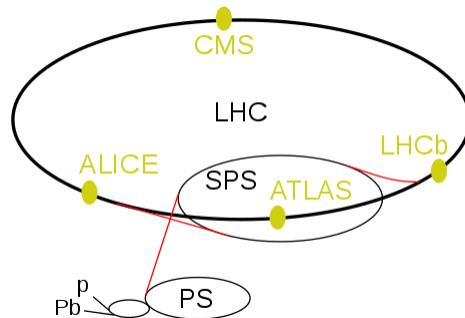


Large Hadron Collider

The **Large Hadron Collider (LHC)** is the world's largest and highest-energy particle collider and the largest machine in the world.^{[1][2]} It was built by the European Organization for Nuclear Research (CERN) between 1998 and 2008 in collaboration with over 10,000 scientists and hundreds of universities and laboratories, as well as

more than 100 countries.^[3] It lies in a tunnel 27 kilometres (17 mi) in circumference and as deep as 175 metres (574 ft) beneath the France–Switzerland border near Geneva.

Large Hadron Collider (LHC)



LHC experiments

ATLAS

A Toroidal LHC
Apparatus

CMS

Compact Muon
Solenoid

LHCb

LHC-beauty

ALICE

A Large Ion Collider
Experiment

TOTEM

Total Cross Section,
Elastic Scattering and
Diffraction Dissociation

<u>LHCf</u>	LHC-forward
<u>MoEDAL</u>	Monopole and Exotics Detector At the LHC
LHC preaccelerators	
p and Pb	<u>Linear accelerators</u> for <u>protons</u> (Linac 2) and <u>Lead</u> (Linac 3)
(not marked)	<u>Proton Synchrotron</u> <u>Booster</u>
PS	<u>Proton Synchrotron</u>
SPS	<u>Super Proton</u> <u>Synchrotron</u>

Hadron colliders

<u>Intersecting Storage Rings</u>	<u>CERN</u>, 1971–1984
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<u>Proton-Antiproton Collider (SPS)</u>	<u>CERN</u>, 1981–1991
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<u>ISABELLE</u>	<u>BNL</u>, cancelled in 1983
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<u>Tevatron</u>	<u>Fermilab</u>, 1987–2011
------------------------	-----------------------------------

<u>Superconducting Super Collider</u>	Cancelled in 1993
--	-------------------

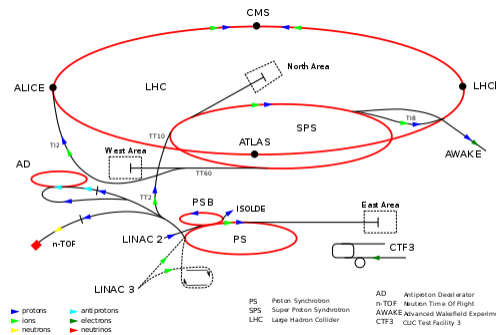
<u>Relativistic Heavy Ion Collider</u>	<u>BNL</u>, 2000–present
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<u>Large Hadron Collider</u>	<u>CERN</u>, 2009–present
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<u>Future Circular Collider</u>	Proposed
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CERN

accelerator complex



List of current particle accelerators at CERN

Linac 2

Accelerates protons

Linac 3

Accelerates ions

Linac 4

Accelerates negative hydrogen ions

AD

Decelerates antiprotons

LHC

Collides protons or heavy ions

<u>LEIR</u>	Accelerates <u>ions</u>
<u>PSB</u>	Accelerates protons or ions
<u>PS</u>	Accelerates protons or ions
<u>SPS</u>	Accelerates protons or ions

First collisions were achieved in 2010 at an energy of 3.5 teraelectronvolts (TeV) per beam, about four times the previous world record.^{[4][5]} After upgrades it reached 6.5 TeV per beam (13 TeV total collision energy, the present world record).^{[6][7][8][9]} At the end of 2018, it entered a two-year shutdown period for further upgrades.

The collider has four crossing points, around which are positioned seven detectors, each designed for certain kinds of research. The LHC primarily collides proton beams, but it can also use beams of heavy ions: Lead–lead collisions and proton-lead collisions are typically done for one month per year. The aim of the LHC's detectors is to allow physicists to test the predictions of different theories of particle physics, including measuring the properties of the Higgs boson^[10] and searching for the large family of new particles predicted by supersymmetric theories,^[11] as well as other unsolved questions of physics.

Background

The term hadron refers to composite particles composed of quarks held together by the strong force (as atoms and molecules are held together by the electromagnetic force).^[12] The best-known hadrons are the baryons such as protons and neutrons; hadrons also include mesons such as the pion and kaon, which were discovered during cosmic ray experiments in the late 1940s and early 1950s.^[13]

A collider is a type of a particle accelerator with two directed beams of particles. In

particle physics, colliders are used as a research tool: they accelerate particles to very high kinetic energies and let them impact other particles.^[1] Analysis of the byproducts of these collisions gives scientists good evidence of the structure of the subatomic world and the laws of nature governing it. Many of these byproducts are produced only by high-energy collisions, and they decay after very short periods of time. Thus many of them are hard or nearly impossible to study in other ways.^[14]

Purpose

Many physicists hope that the Large Hadron Collider will help answer some of the fundamental open questions in physics, which concern the basic laws governing the interactions and forces among the elementary objects, the deep structure of space and time, and in particular the interrelation between quantum mechanics and general relativity.^[15]

Data are also needed from high-energy particle experiments to suggest which versions of current scientific models are more likely to be correct – in particular to choose between the Standard Model and

Higgsless model and to validate their predictions and allow further theoretical development.

Issues explored by LHC collisions include:^{[16][17]}

- is the mass of elementary particles being generated by the Higgs mechanism via electroweak symmetry breaking?^[18] It was expected that the collider experiments will either demonstrate or rule out the existence of the elusive Higgs boson, thereby allowing physicists to consider whether the Standard Model or its Higgsless

alternatives are more likely to be correct.^{[19][20]}

- is supersymmetry, an extension of the Standard Model and Poincaré symmetry, realized in nature, implying that all known particles have supersymmetric partners?^{[21][22][23]}
- Are there extra dimensions,^[24] as predicted by various models based on string theory, and can we detect them?^[25]
- What is the nature of the dark matter that appears to account for 27% of the mass-energy of the universe?

Other open questions that may be explored using high-energy particle collisions:

- It is already known that electromagnetism and the weak nuclear force are different manifestations of a single force called the electroweak force. The LHC may clarify whether the electroweak force and the strong nuclear force are similarly just different manifestations of one universal unified force, as predicted by various Grand Unification Theories.
- Why is the fourth fundamental force (gravity) so many orders of magnitude

weaker than the other three fundamental forces? See also Hierarchy problem.

- Are there additional sources of quark flavour mixing, beyond those already present within the Standard Model?
- Why are there apparent violations of the symmetry between matter and antimatter? See also CP violation.
- What are the nature and properties of quark–gluon plasma, thought to have existed in the early universe and in certain compact and strange astronomical objects today? This will be investigated by *heavy ion collisions*,

mainly in ALICE, but also in CMS, ATLAS and LHCb. First observed in 2010, findings published in 2012 confirmed the phenomenon of jet quenching in heavy-ion collisions.^{[26][27][28]}

Design

The collider is contained in a circular tunnel, with a circumference of 26.7 kilometres (16.6 mi), at a depth ranging from 50 to 175 metres (164 to 574 ft) underground.

Map of the Large Hadron Collider at CERN

The 3.8-metre (12 ft) wide concrete-lined tunnel, constructed between 1983 and 1988, was formerly used to house the Large Electron–Positron Collider.^[29] The tunnel crosses the border between Switzerland and France at four points, with most of it in France. Surface buildings hold ancillary equipment such as compressors, ventilation equipment, control electronics and refrigeration plants.

Superconducting quadrupole electromagnets are used to direct the beams to four intersection points, where interactions between accelerated protons will take place.

The collider tunnel contains two adjacent parallel beamlines (or *beam pipes*) each containing a beam, which travel in opposite directions around the ring. The beams intersect at four points around the ring, which is where the particle collisions take place. Some 1,232 dipole magnets

keep the beams on their circular path (see image^[30]), while an additional 392 quadrupole magnets are used to keep the beams focused, with stronger quadrupole magnets close to the intersection points in order to maximize the chances of interaction where the two beams cross. Magnets of higher multipole orders are used to correct smaller imperfections in the field geometry. In total, about 10,000 superconducting magnets are installed, with the dipole magnets having a mass of over 27 tonnes.^[31] Approximately 96 tonnes of superfluid helium-4 is needed to keep the magnets, made of copper-clad

niobium-titanium, at their operating temperature of 1.9 K ($-271.25\text{ }^{\circ}\text{C}$), making the LHC the largest cryogenic facility in the world at liquid helium temperature. LHC uses 470 tonnes of Nb-Ti superconductor.^[32]

During LHC operations, the CERN site draws roughly 200 MW of electrical power from the French electrical grid, which, for comparison, is about one-third the energy consumption of the city of Geneva; the LHC accelerator and detectors draw about 120 MW thereof.^[33]

When running at the current energy record of 6.5 TeV per proton,^[34] once or twice a day, as the protons are accelerated from 450 GeV to 6.5 TeV, the field of the superconducting dipole magnets is increased from 0.54 to 7.7 teslas (T). The protons each have an energy of 6.5 TeV, giving a total collision energy of 13 TeV. At this energy the protons have a Lorentz factor of about 6,930 and move at about 0.999 999 990 c, or about 3.1 m/s (11 km/h) slower than the speed of light (c). It takes less than 90 microseconds (μs) for a proton to travel 26.7 km around the main ring. This results in 11,245 revolutions per second for

protons whether the particles are at low or high energy in the main ring, since the speed difference between these energies is beyond the fifth decimal.^[35]

Rather than having continuous beams, the protons are bunched together, into up to 2,808 bunches, with 115 billion protons in each bunch so that interactions between the two beams take place at discrete intervals, mainly 25 nanoseconds (ns) apart, providing a bunch collision rate of 40 MHz. It was operated with fewer bunches in the first years. The design luminosity of the LHC is $10^{34} \text{ cm}^{-2}\text{s}^{-1}$,^[36]

which was first reached in June 2016.^[37]

By 2017 twice this value was achieved.^[38]

The LHC protons originate from the small red hydrogen tank.

Before being injected into the main accelerator, the particles are prepared by a series of systems that successively increase their energy. The first system is the linear particle accelerator LINAC 2 generating 50-MeV protons, which feeds

the Proton Synchrotron Booster (PSB). There the protons are accelerated to 1.4 GeV and injected into the Proton Synchrotron (PS), where they are accelerated to 26 GeV. Finally the Super Proton Synchrotron (SPS) is used to increase their energy further to 450 GeV before they are at last injected (over a period of several minutes) into the main ring. Here the proton bunches are accumulated, accelerated (over a period of 20 minutes) to their peak energy, and finally circulated for 5 to 24 hours while collisions occur at the four intersection points.^[39]

The LHC physics programme is mainly based on proton–proton collisions. However, shorter running periods, typically one month per year, with heavy-ion collisions are included in the programme. While lighter ions are considered as well, the baseline scheme deals with lead ions^[40] (see A Large Ion Collider Experiment). The lead ions are first accelerated by the linear accelerator LINAC 3, and the Low Energy Ion Ring (LEIR) is used as an ion storage and cooler unit. The ions are then further accelerated by the PS and SPS before being injected into LHC ring, where they reached an energy of 2.3 TeV per nucleon (or 522 TeV

per ion),^[41] higher than the energies reached by the Relativistic Heavy Ion Collider. The aim of the heavy-ion programme is to investigate quark–gluon plasma, which existed in the early universe.^[42]

Detectors

Seven detectors have been constructed at the LHC, located underground in large caverns excavated at the LHC's intersection points. Two of them, the ATLAS experiment and the Compact Muon Solenoid (CMS), are large general-purpose particle detectors.^[2] ALICE and LHCb have

more specific roles and the last three, TOTEM, MoEDAL and LHCf, are very much smaller and are for very specialized research. The ATLAS and CMS experiments discovered the Higgs boson, which is strong evidence that the Standard Model has the correct mechanism of giving mass to elementary particles.^[43]

CMS detector for LHC

The BBC's summary of the main detectors is:[44]

Detector	Description
<u>ATLAS</u>	One of two general-purpose detectors. ATLAS studies the <u>Higgs boson</u> and looks for signs of new physics, including the origins of mass and extra dimensions.
<u>CMS</u>	The other general-purpose detector, like ATLAS, studies the Higgs boson and look for clues of new physics.
<u>ALICE</u>	ALICE is studying a "fluid" form of matter called <u>quark–gluon plasma</u> that existed shortly after the <u>Big Bang</u> .
<u>LHCb</u>	Equal amounts of matter and <u>antimatter</u> were created in the Big Bang. LHCb investigates what happened to the "missing" antimatter.

Computing and analysis facilities

Data produced by LHC, as well as LHC-related simulation, were estimated at approximately 15 petabytes per year (max throughput while running not stated)^[45]—a major challenge in its own right at the time.

The LHC Computing Grid^[46] was constructed as part of the LHC design, to handle the massive amounts of data expected for its collisions. It is an international collaborative project that consists of a grid-based computer network infrastructure initially connecting 140 computing centres in 35 countries (over 170 in 36 countries as of 2012). It was designed by CERN to handle the significant volume of data produced by LHC experiments,^{[47][48][48]} incorporating both private fibre optic cable links and existing high-speed portions of the public Internet to enable data transfer from CERN to academic institutions around the

world.^[49] The Open Science Grid is used as the primary infrastructure in the United States, and also as part of an interoperable federation with the LHC Computing Grid.

The distributed computing project LHC@home was started to support the construction and calibration of the LHC. The project uses the BOINC platform, enabling anybody with an Internet connection and a computer running Mac OS X, Windows or Linux, to use their computer's idle time to simulate how particles will travel in the beam pipes. With this information, the scientists are able to

determine how the magnets should be calibrated to gain the most stable "orbit" of the beams in the ring.^[50] In August 2011, a second application went live (Test4Theory) which performs simulations against which to compare actual test data, to determine confidence levels of the results.

By 2012 data from over 6 quadrillion (6×10^{15}) LHC proton-proton collisions had been analysed,^[51] LHC collision data was being produced at approximately 25 petabytes per year, and the LHC Computing Grid had become the world's largest computing_grid in 2012, comprising

over 170 computing facilities in a worldwide network across 36 countries.^{[52][53][54]}

Operational history

The LHC first went live on 10 September 2008,^[55] but initial testing was delayed for 14 months from 19 September 2008 to 20 November 2009, following a magnet quench incident that caused extensive damage to over 50 superconducting magnets, their mountings, and the vacuum pipe.^{[56][57][58][59][60]}

During its first run (2010–2013) the LHC collided two opposing particle beams of

either protons at up to 4 teraelectronvolts (4 TeV or 0.64 microjoules), or lead nuclei (574 TeV per nucleus, or 2.76 TeV per nucleon).^{[61][62]} Its first run discoveries included the long-sought Higgs boson, several composite particles (hadrons) like the χ_b (3P) bottomonium state, the first creation of a quark–gluon plasma, and the first observations of the very rare decay of the B_s meson into two muons ($B_s^0 \rightarrow \mu^+ \mu^-$), which challenged the validity of existing models of supersymmetry.^[63]

Construction

Operational challenges

The size of the LHC constitutes an exceptional engineering challenge with unique operational issues on account of the amount of energy stored in the magnets and the beams.^{[39][64]} While operating, the total energy stored in the magnets is 10 GJ (2,400 kilograms of TNT) and the total energy carried by the two beams reaches 724 MJ (173 kilograms of TNT).^[65]

Loss of only one ten-millionth part (10^{-7}) of the beam is sufficient to quench a superconducting magnet, while each of the two beam dumps must absorb 362 MJ (87 kilograms of TNT). These energies are

carried by very little matter: under nominal operating conditions (2,808 bunches per beam, 1.15×10^{11} protons per bunch), the beam pipes contain 1.0×10^{-9} gram of hydrogen, which, in standard conditions for temperature and pressure, would fill the volume of one grain of fine sand.

Cost

With a budget of €7.5 billion (approx. \$9bn or £6.19bn as of June 2010), the LHC is one of the most expensive scientific instruments^[1] ever built.^[66] The total cost of the project is expected to be of the order of 4.6bn Swiss francs (SFr) (approx.

\$4.4bn, €3.1bn, or £2.8bn as of January 2010) for the accelerator and 1.16bn (SFr) (approx. \$1.1bn, €0.8bn, or £0.7bn as of January 2010) for the CERN contribution to the experiments.^[67]

The construction of LHC was approved in 1995 with a budget of SFr 2.6bn, with another SFr 210M toward the experiments. However, cost overruns, estimated in a major review in 2001 at around SFr 480M for the accelerator, and SFr 50M for the experiments, along with a reduction in CERN's budget, pushed the completion date from 2005 to April 2007.^[68] The superconducting magnets were

responsible for SFr 180M of the cost increase. There were also further costs and delays owing to engineering difficulties encountered while building the cavern for the Compact Muon Solenoid,^[69] and also due to magnet supports which were insufficiently strongly designed and failed their initial testing (2007) and damage from a magnet quench and liquid helium escape (inaugural testing, 2008) (see: Construction accidents and delays).^[70] Because electricity costs are lower during the summer, the LHC normally does not operate over the winter months,^[71] although exceptions over the 2009/10 and 2012/2013 winters were

made to make up for the 2008 start-up delays and to improve precision of measurements of the new particle discovered in 2012, respectively.

Construction accidents and delays

- On 25 October 2005, José Pereira Lages, a technician, was killed in the LHC when a switchgear that was being transported fell on top of him.^[72]
- On 27 March 2007 a cryogenic magnet support designed and provided by Fermilab and KEK broke during an initial pressure test involving one of the LHC's inner triplet (focusing quadrupole)

magnet assemblies. No one was injured. Fermilab director Pier Oddone stated "In this case we are dumbfounded that we missed some very simple balance of forces". The fault had been present in the original design, and remained during four engineering reviews over the following years.^[73] Analysis revealed that its design, made as thin as possible for better insulation, was not strong enough to withstand the forces generated during pressure testing. Details are available in a statement from Fermilab, with which CERN is in agreement.^{[74][75]} Repairing the broken magnet and reinforcing the eight

identical assemblies used by LHC delayed the start-up date, then planned for November 2007.

- On 19 September 2008, during initial testing, a faulty electrical connection led to a magnet quench (the sudden loss of a superconducting magnet's superconducting ability owing to warming or electric field effects). Six tonnes of supercooled liquid helium—used to cool the magnets—escaped, with sufficient force to break 10-ton magnets nearby from their mountings, and caused considerable damage and contamination of the vacuum tube (see 2008 quench incident); repairs and

safety checks caused a delay of around 14 months.^{[76][77][78]}

- Two vacuum leaks were found in July 2009, and the start of operations was further postponed to mid-November 2009.^[79]

Initial lower magnet currents

In both of its runs (2010 to 2012 and 2015), the LHC was initially run at energies below its planned operating energy, and ramped up to just 2 x 4 TeV energy on its first run and 2 x 6.5 TeV on its second run, below the design energy of 2 x 7 TeV. This is because massive superconducting magnets require considerable magnet

training to handle the high currents involved without losing their superconducting ability, and the high currents are necessary to allow a high proton energy. The "training" process involves repeatedly running the magnets with lower currents to provoke any quenches or minute movements that may result. It also takes time to cool down magnets to their operating temperature of around 1.9 K (close to absolute zero). Over time the magnet "beds in" and ceases to quench at these lesser currents and can handle the full design current without quenching; CERN media describe the magnets as "shaking out" the unavoidable

tiny manufacturing imperfections in their crystals and positions that had initially impaired their ability to handle their planned currents. The magnets, over time and with training, gradually become able to handle their full planned currents without quenching.^{[80][81]}

Inaugural tests (2008)

The first beam was circulated through the collider on the morning of 10 September 2008.^[44] CERN successfully fired the protons around the tunnel in stages, three kilometres at a time. The particles were fired in a clockwise direction into the

accelerator and successfully steered around it at 10:28 local time.^[55] The LHC successfully completed its major test: after a series of trial runs, two white dots flashed on a computer screen showing the protons travelled the full length of the collider. It took less than one hour to guide the stream of particles around its inaugural circuit.^[82] CERN next successfully sent a beam of protons in an anticlockwise direction, taking slightly longer at one and a half hours owing to a problem with the cryogenics, with the full circuit being completed at 14:59.

Quench incident

Wikinews has related news: **CERN**
says repairs to LHC particle
accelerator to cost €16.6 million

On 19 September 2008, a magnet quench occurred in about 100 bending magnets in sectors 3 and 4, where an electrical fault led to a loss of approximately six tonnes of liquid helium (the magnets' cryogenic coolant), which was vented into the tunnel. The escaping vapour expanded with explosive force, damaging a total of 53 superconducting magnets and their mountings, and contaminating the vacuum pipe, which also lost vacuum conditions.^{[56][57][83]}

Shortly after the incident CERN reported that the most likely cause of the problem was a faulty electrical connection between two magnets, and that – owing to the time needed to warm up the affected sectors and then cool them back down to operating temperature – it would take at least two months to fix.^[84] CERN released an interim technical report^[83] and preliminary analysis of the incident on 15 and 16 October 2008 respectively,^[85] and a more detailed report on 5 December 2008.^[77] The analysis of the incident by CERN confirmed that an electrical fault had indeed been the cause. The faulty electrical connection had led (correctly) to

a failsafe power abort of the electrical systems powering the superconducting magnets, but had also caused an electric arc (or discharge) which damaged the integrity of the supercooled helium's enclosure and vacuum insulation, causing the coolant's temperature and pressure to rapidly rise beyond the ability of the safety systems to contain it,^[83] and leading to a temperature rise of about 100 degrees Celsius in some of the affected magnets. Energy stored in the superconducting magnets and electrical noise induced in other quench detectors also played a role in the rapid heating. Around two tonnes of liquid helium escaped explosively before

detectors triggered an emergency stop, and a further four tonnes leaked at lower pressure in the aftermath.^[83] A total of 53 magnets were damaged in the incident and were repaired or replaced during the winter shutdown.^[86] This accident was thoroughly discussed in a 22 February 2010 *Superconductor Science and Technology* article by CERN physicist Lucio Rossi.^[87]

In the original timeline of the LHC commissioning, the first "modest" high-energy collisions at a centre-of-mass energy of 900 GeV were expected to take place before the end of September 2008,

and the LHC was expected to be operating at 10 TeV by the end of 2008.^[88] However, owing to the delay caused by the above-mentioned incident, the collider was not operational until November 2009.^[89]

Despite the delay, LHC was officially inaugurated on 21 October 2008, in the presence of political leaders, science ministers from CERN's 20 Member States, CERN officials, and members of the worldwide scientific community.^[90]

Most of 2009 was spent on repairs and reviews from the damage caused by the quench incident, along with two further vacuum leaks identified in July 2009 which

pushed the start of operations to November of that year.^[79]

Run 1: first operational run (2009–2013)

Seminar on the physics of LHC by John Iliopoulos (2009).^[91]

On 20 November 2009, low-energy beams circulated in the tunnel for the first time since the incident, and shortly after, on 30

November, the LHC achieved 1.18 TeV per beam to become the world's highest-energy particle accelerator, beating the Tevatron's previous record of 0.98 TeV per beam held for eight years.^[92]

The early part of 2010 saw the continued ramp-up of beam in energies and early physics experiments towards 3.5 TeV per beam and on 30 March 2010, LHC set a new record for high-energy collisions by colliding proton beams at a combined energy level of 7 TeV. The attempt was the third that day, after two unsuccessful attempts in which the protons had to be "dumped" from the collider and new

beams had to be injected.^[93] This also marked the start of the main research programme.

The first proton run ended on 4 November 2010. A run with lead ions started on 8 November 2010, and ended on 6 December 2010,^[94] allowing the ALICE experiment to study matter under extreme conditions similar to those shortly after the Big Bang.^[95]

CERN originally planned that the LHC would run through to the end of 2012, with a short break at the end of 2011 to allow for an increase in beam energy from 3.5 to

4 TeV per beam.^[5] At the end of 2012 the LHC was planned to get shut down until around 2015 to allow upgrade to a planned beam energy of 7 TeV per beam.^[96] In late 2012, in light of the July 2012 discovery of the Higgs boson, the shutdown was postponed for some weeks into early 2013, to allow additional data to be obtained before shutdown.

Long Shutdown 1 (2013–2015)

A section of the LHC

The LHC was shut down on 13 February 2013 for its 2-year upgrade called Long Shutdown 1 (LS1), which was to touch on many aspects of the LHC: enabling collisions at 14 TeV, enhancing its detectors and pre-accelerators (the Proton Synchrotron and Super Proton Synchrotron), as well as replacing its ventilation system and 100 km (62 mi) of cabling impaired by high-energy collisions from its first run.^[97] The upgraded collider began its long start-up and testing process in June 2014, with the Proton Synchrotron Booster starting on 2 June 2014, the final

interconnection between magnets completing and the Proton Synchrotron circulating particles on 18 June 2014, and the first section of the main LHC supermagnet system reaching operating temperature of 1.9 K ($-271.25\text{ }^{\circ}\text{C}$), a few days later.^[98] Due to the slow progress with "training" the superconducting magnets, it was decided to start the second run with a lower energy of 6.5 TeV per beam, corresponding to a current of 11,000 amperes. The first of the main LHC magnets were reported to have been successfully trained by 9 December 2014, while training the other magnet sectors was finished in March 2015.^[99]

Run 2: second operational run (2015–2018)

On 5 April 2015, the LHC restarted after a two-year break, during which the electrical connectors between the bending magnets were upgraded to safely handle the current required for 7 TeV per beam (14 TeV).^{[6][100]} However, the bending magnets were only trained to handle up to 6.5 TeV per beam (13 TeV total), which became the operating energy for 2015 to 2017.^[80] The energy was first reached on 10 April 2015.^[101] The upgrades culminated in colliding protons together with a combined energy of 13 TeV.^[102] On 3 June 2015 the

LHC started delivering physics data after almost two years offline.^[103] In the following months it was used for proton-proton collisions, while in November the machine switched to collisions of lead ions and in December the usual winter shutdown started.

In 2016, the machine operators focused on increasing the luminosity for proton-proton collisions. The design value was first reached 29 June,^[37] and further improvements increased the collision rate to 40% above the design value.^[104] The total number of collisions in 2016 exceeded the number from Run 1 - at a

higher energy per collision. The proton-proton run was followed by four weeks of proton-lead collisions.^[105]

In 2017 the luminosity was increased further and reached twice the design value. The total number of collisions was higher than in 2016 as well.^[38]

The 2018 physics run began on 17 April and stopped on 3 December, including four weeks of lead–lead collisions.^[106]

Long Shutdown 2 (2018-2021) and beyond

Long Shutdown 2 (LS2) started 10 December 2018. The LHC and the whole CERN accelerator complex is being maintained and upgraded. The goal of the upgrades is to implement the High Luminosity Large Hadron Collider (HL-LHC) project, that will increase the luminosity by a factor of 10. LS2 is projected to end in 2021, followed by Run 3.^[107] The HL-LHC should be operational by 2026. The Long Shutdown (LS3) in 2020s will take place before HL-LHC project is done.

Timeline of operations

Date	Event
10 Sep 2008	<u>CERN</u> successfully fired the first protons around the entire tunnel circuit in stages.
19 Sep 2008	<u>Magnetic quench</u> occurred in about 100 bending <u>magnets</u> in sectors 3 and 4, causing a loss of approximately 6 tonnes of liquid <u>helium</u> .
30 Sep 2008	First "modest" <u>high-energy</u> collisions planned but postponed due to accident. ^[31]
16 Oct 2008	CERN released a preliminary analysis of the accident.
21 Oct 2008	Official inauguration.

5 Dec 2008	CERN released detailed analysis.
20 Nov 2009	Low-energy beams circulated in the tunnel for the first time since the accident. ^[59]
23 Nov 2009	First particle collisions in all four detectors at 450 GeV.
30 Nov 2009	LHC becomes the world's highest-energy particle accelerator achieving 1.18 TeV per beam, beating the <u>Tevatron</u> 's previous record of 0.98 TeV per beam held for eight years. ^[92]
15 Dec 2009	First scientific results, covering 284 collisions in the <u>ALICE</u> detector. ^[108]

30 Mar 2010	The two beams collided at 7 TeV (3.5 TeV per beam) in the LHC at 13:06 CEST, marking the start of the LHC research programme.
8 Nov 2010	Start of the first run with lead ions.
6 Dec 2010	End of the run with lead ions. Shutdown until early 2011.
13 Mar 2011	Beginning of the 2011 run with proton beams. ^[109]
21 Apr 2011	LHC becomes the world's highest-luminosity hadron accelerator achieving a peak luminosity of $4.67 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, beating

	the Tevatron's previous record of $4 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ held for one year. ^[110]
24 May 2011	ALICE reports that a <u>Quark–gluon plasma</u> has been achieved with earlier lead collisions. ^[111]
17 Jun 2011	The high-luminosity experiments ATLAS and CMS reach 1 <u>fb</u> ⁻¹ of collected data. ^[112]
14 Oct 2011	LHCb reaches 1 fb ⁻¹ of collected data. ^[113]
23 Oct 2011	The high-luminosity experiments ATLAS and CMS reach 5 fb ⁻¹ of collected data.

Nov 2011	Second run with lead ions.
22 Dec 2011	First new composite particle discovery, the χ_b (3P) <u>bottomonium</u> meson, observed with proton-proton collisions in 2011. ^[114]
5 Apr 2012	First collisions with stable beams in 2012 after the winter shutdown. The energy is increased to 4 TeV per beam (8 TeV in collisions). ^[115]
4 Jul 2012	First new elementary particle discovery, a new boson observed that is "consistent with" the theorized Higgs boson. (This has now been

	confirmed as the Higgs boson itself. ^[116])
8 Nov 2012	First observation of the very rare decay of the B_s <u>meson</u> into two <u>muons</u> ($B_s^0 \rightarrow \mu^+\mu^-$), a major test of <u>supersymmetry</u> theories, ^[117] shows results at 3.5 sigma that match the Standard Model rather than many of its super-symmetrical variants.
20 Jan 2013	Start of the first run colliding protons with lead ions.
11 Feb 2013	End of the first run colliding protons with lead ions.
14 Feb 2013	Beginning of the first long shutdown to prepare the

	collider for a higher energy and luminosity. ^[118]
7 Mar 2015	Injection tests for Run 2 send protons towards LHCb & ALICE
5 Apr 2015	Both beams circulated in the collider. ^[6] Four days later, a new record energy of 6.5 TeV per proton was achieved. ^[119]
20 May 2015	Protons collided in the LHC at the record-breaking collision energy of 13 TeV. ^[102]
3 Jun 2015	Start of delivering the physics data after almost two years offline for recommissioning. ^[103]

4 Nov 2015	End of proton collisions in 2015, start of preparations for ion collisions.
25 Nov 2015	First ion collisions at a record-breaking energy of more than 1 PeV (10^{15} eV) ^[120]
13 Dec 2015	End of ion collisions in 2015
23 Apr 2016	Data-taking in 2016 begins
29 June 2016	The LHC achieves a luminosity of $1.0 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, its design value. ^[37] Further improvements over the year increased the luminosity to 40% above the design value. ^[104]

26 Oct 2016	End of 2016 proton-proton collisions
10 Nov 2016	Beginning of 2016 proton-lead collisions
3 Dec 2016	End of 2016 proton-lead collisions
24 May 2017	Start of 2017 proton-proton collisions. During 2017, the luminosity increased to twice its design value. ^[38]
10 Nov 2017	End of regular 2017 proton-proton collision mode. ^[38]
17 Apr 2018	Start of 2018 proton-proton collisions.
12 Nov 2018	End of 2018 proton operations at CERN. ^[121]

3 Dec 2018	End of 2018 lead-ion run. ^[121]
10 Dec 2018	End of 2018 physics operation and start of Long Shutdown 2. ^[121]

Findings and discoveries

An initial focus of research was to investigate the possible existence of the Higgs boson, a key part of the Standard Model of physics which is predicted by theory but had not yet been observed before due to its high mass and elusive nature. CERN scientists estimated that, if the Standard Model were correct, the LHC would produce several Higgs bosons every

minute, allowing physicists to finally confirm or disprove the Higgs boson's existence. In addition, the LHC allowed the search for supersymmetric particles and other hypothetical particles as possible unknown areas of physics.^[61] Some extensions of the Standard Model predict additional particles, such as the heavy W' and Z' gauge bosons, which are also estimated to be within reach of the LHC to discover.^[122]

First run (data taken 2009–2013)

The first physics results from the LHC, involving 284 collisions which took place

in the ALICE detector, were reported on 15 December 2009.^[108] The results of the first proton–proton collisions at energies higher than Fermilab's Tevatron proton–antiproton collisions were published by the CMS collaboration in early February 2010, yielding greater-than-predicted charged-hadron production.^[123]

After the first year of data collection, the LHC experimental collaborations started to release their preliminary results concerning searches for new physics beyond the Standard Model in proton–proton collisions.^{[124][125][126][127]} No evidence of new particles was detected in

the 2010 data. As a result, bounds were set on the allowed parameter space of various extensions of the Standard Model, such as models with large extra dimensions, constrained versions of the Minimal Supersymmetric Standard Model, and others.^{[128][129][130]}

On 24 May 2011, it was reported that quark–gluon plasma (the densest matter thought to exist besides black holes) had been created in the LHC.^[111]

A Feynman diagram of one way the Higgs boson may be produced at the LHC. Here, two quarks each emit a W or Z boson, which combine to make a neutral Higgs.

Between July and August 2011, results of searches for the Higgs boson and for exotic particles, based on the data collected during the first half of the 2011 run, were presented in conferences in Grenoble^[131] and Mumbai.^[132] In the latter conference it was reported that, despite hints of a Higgs signal in earlier data, ATLAS and CMS exclude with 95% confidence level (using the CLs method) the existence of a Higgs boson with the properties predicted by the Standard

Model over most of the mass region between 145 and 466 GeV.^[133] The searches for new particles did not yield signals either, allowing to further constrain the parameter space of various extensions of the Standard Model, including its supersymmetric extensions.^{[134][135]}

On 13 December 2011, CERN reported that the Standard Model Higgs boson, if it exists, is most likely to have a mass constrained to the range 115–130 GeV. Both the CMS and ATLAS detectors have also shown intensity peaks in the 124–125 GeV range, consistent with either

background noise or the observation of the Higgs boson.^[136]

On 22 December 2011, it was reported that a new composite particle had been observed, the χ_b (3P) bottomonium state.^[114]

On 4 July 2012, both the CMS and ATLAS teams announced the discovery of a boson in the mass region around 125–126 GeV, with a statistical significance at the level of 5 sigma each. This meets the formal level required to announce a new particle. The observed properties were consistent with the Higgs boson, but

scientists were cautious as to whether it is formally identified as actually being the Higgs boson, pending further analysis.^[137]

On 8 November 2012, the LHCb team reported on an experiment seen as a "golden" test of supersymmetry theories in physics,^[117] by measuring the very rare decay of the meson into two muons (). The results, which match those predicted by the non-supersymmetrical Standard Model rather than the predictions of many branches of supersymmetry, show the decays are less common than some forms of supersymmetry predict, though could still

match the predictions of other versions of supersymmetry theory. The results as initially drafted are stated to be short of proof but at a relatively high 3.5 sigma level of significance.^[138] The result was later confirmed by the CMS collaboration.^[139]

In August 2013 the LHCb team revealed an anomaly in the angular distribution of B meson decay products which could not be predicted by the Standard Model; this anomaly had a statistical certainty of 4.5 sigma, just short of the 5 sigma needed to be officially recognized as a discovery. It is unknown what the cause of this anomaly

would be, although the Z' boson has been suggested as a possible candidate.^[140]

On 19 November 2014, the LHCb experiment announced the discovery of two new heavy subatomic particles, $\Xi_b'^-$ and Ξ_b^{*-} . Both of them are baryons that are composed of one bottom, one down, and one strange quark. They are excited states of the bottom Xi baryon.^{[141][142]}

The LHCb collaboration has observed multiple exotic hadrons, possibly pentaquarks or tetraquarks, in the Run 1 data. On 4 April 2014, the collaboration confirmed the existence of the tetraquark

candidate $\underline{Z(4430)}$, with a significance of over 13.9 sigma.^{[143][144]} On 13 July 2015, results consistent with pentaquark states in the decay of bottom Lambda baryons (Λ_b^0) were reported.^{[145][146][147]}

On 28 June 2016, the collaboration announced four tetraquark-like particles decaying into a J/ψ and a ϕ meson, only one of which was well established before ($X(4274)$, $X(4500)$ and $X(4700)$ and $\underline{X(4140)}$).^{[148][149]}

In December 2016, ATLAS presented a measurement of the W boson mass,

researching the precision of analyses done at the Tevatron.^[150]

Second run (2015-2018)

At the conference EPS-HEP 2015 in July, the collaborations presented first cross-section measurements of several particles at the higher collision energy.

On 15 December 2015, the ATLAS and CMS experiments both reported a number of preliminary results for Higgs physics, supersymmetry (SUSY) searches and exotics searches using 13 TeV proton collision data. Both experiments saw a

moderate excess around 750 GeV in the two-photon invariant mass spectrum,^{[151][152][153]} but the experiments did not confirm the existence of the hypothetical particle in an August 2016 report.^{[154][155][156]}

In July 2017, many analyses based on the large dataset collected in 2016 were shown. The properties of the Higgs boson were studied in more detail and the precision of many other results was improved.^[157]

Planned "high-luminosity" upgrade

After some years of running, any particle physics experiment typically begins to suffer from diminishing returns: as the key results reachable by the device begin to be completed, later years of operation discover proportionately less than earlier years. A common response is to upgrade the devices involved, typically in collision energy, luminosity, or improved detectors. In addition to a possible increase to 14 TeV collision energy in 2018, a luminosity upgrade of the LHC, called the High Luminosity LHC, started in June 2018 that will boost the accelerator's potential for new discoveries in physics, starting in 2026.^[158] The upgrade aims at increasing

the luminosity of the machine by a factor of 10, up to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$, providing a better chance to see rare processes and improving statistically marginal measurements.

Safety of particle collisions

The experiments at the Large Hadron Collider sparked fears that the particle collisions might produce doomsday phenomena, involving the production of stable microscopic black holes or the creation of hypothetical particles called strangelets.^[159] Two CERN-commissioned safety reviews examined these concerns

and concluded that the experiments at the LHC present no danger and that there is no reason for concern,^{[160][161][162]} a conclusion endorsed by the American Physical Society.^[163]

The reports also noted that the physical conditions and collision events that exist in the LHC and similar experiments occur naturally and routinely in the universe without hazardous consequences,^[161] including ultra-high-energy cosmic rays observed to impact Earth with energies far higher than those in any man-made collider.

Popular culture

The Large Hadron Collider gained a considerable amount of attention from outside the scientific community and its progress is followed by most popular science media. The LHC has also inspired works of fiction including novels, TV series, video games and films.

CERN employee Katherine McAlpine's "Large Hadron Rap"^[164] surpassed 7 million YouTube views.^{[165][166]} The band Les Horribles Cernettes was founded by women from CERN. The name was chosen so to have the same initials as the LHC.^{[167][168]}

National Geographic Channel's *World's Toughest Fixes*, Season 2 (2010), Episode 6 "Atom Smasher" features the replacement of the last superconducting magnet section in the repair of the collider after the 2008 quench incident. The episode includes actual footage from the repair facility to the inside of the collider, and explanations of the function, engineering, and purpose of the LHC.^[169]

The Large Hadron Collider was the focus of the 2012 student film *Decay*, with the movie being filmed on location in CERN's maintenance tunnels.^[170]

The feature documentary *Particle Fever* follows the experimental physicists at CERN who run the experiments, as well as the theoretical physicists who attempt to provide a conceptual framework for the LHC's results. It won the Sheffield International Doc/Fest in 2013.

Fiction

The novel *Angels & Demons*, by Dan Brown, involves antimatter created at the LHC to be used in a weapon against the Vatican. In response, CERN published a "Fact or Fiction?" page discussing the accuracy of the book's portrayal of the LHC, CERN, and

particle physics in general.^[171] The movie version of the book has footage filmed on-site at one of the experiments at the LHC; the director, Ron Howard, met with CERN experts in an effort to make the science in the story more accurate.^[172]

In the visual novel/manga/anime-series "Steins;Gate", SERN (a deliberate misspelling of CERN) is an organization that uses the miniature black holes created from experiments in the LHC to master time travel and take over the world. It is also involved in mass vigilance through the "ECHELON" project and has connection with many mercenary groups

worldwide, to avoid the creation of other time machines.

The novel *FlashForward*, by Robert J. Sawyer, involves the search for the Higgs boson at the LHC. CERN published a "Science and Fiction" page interviewing Sawyer and physicists about the book and the TV series based on it.^[173]

See also

Book: Large Hadron Collider

- List of accelerators in particle physics
- Accelerator projects

- Compact Linear Collider
- Future Circular Collider
- International Linear Collider
- Very Large Hadron Collider

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