

THE *Current*

July 5, 2022

Current Staff

The Higgs Discovery at 10

Ten years ago, on July 4 2012, the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) announced the discovery of a new particle with features consistent with those of the Higgs boson predicted by the Standard Model of particle physics. The discovery was a landmark in the history of science and captured the world's attention. One year later it won François Englert and Peter Higgs the Nobel Prize in Physics for their prediction made decades earlier, together with the late Robert Brout, of a new fundamental field, known as the Higgs field, that pervades the universe, manifests itself as the Higgs boson and gives mass to the elementary particles.

“The discovery of the Higgs boson was a monumental milestone in particle physics. It marked both the end of a decades-long journey of exploration and the beginning of a new era of studies of this very special particle,” said Fabiola Gianotti, CERN’s Director-General and the project leader (‘spokesperson’) of the ATLAS experiment at the time of the discovery. “I remember with emotion the day of the announcement, a day of immense joy for the worldwide particle physics community and for all the people who worked tirelessly over decades to make this discovery possible.”

The search for the Higgs boson was an international effort, with the participation of scientists from research institutions all over the world, including UC Santa Barbara. Physics professors Claudio Campagnari, Joe Incandela, Jeffrey Richman and David Stuart — members of UCSB's High Energy Physics Group — along with their teams of students, postdocs and engineers were among the scientists who ushered in the discovery of the Higgs boson. Incandela also served as project leader for the CMS

collaboration at the time of the discovery.

In just ten years physicists have made tremendous steps forward in our understanding of the universe, not only confirming early on that the particle discovered in 2012 is indeed the Higgs boson but also allowing researchers to start building a picture of how the pervasive presence of a Higgs field throughout the universe was established a tenth of a billionth of a second after the Big Bang.

The new journey so far

The new particle discovered by the international ATLAS and CMS collaborations in 2012 appeared very much like the Higgs boson predicted by the Standard Model. But was it actually that long-sought-after particle? As soon as the discovery had been made, ATLAS and CMS set out to investigate in detail whether the properties of the particle they had discovered truly matched those predicted by the Standard Model. By using data from the disintegration, or 'decay', of the new particle into two photons, the carriers of the electromagnetic force, the experiments have demonstrated that the new particle has no intrinsic angular momentum, or quantum spin – exactly like the Higgs boson predicted by the Standard Model. By contrast, all other known elementary particles have spin: the matter particles, such as the 'up' and 'down' quarks that form protons and neutrons, and the force-carrying particles, such as the W and Z bosons.

By observing the Higgs bosons being produced from and decaying into pairs of W or Z bosons, ATLAS and CMS confirmed that these gain their mass through their interactions with the Higgs field, as predicted by the Standard Model. The strength of these interactions explains the short range of the weak force, which is responsible for a form of radioactivity and initiates the nuclear fusion reaction that powers the Sun.

The experiments have also demonstrated that the top quark, bottom quark and tau lepton – which are the heaviest fermions – obtain their mass from their interactions with the Higgs field, again as predicted by the Standard Model. They did so by observing, in the case of the top quark, the Higgs boson being produced together with pairs of top quarks, and in the cases of the bottom quark and tau lepton, the boson's decay into pairs of bottom quarks and tau leptons respectively. These observations confirmed the existence of an interaction, or force, called the Yukawa interaction, which is part of the Standard Model but is unlike all other forces in the

Standard Model: it is mediated by the Higgs boson, and its strength is not quantized, that is, it doesn't come in multiples of a certain unit.

ATLAS and CMS measured the Higgs boson's mass to be 125 billion electronvolts (GeV), with an impressive precision of almost one per mil. The mass of the Higgs boson is a fundamental constant of nature that is not predicted by the Standard Model. Moreover, together with the mass of the heaviest known elementary particle, the top quark, and other parameters, the Higgs boson's mass may determine the stability of the universe's vacuum.

These are just a few of the concrete results of ten years of exploration of the Higgs boson at the world's largest and most powerful collider – the only place in the world where this unique particle can be produced and studied in detail.

“The large data samples provided by the LHC, the exceptional performance of the ATLAS and CMS detectors, and new analysis techniques have allowed both collaborations to extend the sensitivity of their Higgs-boson measurements beyond what was thought possible when the experiments were designed,” said ATLAS spokesperson Andreas Hoecker.

In addition, since the LHC started colliding protons at record energies in 2010, and thanks to the unprecedented sensitivity and precision of the four main experiments, the LHC collaborations have discovered more than 60 composite particles predicted by the Standard Model, some of which are exotic ‘tetraquarks’ and ‘pentaquarks’. The experiments have also revealed a series of intriguing hints of deviations from the Standard Model that compel further investigation, and have studied the quark–gluon plasma that filled the universe in its early moments in unprecedented detail. They have also observed many rare particle processes, made ever more precise measurements of Standard Model phenomena, and broken new ground in searches for new particles beyond those predicted by the Standard Model, including particles that may make up the dark matter that accounts for most of the mass of the universe.

The results of these searches add important pieces to our understanding of fundamental physics. “Discoveries in particle physics don't have to mean new particles,” said CERN's Director for Research and Computing, Joachim Mnich. “The LHC results obtained over a decade of operation of the machine have allowed us to spread a much wider net in our searches, setting strong bounds on possible

extensions of the Standard Model, and to come up with new search and data-analysis techniques.”

Remarkably, all of the LHC results obtained so far are based on just 5% of the total amount of data that the collider will deliver in its lifetime. “With this ‘small’ sample, the LHC has allowed big steps forward in our understanding of elementary particles and their interactions,” said CERN theorist Michelangelo Mangano. “And while all the results obtained so far are consistent with the Standard Model, there is still plenty of room for new phenomena beyond what is predicted by this theory.”

“The Higgs boson itself may point to new phenomena, including some that could be responsible for the dark matter in the universe,” said CMS spokesperson Luca Malgeri. “ATLAS and CMS are performing many searches to probe all forms of unexpected processes involving the Higgs boson.”

The journey that still lies ahead

What’s left to be learned about the Higgs field and the Higgs boson ten years on? A lot. Does the Higgs field also give mass to the lighter fermions or could another mechanism be at play? Is the Higgs boson an elementary or composite particle? Can it interact with dark matter and reveal the nature of this mysterious form of matter? What generates the Higgs boson’s mass and self-interaction? Does it have twins or relatives?

Finding the answers to these and other intriguing questions will not only further our understanding of the universe at the smallest scales but may also help unlock some of the biggest mysteries of the universe as a whole, such as how it came to be the way it is and what its ultimate fate might be. The Higgs boson’s self-interaction, in particular, might hold the keys to a better understanding of the imbalance between matter and antimatter and the stability of the vacuum in the universe.

Since the discovery of the Higgs boson ten years ago, members of the UCSB High Energy Physics group have been busy studying some of the properties of this particle such as its lifetime and its interactions with top and charmed quarks. They have also used Higgs bosons as a tool to search for new physics phenomena. The effort at UCSB is broad, with many postdocs, graduate students, and undergraduates involved in the effort to build the detector, operate and upgrade it, develop the software algorithms, analyze the data, and publish the results. UCSB’s

effort has been funded throughout the time of the Higgs discovery, and since, by the US Dept. of Energy Office of Science and the National Science Foundation.

While answers to some of the new questions might be provided by data from the imminent third run of the LHC or from the collider's major upgrade, the high-luminosity LHC, from 2029 onwards, answers to other enigmas are thought to be beyond the reach of the LHC, requiring a future 'Higgs factory'. For this reason, CERN and its international partners are investigating the technical and financial feasibility of a much larger and more powerful machine, the Future Circular Collider, in response to a recommendation made in the latest update of the European Strategy for Particle Physics.

"High-energy colliders remain the most powerful microscope at our disposal to explore nature at the smallest scales and to discover the fundamental laws that govern the universe," said Gian Giudice, head of CERN's Theory department. "Moreover, these machines also bring tremendous societal benefits."

Historically, the accelerator, detector and computing technologies associated with high-energy colliders have had a major positive impact on society, with inventions such as the World Wide Web, the detector developments that led to the PET (Positron Emission Tomography) scanner, and the design of accelerators for hadron therapy in the treatment of cancers. Furthermore, the design, construction and operation of particle physics colliders and experiments have resulted in the training of new generations of scientists and professionals in other fields, and in a unique model of international collaboration.

-Sarah Charley, CERN

About UC Santa Barbara

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