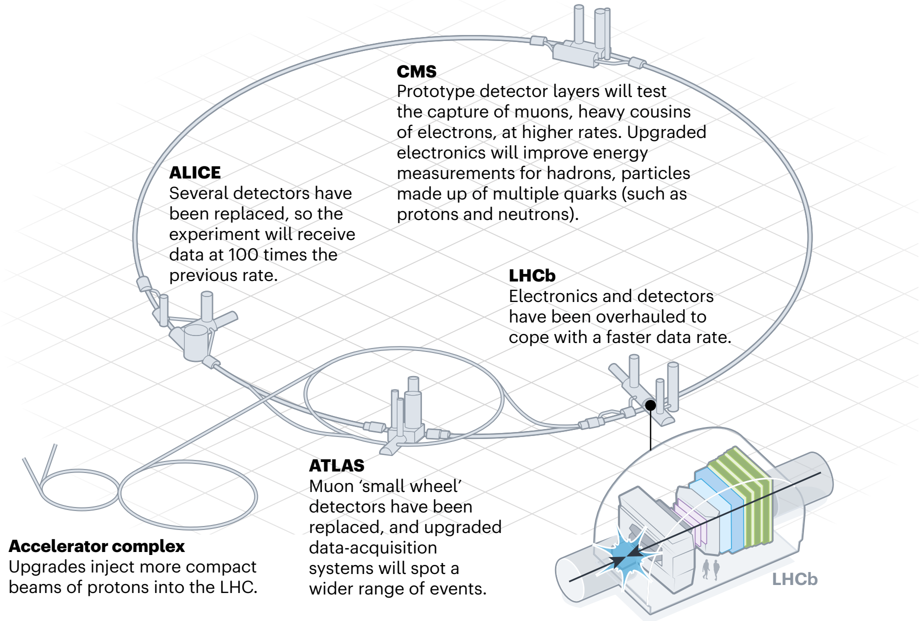
DATA BOOST

In the third run of the Large Hadron Collider (LHC), researchers expect to collect as much information on particle collisions as in the machine's first two runs combined. That's thanks to more tightly packed beams and upgrades at the machine's four main detectors.



CMS
Prototype detector layers will test the capture of muons, heavy cousins of electrons, at higher rates. Upgraded electronics will improve energy measurements for hadrons, particles made up of multiple quarks (such as protons and neutrons).

ALICE
Several detectors have been replaced, so the experiment will receive data at 100 times the previous rate.

LHCb
Electronics and detectors have been overhauled to cope with a faster data rate.

ATLAS
Muon 'small wheel' detectors have been replaced, and upgraded data-acquisition systems will spot a wider range of events.

Accelerator complex
Upgrades inject more compact beams of protons into the LHC.

NIK SPENCER/*NATURE*; SOURCE: CERN

These discrepancies include an apparent preference for bottom quarks to decay into electrons rather than their heavier cousins, muons, when the standard model predicts roughly equal numbers of both. If such anomalies are genuine, they could help physicists to explain mysterious features of the Universe that the standard model can't account for – such as why matter is everywhere but antimatter is scarce. But, if the anomalies arose through chance fluctuations, more data would see the hints fade away.

Back on the beam

Beams have been circulating in the LHC since April, and some collisions have taken place. But only on 5 July was the beam declared safe enough for the experiments to be switched on. Among them are ATLAS and CMS, the LHC's general-purpose experiments designed to study a wide range of physics.

The particle beam has the power to damage detectors and machinery, so engineers will start cautiously, circulating only a minimum number of protons. This number will then increase over the course of the year, says Mike Lamont, who is director for accelerators and technology at CERN. Eventually, the energy of the beam will be that of a train going at 150 kilometres per hour, "so we have to be very, very careful about this", he says.

During the shutdown – extended by the COVID-19 pandemic – the CERN team upgraded the accelerator complex, which generates and accelerates the particle beam. This included installing a new proton source to replace technology that had been in use since 1978. Physicists upgraded the experiments' detectors, in particular improving their electronics and computing system to deal with the greater collision intensity. In the CMS and ATLAS experiments, the LHC will collide bunches of around 100 billion protons at a rate of 40 million collisions per second. Each one will produce around 60 proton–proton smashes – each of which will generate hundreds of particles.

Two large experiments have been completely overhauled: LHCb and ALICE, which studies a dense form of matter known as quark–gluon plasma. Whereas CMS and ATLAS should, in effect, double their rates of data creation, LHCb's rate will be 10 times higher than it was, and ALICE will aim to record 50 times as many collisions as before.

High-luminosity machine

The beam, which feeds all the detectors, starts at a low intensity, so it will take months before enough data are available for analysis to begin in earnest, says Shears. Physicists will need to recalibrate the experiments to the new beam and check that the revamped detectors are working as hoped, before making new findings. "You're not going to see results coming out on day one," she says.

The LHC will run for four years, until collisions stop to make way for upgrades to an even more intensive machine. This one, known as the High-Luminosity LHC, will start operating in 2029 and will ultimately produce ten times the data of the LHC's first three runs combined.

Ahead of the start-up, CERN director-general Fabiola Gianotti said it was her dream for the LHC's third run to find particles that make up dark matter – the mysterious substance that physicists think accounts for 85% of the matter in the Universe. But the experiments' goals are not to chase any particular theory but to "understand how nature works at the most fundamental level", she said.

HIGGS BOSON 10 YEARS ON: WHAT SCIENTISTS DO AND DON'T KNOW

It's been a decade since the particle's discovery. But many of its properties remain mysterious.

By Elizabeth Gibney

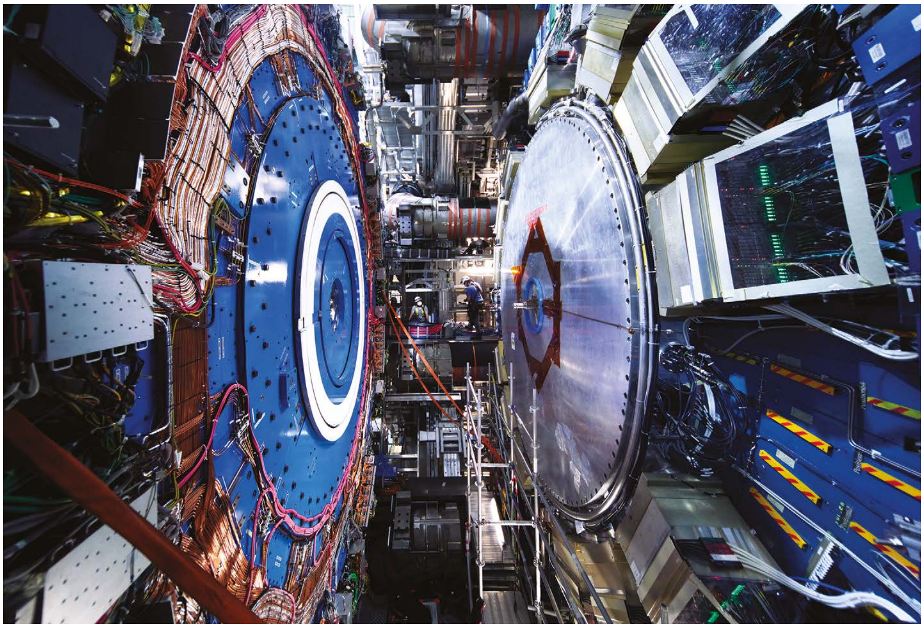
On 4 July 2012, physicists at CERN, Europe's particle-physics laboratory, declared victory in their long search for the Higgs boson. The elusive particle's discovery filled in the last gap in the standard model – physicists' best description of particles and forces – and opened a new window on physics by providing a way to learn about the Higgs field, which involves a previously unstudied kind of interaction that gives particles their masses.

Since then, researchers at CERN's Large Hadron Collider (LHC) near Geneva, Switzerland, have been busy, publishing almost 350 scientific articles about the Higgs boson. Nevertheless, many of its properties remain a mystery.

Ten years after the Higgs boson's discovery, *Nature* looks at what it has taught us about the Universe, as well as some of the big questions that remain.

4 things scientists have learnt

The Higgs boson's mass is 125 billion electronvolts. Physicists expected to find the Higgs boson eventually, but they didn't know when. In the 1960s, physicist Peter Higgs and others theorized that what's now called a Higgs field could explain why the photon has no mass and why the *W* and *Z* bosons, which carry the weak nuclear force that is behind radioactivity,



Part of the Large Hadron Collider's ATLAS detector.

MAXIMILIEN BRICE, JULIEN MARIUS ORDAN/CERN

are heavy (for subatomic particles). The special properties of the Higgs field allowed the same mathematics to account for the masses of all particles, and it became an essential part of the standard model.

The LHC started gathering data in its search for the Higgs in 2009, and both ATLAS and CMS, the accelerator's general-purpose detectors, saw it in 2012. The detectors observed the decay of just a few dozen Higgs bosons into photons, *W*s and *Z*s, which revealed a bump in the data at 125 billion electronvolts (GeV), about 125 times the mass of the proton.

The Higgs's mass of 125 GeV puts it in a sweet spot that means the boson decays into a wide range of particles at a frequency high enough for LHC experiments to observe, says Matthew Mccullough, a theoretical physicist at CERN. "It's very bizarre and probably happenstance, but it just so happens that [at this mass] you can measure loads of different things about the Higgs."

The Higgs boson is a spin-zero particle. Spin is an intrinsic quantum-mechanical property of a particle, often pictured as an internal bar magnet. All other known fundamental particles have a spin of 1/2 or 1, but theories predicted that the Higgs should be unique in having a spin of zero (it was also correctly predicted to have zero charge).

In 2013, CERN experiments studied the angle at which photons produced in Higgs boson decays flew out into the detectors, and used this to show with high probability that the particle had zero spin.

The Higgs's properties rule out some theories that extend the standard model. Physicists know that the standard model is not complete. It breaks down at high energies and can't explain key observations, such as the existence of dark matter or why there is so little antimatter in the Universe. So physicists have come up with extensions to the model that account for these. Discovering the Higgs boson's 125-GeV mass has made some of these theories less attractive. But the mass is in a grey zone, which means it rules out very little categorically, says Freya Blekman, a particle physicist at the German Electron Synchrotron (DESY) in Hamburg. "What we have is a particle that's consistent with more or less anything," she says.

The Universe is stable – but only just. Calculations using the mass of the Higgs boson suggest that the Universe might be only temporarily stable, and there's a vanishingly small chance that it could shift into a lower energy state – with catastrophic consequences.

Unlike other known fields, the Higgs field has a lowest energy state above zero even in a vacuum, and it pervades the entire Universe. According to the standard model, this 'ground state' depends on how particles interact with the field. Soon after physicists discovered the Higgs boson's mass, theorists used the value to predict that there also exists a lower, more preferable energy state.

Shifting to this other state would require it to overcome an enormous energy barrier, and the probability of this is so small that it is unlikely to occur on the timescale of the lifetime of the Universe. "Our doomsday will be much sooner, for other reasons," says Mccullough.

> **"It just so happens that you can measure loads of different things about the Higgs."**

4 things scientists still want to know

Can we make Higgs measurements more precise? So far, the Higgs boson's properties – such as its interaction strength – match those predicted by the standard model, but with an uncertainty of around 10%. This is not good enough to reveal the subtle differences predicted by new physics theories, which are only slightly different from the standard model, says Blekman.

More data will increase the precision of these measurements and the LHC has collected just one-twentieth of the total amount of information it is expected to gather.

Does the Higgs interact with lighter particles? Until now, the Higgs boson's interactions have seemed to fit with the standard model, but physicists have seen it decay into only the heaviest matter particles, such as the bottom quark. Physicists now want to check whether it interacts in the same way with particles from lighter families, known as generations. In 2020, CMS and ATLAS saw one such interaction – the rare decay of a Higgs to a second-generation cousin of the electron called the muon (The CMS collaboration. *J. High Energ. Phys.* **2021**, 148; 2021). Although this is evidence that the relationship between mass and interaction strength holds for lighter particles, physicists need more data to confirm it.

Does the Higgs interact with itself? The Higgs boson has mass, so it should interact with itself. But such interactions – for example, the decay of an energetic Higgs boson to two less energetic ones – are extremely rare, because all the particles involved are so heavy. ATLAS and CMS hope to find hints of the interactions after a planned upgrade to the LHC from 2026, but conclusive evidence will probably require a more powerful collider.

What is the Higgs boson's lifetime? Physicists want to know the lifetime of the Higgs – how long, on average, it sticks around before decaying to other particles – because any deviation from predictions could point to interactions with unknown particles, such as those that make up dark matter. But its lifetime is too small to measure directly.

To measure it indirectly, physicists look at the spread, or 'width', of the particle's energy over multiple measurements (quantum physics says that uncertainty in the particle's energy should be inversely related to its lifetime). Last year, CMS physicists produced their first rough measurement of the Higgs's lifetime: 2.1×10^{-22} seconds (The CMS collaboration. Preprint at https://arxiv.org/abs/2202.06923; 2022). The results suggest that the lifetime is consistent with the standard model.