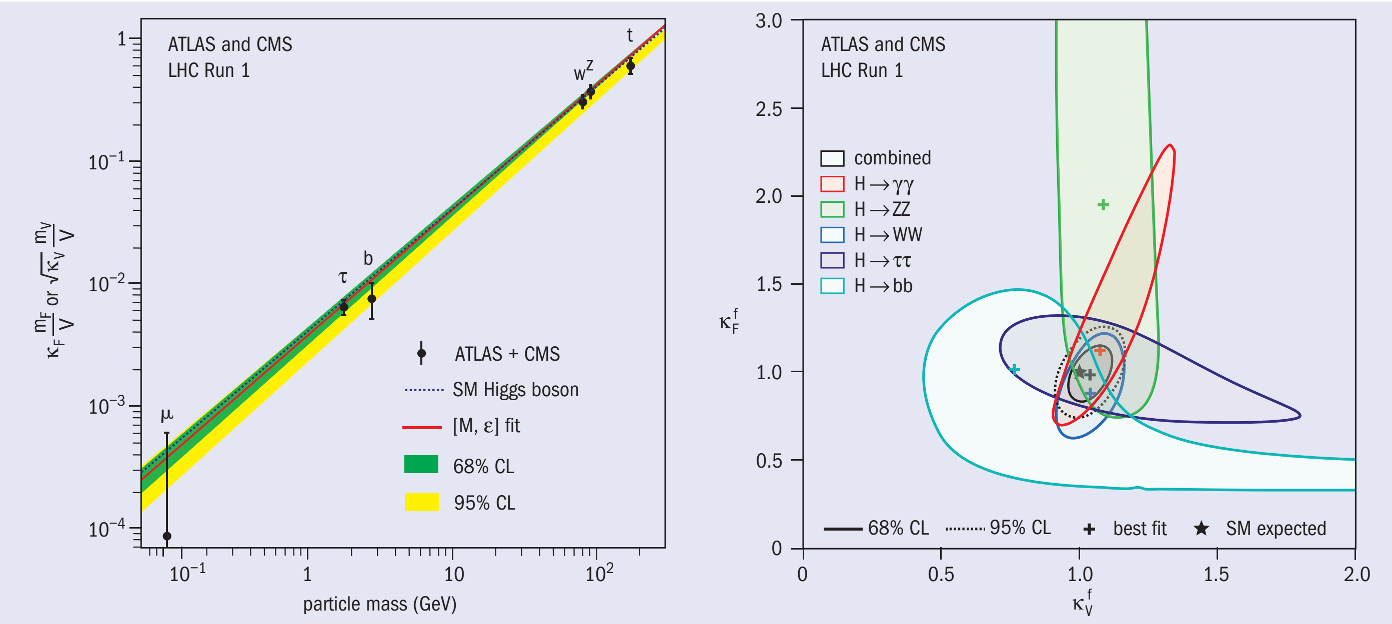

Fig. 4. (Left) The mass the Higgs boson bestows on other particles depends on its interaction strength with that particle. Knowing the mass of a particle we may therefore predict (dashed blue line) how strongly it interacts with the Higgs boson. LHC measurements are shown in black, corroborating the predictions of the SM over many orders of magnitude in interaction strength. (Right) The strength of the Higgs coupling to fermions versus vector bosons, as measured by ATLAS and CMS based on Run 1 data for individual decay channels (colours) and their global combination (grey).

direct evidence of Higgs interactions with leptons.

The scope of the Higgs programme has also broadened since the early days of the discovery. This applies not only to the precision with which certain couplings are measured, but also to the energy at which they are measured. For example, when the Higgs boson is produced via the fusion of two gluons at the LHC, additional gluons or quarks may be emitted at high energies. By observing such "associated production" we may gain information about the magnitude of a Higgs interaction and about its detailed structure. Hence, if new particles that influence Higgs boson interactions exist at high energies, probing Higgs couplings at high energies may reveal their existence. The price to be paid for associated production is that the probability, and hence the rate, is low (figure 2). As an ever increasing number of Higgs production events have been recorded at the LHC in the past five years, this has allowed physicists to begin mapping the nature of the Higgs boson's interactions.

What's next?

We have much to anticipate. Although the Higgs is too light to be able to decay into pairs of top quarks, experimentalists will study its interactions with the top quark by observing Higgs produced in association with pairs of top quarks. Another anticipated discovery, which is difficult to pick out above other background processes, is the decay of the Higgs to bottom quarks. Amazingly, despite the incredibly rare signal rate, the upgraded High-Luminosity LHC will be able to discover Higgs decays to muons. This would be the first observation of Higgs interactions with the second generation of fermions, pointing a floodlight towards the flavour puzzle. These measurements will bring the overall picture of how the Higgs generates particle masses into closer focus. Even now, after only five years, the picture is becoming clear: Higgs physics is becoming a precision science at the LHC (figure 4).

There is more to Higgs physics than a shopping list of couplings, however. By the end of the LHC's operation in the mid-2030s, more than one hundred million Higgs bosons will have been produced. That will allow us to search for extremely rare and exotic Higgs production and decay modes, perhaps revealing a first crack in the SM. On the opposing flank, by observing the standard production processes in extreme kinematic corners, such as Higgs production at very high momentum, we will be able to measure its interactions over a range of energies. In both cases the challenge will not only be experimental, as the SM predictions must also keep pace with the accuracy of the measurements – a fact which is already driving revolutions in our theoretical understanding (*CERN Courier* April 2017 p18).

Setting our sights on the distant future of Higgs physics, it would be remiss to overlook the "white whale" of Higgs physics: the Higgs self-interaction. In yet another unique twist, the Higgs is the only particle in the SM that can scatter off itself (figure 5). In contrast, gluons only interact with other non-identical gluons. If we could access the Higgs self-interactions, by determining how a Higgs boson scatters on itself in measurements of Higgs boson pair-production processes, we would be measuring the shape of the Higgs scalar potential. This is tremendously important because, in theory, it determines the fate of the entire universe: if the scalar potential "turns back over" again at high field values, it would imply that we live in a metastable state. There is mounting evidence, in the form of the measured SM parameters such as the mass of the top quark, that this may be the case. Unfortunately, with the LHC we will not be able to measure this

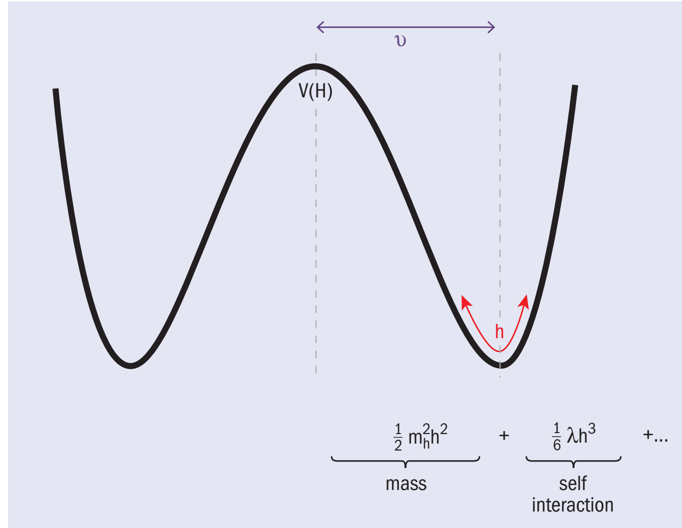

Fig. 5. The Higgs field sits at the bottom of its so-called "Mexican-hat" scalar potential. The second derivative of this potential is its mass, the third is its self-interaction, and so on to the fourth derivative, which allows four Higgs bosons to interact. Thus by measuring these interactions we would directly probe the shape of the scalar potential, and hence the dynamical mechanism by which the Higgs field spontaneously broke electroweak symmetry in the early universe.

interaction well enough to definitively determine the shape of the Higgs scalar potential, and so we must ultimately look to future colliders to answer this question, among others.

The Higgs is the keystone of the SM and therefore everything we learn about this new particle is central to the deepest laws of nature. When huddled over my laptop at 3.00 a.m. on 4 July 2012, I was 27 years old and in the first year of my first postdoctoral position. To me, and presumably the rest of my generation, it felt like a new scientific continent had been discovered, one that would take a lifetime to explore. On that day we finally knew it existed. Today, after five years of feverish exploration, we have in our hands a sketch of the coastline. We have much to learn before the mountains and valleys of the enigmatic Higgs boson are revealed.

Résumé

L'aventure du Higgs fête ses cinq ans

Cela fait cinq ans que les collaborations ATLAS et CMS ont annoncé la découverte du boson de Higgs au CERN. Depuis lors, la moisson de données du LHC nous en a appris beaucoup sur les propriétés de cette nouvelle particule scalaire, mais nous n'en sommes encore qu'au début. Particule finale et peut-être la plus intéressante du Modèle standard de la physique des particules, le boson de Higgs, qui est lié à certains des plus grands mystères actuels de la physique, restera ces prochaines années un important sujet d'étude pour les expérimentateurs comme pour les théoriciens. Il s'agit également d'un ingrédient crucial en ce qui concerne les arguments scientifiques pour un collisionneur post-LHC.

Matthew McCullough, CERN.