

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.

The 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.

Contents

Background

Purpose

Design

Detectors

Computing and analysis facilities

Operational history

Construction

Operational challenges

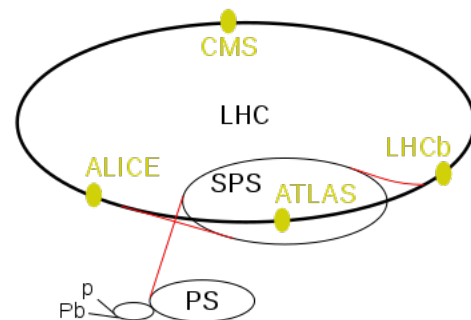
Cost

Construction accidents and delays

Initial lower magnet currents

Inaugural tests (2008)

Large Hadron Collider (LHC)



LHC experiments

| | |
|----------------------|--|
| <u>ATLAS</u> | A Toroidal LHC Apparatus |
| <u>CMS</u> | Compact Muon Solenoid |
| <u>LHCb</u> | LHC-beauty |
| <u>ALICE</u> | A Large Ion Collider Experiment |
| <u>TOTEM</u> | Total Cross Section, Elastic Scattering and Diffraction Dissociation |
| <u>LHCf</u> | LHC-forward |
| <u>MoEDAL</u> | Monopole and Exotics Detector At the LHC |
| <u>FASER</u> | ForwArd Search ExpeRiment |

LHC preaccelerators

| | |
|----------------------------|---|
| <u>p and Pb</u> | <u>Linear accelerators</u> for <u>protons</u> (Linac 4) and <u>lead</u> (Linac 3) |
| <u>(not marked)</u> | <u>Proton Synchrotron Booster</u> |
| <u>PS</u> | <u>Proton Synchrotron</u> |

Quench incident

Run 1: first operational run (2009–2013)

Long Shutdown 1 (2013–2015)

Run 2: second operational run (2015–2018)

Long Shutdown 2 (2018–2021) and beyond

Timeline of operations

Findings and discoveries

First run (data taken 2009–2013)

Second run (2015–2018)

Planned "high-luminosity" upgrade

Safety of particle collisions

Popular culture

Fiction

See also

References

External links

Background

The term *hadron* refers to subatomic 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

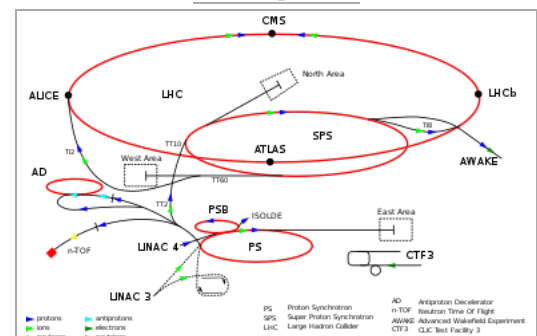
Many physicists hope that the Large Hadron Collider will help answer some of the fundamental open questions in physics, which concern the basic laws governing the interactions and forces among the elementary objects, the deep structure of space and time, and in particular the interrelation between quantum

SPS Super Proton
Synchrotron

Hadron colliders

| | |
|--|--------------------------------------|
| <u>Intersecting Storage Rings</u> | <u>CERN</u> , 1971–1984 |
| <u>Proton-Antiproton Collider (SPS)</u> | <u>CERN</u> , 1981–1991 |
| <u>ISABELLE</u> | <u>BNL</u> , cancelled in 1983 |
| <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 |
| <u>Large Hadron Collider</u> | <u>CERN</u> , 2009– present |
| <u>Future Circular Collider</u> | Proposed |

CERN accelerator complex



List of current particle accelerators at CERN

| | |
|---------------------|---------------------------------------|
| <u>Linac</u> | Accelerates <u>ions</u> |
| <u>3</u> | |
| <u>AD</u> | Decelerates <u>antiprotons</u> |
| <u>LHC</u> | Collides protons or heavy <u>ions</u> |
| <u>LEIR</u> | Accelerates <u>ions</u> |
| <u>PSB</u> | Accelerates protons or <u>ions</u> |

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]}

| | |
|------------|-----------------------------|
| PS | Accelerates protons or ions |
| SPS | Accelerates protons or ions |

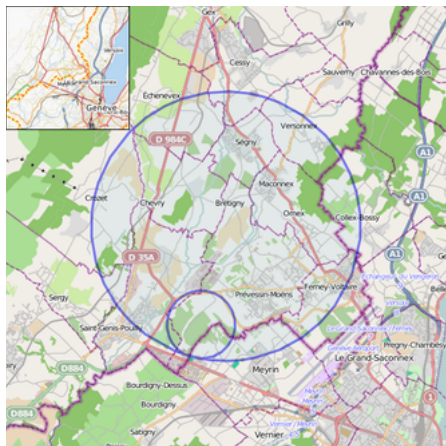
- is the mass of elementary particles being generated by the Higgs mechanism via electroweak symmetry breaking?^[18] It was expected that the collider experiments will either demonstrate or rule out the existence of the elusive Higgs boson, thereby allowing physicists to consider whether the Standard 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. The variation in depth was deliberate, to reduce the amount of tunnel that lies under the Jura Mountains to avoid having to excavate a vertical access shaft there. A tunnel was chosen to avoid having to purchase expensive land on the surface, which would also have an impact on the landscape and to take advantage of the shielding against background radiation that the earth's crust provides.^[29]

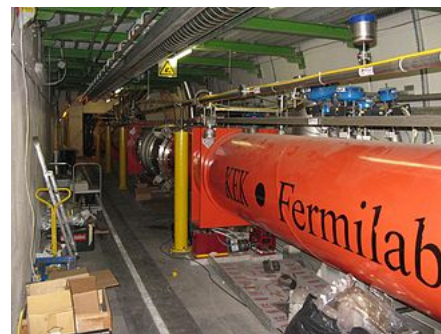


Map of the Large Hadron Collider at CERN

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.^[30] 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.

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^[31]), 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.^[32] 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 °C), making the LHC the largest cryogenic facility in the world at liquid helium temperature. LHC uses 470 tonnes of Nb–Ti superconductor.^[33]



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

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.^[34] Each day of its operation generates 140 terabytes of data.^[35]

When running at the current energy record of 6.5 TeV per proton,^[36] 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.^[37]

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 10³⁴ cm^{−2}s^{−1},^[38] which was first reached in June 2016.^[39] By 2017, twice this value was achieved.^[40]

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 4 generating 160-MeV negative hydrogen ions (H[−] ions), which feeds the Proton Synchrotron Booster (PSB). There, both



The LHC protons originate from the small red hydrogen tank.

electrons are stripped of the hydrogen ions leaving only the nucleus containing one proton. Protons are then accelerated to 2 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.^[41]

The LHC physics programme is mainly based on proton–proton collisions. However, shorter running periods, typically one month per year, heavy-ion collisions are included in the programme. While

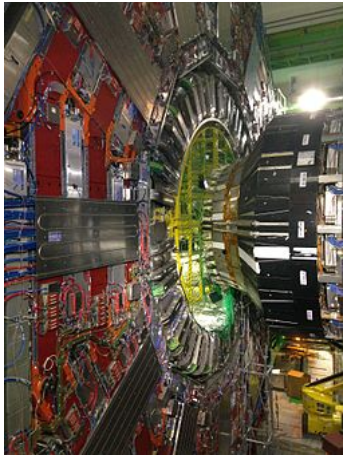
lighter ions are considered as well, the baseline scheme deals with lead ions^[42] (see A Large Ion Collider Experiment). The lead ions are first accelerated by the linear accelerator LINAC 3, and the Low Energy Ion Ring (LEIR) is used as an ion storage and cooler unit. The ions are then further accelerated by the PS and SPS before being injected into LHC ring, where they reach an energy of 2.3 TeV per nucleon (or 522 TeV per ion),^[43] 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.^[44]

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.^[45]

The BBC's summary of the main detectors is:^[46]

| 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> | LHCb investigates what happened to the "missing" antimatter from when equal amounts of matter and <u>antimatter</u> were created in the Big Bang. |



CMS detector for LHC

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 is not stated)^[47]—a major challenge in its own right at the time.

The LHC Computing Grid^[48] 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,^{[49][50]} 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.^[51] 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.^[52] In August 2011, a second application (Test4Theory) went live 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,^[53] 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.^{[54][55][56]}

Operational history

The LHC first went live on 10 September 2008,^[57] 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.^{[58][59][60][61][62]}

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).^{[63][64]} 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.^[65]

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.^{[41][66]} 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).^[67]

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.^[68] 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.^[69]

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.^[70] 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,^[71] 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*).^[72] Because electricity costs are lower during the summer, the LHC normally does not operate over the winter months,^[73] 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.^[74]
- 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.^[75] 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.^{[76][77]} 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.^{[78][79][80]}
- Two vacuum leaks were found in July 2009, and the start of operations was further postponed to mid-November 2009.^[81]

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.^{[82][83]}

Inaugural tests (2008)

The first beam was circulated through the collider on the morning of 10 September 2008.^[46] 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.^[57] 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.^[84] 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

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.^{[58][59][85]}

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.^[86] CERN released an interim technical report^[85] and preliminary analysis of the incident on 15 and 16 October 2008 respectively,^[87] and a more detailed report on 5 December 2008.^[79] 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,^[85] 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.^[85] A total of 53 magnets were damaged in the incident and were repaired or replaced during the winter shutdown.^[88] This accident was thoroughly discussed in a 22 February 2010 *Superconductor Science and Technology* article by CERN physicist Lucio Rossi.^[89]

In the original schedule for 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.^[90] However, owing to the delay caused by the incident, the collider was not operational until November 2009.^[91] 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.^[92]

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; this pushed the start of operations to November of that year.^[81]

Run 1: first operational run (2009–2013)

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.^[94]

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.^[95] This also marked the start of the main research programme.



Seminar on the physics of LHC by John Iliopoulos (2009).^[93]

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,^[96] allowing the ALICE experiment to study matter under extreme conditions similar to those shortly after the Big Bang.^[97]

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.^[98] 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)

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.^[99] 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 °C), a few days later.^[100] 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.^[101]



A section of the LHC

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][102]} 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.^[82] The energy was first reached on 10 April 2015.^[103] The upgrades culminated in colliding protons together with a combined energy of 13 TeV.^[104] On 3 June 2015, the LHC started delivering physics data after almost two years offline.^[105] 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,^[39] and further improvements increased the collision rate to 40% above the design value.^[106] 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.^[107]

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.^[40]

The 2018 physics run began on 17 April and stopped on 3 December, including four weeks of lead–lead collisions.^[108]

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.^[109] 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 | CERN successfully fired the first protons around the entire tunnel circuit in stages. |
| 19 Sep 2008 | Magnetic quench occurred in about 100 bending magnets 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. ^[32] |
| 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. ^[61] |
| 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. ^[110] |
| 15 Dec 2009 | First scientific results, covering 284 collisions in the <u>ALICE</u> detector. ^[111] |
| 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. ^[112] |
| 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. ^[113] |
| 24 May 2011 | ALICE reports that a <u>Quark-gluon plasma</u> has been achieved with earlier lead collisions. ^[114] |
| 17 Jun 2011 | The high-luminosity experiments ATLAS and CMS reach 1 fb^{-1} of collected data. ^[115] |
| 14 Oct 2011 | LHCb reaches 1 fb^{-1} of collected data. ^[116] |
| 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. ^[117] |
| 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). ^[118] |

| | |
|--------------|---|
| 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. ^[119]) |
| 8 Nov 2012 | First observation of the very rare decay of the B_s meson into two muons ($B_s^0 \rightarrow \mu^+\mu^-$), a major test of supersymmetry theories, ^[120] shows results at 3.5 sigma that match the Standard Model rather than many of its supersymmetrical 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. ^[121] |
| 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. ^[122] |
| 20 May 2015 | Protons collided in the LHC at the record-breaking collision energy of 13 TeV. ^[104] |
| 3 Jun 2015 | Start of delivering the physics data after almost two years offline for recommissioning. ^[105] |
| 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) ^[123] |
| 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. ^[39] Further improvements over the year increased the luminosity to 40% above the design value. ^[106] |
| 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. ^[40] |
| 10 Nov 2017 | End of regular 2017 proton-proton collision mode. ^[40] |
| 17 Apr 2018 | Start of 2018 proton-proton collisions. |
| 12 Nov 2018 | End of 2018 proton operations at CERN. ^[124] |
| 3 Dec 2018 | End of 2018 lead-ion run. ^[124] |
| 10 Dec 2018 | End of 2018 physics operation and start of Long Shutdown 2. ^[124] |

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.^[63] 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.^[125]

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.^[111] 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.^[126]

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.^{[127][128][129][130]} 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.^{[131][132][133]}

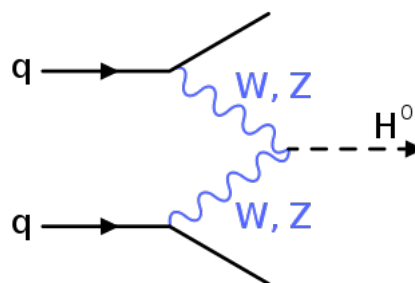
On 24 May 2011, it was reported that quark–gluon plasma (the densest matter thought to exist besides black holes) had been created in the LHC.^[114]

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^[134] and Mumbai.^[135] 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.^[136] 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.^{[137][138]}

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.^[139]

On 22 December 2011, it was reported that a new composite particle had been observed, the χ_b (3P) bottomonium state.^[117]

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



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.

further analysis.^[140] On 14 March 2013, CERN announced confirmation that the observed particle was indeed the predicted Higgs Boson.^[141]

On 8 November 2012, the LHCb team reported on an experiment seen as a "golden" test of supersymmetry theories in physics,^[120] by measuring the very rare decay of the B_s meson into two muons ($B_s^0 \rightarrow \mu^+ \mu^-$). 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.^[142] The result was later confirmed by the CMS collaboration.^[143]

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.^[144]

On 19 November 2014, the LHCb experiment announced the discovery of two new heavy subatomic particles, Ξ_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.^{[145][146]}

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 Z(4430) with a significance of over 13.9 sigma.^{[147][148]} On 13 July 2015, results consistent with pentaquark states in the decay of bottom Lambda baryons (Λ_b^0) were reported.^{[149][150][151]}

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 X(4140)).^{[152][153]}

In December 2016, ATLAS presented a measurement of the W boson mass, researching the precision of analyses done at the Tevatron.^[154]

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,^{[155][156][157]} but the experiments did not confirm the existence of the hypothetical particle in an August 2016 report.^{[158][159][160]}

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.^[161]

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, a luminosity upgrade of the LHC, called the High Luminosity Large Hadron Collider, started in June 2018 that will boost the accelerator's potential for new discoveries in physics, starting in 2027.^[162] The upgrade aims at increasing the luminosity of the machine by a factor of 10, up to 10^{35} cm^{−2}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.^[163] 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,^{[164][165][166]} a conclusion endorsed by the American Physical Society.^[167]

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,^[165] 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"^[168] surpassed 7 million YouTube views.^{[169][170]} The band Les Horribles Cernettes was founded by women from CERN. The name was chosen so to have the same initials as the LHC.^{[171][172]}

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.^[173]

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.^[174]

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.^[175] 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.^[176]

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.^[177]

In the *American Dad* episode *The 200*, Roger accidentally falls into the Large Hadron Collider, resulting in a huge explosion that creates two hundred clones of his multiple personas.

"The Large Hadron Collision" is the fifteenth episode of the third season of the American sitcom The Big Bang Theory in which Leonard (a character in the show) is offered a chance to visit the Large Hadron Collider.

See also

- List of accelerators in particle physics
- Accelerator projects
 - Compact Linear Collider
 - Future Circular Collider
 - International Linear Collider
 - Very Large Hadron Collider

References

1. "The Large Hadron Collider" (<https://home.cern/topics/large-hadron-collider>). CERN.
2. Joel Achenbach (March 2008). "The God Particle" (<http://ngm.nationalgeographic.com/2008/03/god-particle/achenbach-text>). *National Geographic Magazine*. Retrieved 25 February 2008.
3. Highfield, Roger (16 September 2008). "Large Hadron Collider: Thirteen ways to change the world" (<https://www.telegraph.co.uk/science/large-hadron-collider/3351899/Large-Hadron-Collider-thirteen-ways-to-change-the-world.html>). *The Daily Telegraph*. London. Retrieved 10 October 2008.
4. "CERN LHC sees high-energy success" (<http://news.bbc.co.uk/2/hi/science/nature/8593780.stm>). *BBC News*. 30 March 2010. Retrieved 30 March 2010.
5. "LHC to run at 4 TeV per beam in 2012" (<http://press.cern/press-releases/2012/02/lhc-run-4-tev-beam-2012>). *Media and Press Relations* (Press release). CERN. 13 February 2012.
6. Jonathan Webb (5 April 2015). "Large Hadron collider restarts after pause" (<https://www.bbc.com/news/science-environment-32160755>). *BBC*. Retrieved 5 April 2015.
7. O'Luanaigh, Cian. "Proton beams are back in the LHC" (<http://home.web.cern.ch/about/updates/2015/04/proton-beams-are-back-lhc>). CERN. Retrieved 24 April 2015.
8. Rincon, Paul (3 June 2015). "Large Hadron Collider turns on 'data tap' " (<https://www.bbc.co.uk/news/science-environment-32976838>). Retrieved 28 August 2015.
9. Webb, Jonathan (21 May 2015). "LHC smashes energy record with test collisions" (<https://www.bbc.co.uk/news/science-environment-32809636>). Retrieved 28 August 2015.
10. "Missing Higgs" (<http://public.web.cern.ch/public/en/Science/Higgs-en.html>). CERN. 2008. Retrieved 10 October 2008.

- l1. "Towards a superforce" (<http://public.web.cern.ch/public/en/Science/Superforce-en.html>). CERN. 2008. Retrieved 10 October 2008.
- l2. "LHCb – Large Hadron Collider beauty experiment" (<http://lhcb-public.web.cern.ch/lhcb-public/en/Physics/Antimatter-en.html>). *lhcb-public.web.cern.ch*.
- l3. Street, J.; Stevenson, E. (1937). "New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron" (<https://semanticscholar.org/paper/1ae47904c340d34a8bc77f550fa7fd399b85ed3a>). *Physical Review*. **52** (9): 1003. Bibcode:1937PhRv...52.1003S (<https://ui.adsabs.harvard.edu/abs/1937PhRv...52.1003S>). doi:10.1103/PhysRev.52.1003 (<https://doi.org/10.1103%2FPhysRev.52.1003>). S2CID 1378839 (<https://api.semanticscholar.org/CorpusID:1378839>).
- l4. "The Physics" (<https://atlas.cern/discover/physics>). *ATLAS Experiment at CERN*. 26 March 2015.
- l5. Overbye, Dennis (15 May 2007). "CERN – Large Hadron Collider – Particle Physics – A Giant Takes On Physics' Biggest Questions" (<https://www.nytimes.com/2007/05/15/science/15cern.html>). *The New York Times*. ISSN 0362-4331 (<https://www.worldcat.org/issn/0362-4331>). Retrieved 23 October 2019.
- l6. Giudice, G. F. (2010). *A Zeptospace Odyssey: A Journey Into the Physics of the LHC* (<https://web.archive.org/web/20131101054656/http://giudice.web.cern.ch/giudice/zeptospace/zepto-eng.html>). Oxford University Press. ISBN 978-0-19-958191-7. Archived from the original (<http://giudice.web.cern.ch/giudice/zeptospace/zepto-eng.html>) on 1 November 2013. Retrieved 11 August 2013.
- l7. Brian Greene (11 September 2008). "The Origins of the Universe: A Crash Course" (https://www.nytimes.com/2008/09/12/opinion/12greene.html?_r=1&oref=slogin). *The New York Times*. Retrieved 17 April 2009.
- l8. "... in the public presentations of the aspiration of particle physics we hear too often that the goal of the LHC or a linear collider is to check off the last missing particle of the Standard Model, this year's *Holy Grail* of particle physics, the Higgs boson. *The truth is much less boring than that!* What we're trying to accomplish is much more exciting, and asking what the world would have been like without the Higgs mechanism is a way of getting at that excitement." – Chris Quigg (2005). "Nature's Greatest Puzzles". *Econf C*. **040802** (1). arXiv:hep-ph/0502070 (<https://arxiv.org/abs/hep-ph/0502070>). Bibcode:2005hep.ph....2070Q (<https://ui.adsabs.harvard.edu/abs/2005hep.ph....2070Q>).
- l9. "Why the LHC" (<http://public.web.cern.ch/public/en/LHC/WhyLHC-en.html>). CERN. 2008. Retrieved 28 September 2009.
- l0. "Accordingly, in common with many of my colleagues, I think it highly likely that both the Higgs boson and other new phenomena will be found with the LHC."..."This mass threshold means, among other things, that something new – either a Higgs boson or other novel phenomena – is to be found when the LHC turns the thought experiment into a real one."Chris Quigg (February 2008). "The coming revolutions in particle physics" (<https://www.osti.gov/biblio/987233>). *Scientific American*. **298** (2): 38–45. Bibcode:2008SciAm.298b..46Q (<https://ui.adsabs.harvard.edu/abs/2008SciAm.298b..46Q>). doi:10.1038/scientificamerican0208-46 (<https://doi.org/10.1038%2Fscientificamerican0208-46>). OSTI 987233 (<https://www.osti.gov/biblio/987233>). PMID 18376670 (<https://pubmed.ncbi.nlm.nih.gov/18376670/>).
- l1. Shaaban Khalil (2003). "Search for supersymmetry at LHC". *Contemporary Physics*. **44** (3): 193–201. Bibcode:2003ConPh..44..193K (<https://ui.adsabs.harvard.edu/abs/2003ConPh..44..193K>). doi:10.1080/0010751031000077378 (<https://doi.org/10.1080%2F0010751031000077378>). S2CID 121063627 (<https://api.semanticscholar.org/CorpusID:121063627>).

22. Alexander Belyaev (2009). "Supersymmetry status and phenomenology at the Large Hadron Collider". *Pramana*. **72** (1): 143–160. Bibcode:2009Prma..72..143B (<https://ui.adsabs.harvard.edu/abs/2009Prma..72..143B>). doi:10.1007/s12043-009-0012-0 (<https://doi.org/10.1007%2Fs12043-009-0012-0>). S2CID 122457391 (<https://api.semanticscholar.org/CorpusID:122457391>).
23. Anil Ananthaswamy (11 November 2009). "In SUSY we trust: What the LHC is really looking for" (<https://www.newscientist.com/article/mg20427341.200-in-susy-we-trust-what-the-lhc-is-really-looking-for.html>). *New Scientist*.
24. Lisa Randall (2002). "Extra Dimensions and Warped Geometries" (<https://web.archive.org/web/20181007125941/http://randall.physics.harvard.edu/RandallCV/Sciencearticle.pdf>) (PDF). *Science*. **296** (5572): 1422–1427. Bibcode:2002Sci...296.1422R (<https://ui.adsabs.harvard.edu/abs/2002Sci...296.1422R>). doi:10.1126/science.1072567 (<https://doi.org/10.1126%2Fscience.1072567>). PMID 12029124 (<https://pubmed.ncbi.nlm.nih.gov/12029124>). S2CID 13882282 (<https://api.semanticscholar.org/CorpusID:13882282>). Archived from the original (<http://randall.physics.harvard.edu/RandallCV/Sciencearticle.pdf>) (PDF) on 7 October 2018. Retrieved 3 September 2008.
25. Panagiota Kanti (2009). "Black Holes at the Large Hadron Collider". *Physics of Black Holes*. Lecture Notes in Physics. **769**. pp. 387–423. arXiv:0802.2218 (<https://arxiv.org/abs/0802.2218>). Bibcode:2009LNP...769..387K (<https://ui.adsabs.harvard.edu/abs/2009LNP...769..387K>). doi:10.1007/978-3-540-88460-6_10 (https://doi.org/10.1007%2F978-3-540-88460-6_10). ISBN 978-3-540-88459-0. S2CID 17651318 (<https://api.semanticscholar.org/CorpusID:17651318>).
26. "Heavy ions and quark-gluon plasma" (<http://home.web.cern.ch/about/physics/heavy-ions-and-quark-gluon-plasma>). CERN. 18 July 2012.
27. "LHC experiments bring new insight into primordial universe" (<http://press.cern/press-releases/2010/11/lhc-experiments-bring-new-insight-primordial-universe>). *Media and Press Relations* (Press release). CERN. 26 November 2010. Retrieved 2 December 2010.
28. Aad, G.; et al. (ATLAS Collaboration) (2010). "Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC" (<https://doi.org/10.1103%2FPhysRevLett.105.252303>). *Physical Review Letters*. **105** (25): 252303. arXiv:1011.6182 (<https://arxiv.org/abs/1011.6182>). Bibcode:2010PhRvL.105y2303A (<https://ui.adsabs.harvard.edu/abs/2010PhRvL.105y2303A>). doi:10.1103/PhysRevLett.105.252303 (<https://doi.org/10.1103%2FPhysRevLett.105.252303>). PMID 21231581 (<https://pubmed.ncbi.nlm.nih.gov/21231581>).
29. <https://cds.cern.ch/record/2255762/files/CERN-Brochure-2017-002-Eng.pdf>
30. "The Z factory" (<http://public.web.cern.ch/PUBLIC/en/Research/LEP-en.html>). CERN. 2008. Retrieved 17 April 2009.
31. Henley, E. M.; Ellis, S. D., eds. (2013). *100 Years of Subatomic Physics*. World Scientific. doi:10.1142/8605 (<https://doi.org/10.1142%2F8605>). ISBN 978-981-4425-80-3.
32. Stephen Myers (4 October 2013). "The Large Hadron Collider 2008-2013" (<https://doi.org/10.1142%2FS0217751X13300354>). *International Journal of Modern Physics A*. **28** (25): 1330035-1–1330035-65. Bibcode:2013IJMPA..2830035M (<https://ui.adsabs.harvard.edu/abs/2013IJMPA..2830035M>). doi:10.1142/S0217751X13300354 (<https://doi.org/10.1142%2FS0217751X13300354>).
33. "Status of the LHC superconducting cable mass production 2002" (<https://www.researchgate.net/publication/224055541>).

34. "Powering CERN" (<https://home.cern/about/engineering/powering-cern>). CERN. 2018. Retrieved 23 June 2018.
35. Brady, Henry E. (11 May 2019). "The Challenge of Big Data and Data Science" (<http://www.annualreviews.org/doi/10.1146/annurev-polisci-090216-023229>). *Annual Review of Political Science*. **22** (1): 297–323. doi:10.1146/annurev-polisci-090216-023229 (<https://doi.org/10.1146%2Fannurev-polisci-090216-023229>). ISSN 1094-2939 (<https://www.worldcat.org/issn/1094-2939>).
36. "First successful beam at record energy of 6.5 TeV" (<http://home.cern/about/updates/2015/04/first-successful-beam-record-energy-65-tev>). 10 April 2015. Retrieved 10 January 2016.
37. Deboy, D.; Assmann, R.W.; Burkart, F.; Cauchi, M.; Wollmann, D. (29 August 2011). "Acoustic measurements at LHC collimators" (https://indico.cern.ch/event/138175/contributions/143308/attachments/115687/164260/2011_08_WGMeeting_ddeboy.pdf) (PDF). *LHC Collimation Project*. "The ring operates with an acoustic fundamental and overtones of 11.245 kHz"
38. "Operational Experience of the ATLAS High Level Trigger with Single-Beam and Cosmic Rays" (<http://cdsweb.cern.ch/record/1228285/files/ATL-DAQ-PROC-2009-044.pdf>) (PDF). Retrieved 29 October 2010.
39. "LHC performance reaches new highs" (<https://home.cern/about/updates/2016/07/lhc-performance-reaches-new-highs>). 13 July 2016. Retrieved 13 May 2017.
40. "Record luminosity: well done LHC" (<https://home.cern/about/updates/2017/11/record-luminosity-well-done-lhc>). 15 November 2017. Retrieved 2 December 2017.
41. Jörg Wenninger (November 2007). "Operational challenges of the LHC" (<http://irfu.ccea.fr/Phocea/file.php?class=std&file=Seminaires/1595/Dapnia-Nov07-partB.ppt>) (PowerPoint). p. 53. Retrieved 17 April 2009.
42. "Ions for LHC (I-LHC) Project" (<http://project-i-lhc.web.cern.ch/project-i-lhc/Welcome.htm>). CERN. 1 November 2007. Retrieved 17 April 2009.
43. "Opinion: A new energy frontier for heavy ions" (<http://home.cern/about/opinion/2015/11/new-energy-frontier-heavy-ions>). 24 November 2015. Retrieved 10 January 2016.
44. Charley, Sarah. "Revamped LHC goes heavy metal" (<https://www.symmetrymagazine.org/article/revamped-lhc-goes-heavy-metal>). *symmetry magazine*. Retrieved 23 October 2019.
45. "How the Higgs Boson Was Found" (<https://www.smithsonianmag.com/science-nature/how-the-higgs-boson-was-found-4723520/>). *Smithsonian*. Retrieved 23 October 2019.
46. Paul Rincon (10 September 2008). "'Big Bang' experiment starts well" (<http://news.bbc.co.uk/1/hi/sci/tech/7604293.stm>). BBC News. Retrieved 17 April 2009.
47. "Worldwide LHC Computing Grid" (<http://public.web.cern.ch/public/en/LHC/Computing-en.html>). CERN. 2008. Retrieved 2 October 2011.
48. "grille de production : les petits pc du lhc" (http://www.cite-sciences.fr/francais/ala_cite/science_actualites/sitesactu/question_actu.php?langue=fr&id_article=16043). Cite-sciences.fr. Retrieved 22 May 2011.
49. "Welcome to the Worldwide LHC Computing Grid" (<http://wlcg.web.cern.ch/>). *WLCG – Worldwide LHC Computing Grid*. CERN. Retrieved 13 May 2017.
50. "About" (<http://wlcg-public.web.cern.ch/about>). *WLCG – Worldwide LHC Computing Grid*. CERN. Retrieved 13 May 2017.

51. "Worldwide LHC Computing Grid" (<https://web.archive.org/web/20111001180149/http://lcg.web.cern.ch/LCG/public/>). *Official public website*. CERN. Archived from the original (<http://lcg.web.cern.ch/LCG/public/>) on 1 October 2011. Retrieved 2 October 2011.
52. "LHC@home" (<http://boinc.berkeley.edu/wiki/LHC@home>). *berkeley.edu*.
53. Craig Lloyd (18 December 2012). "First LHC proton run ends in success, new milestone" (<http://www.slashgear.com/first-lhc-proton-run-ends-in-success-new-milestone-18261452/>). Retrieved 26 December 2014.
54. "Hunt for Higgs boson hits key decision point" (<http://www.nbcnews.com/id/47783507>). *NBC News – Science – Technology & Science*.
55. "Welcome to the Worldwide LHC Computing Grid" (<http://wlcg.web.cern.ch/>). *WLCG – Worldwide LHC Computing Grid*. CERN. "[A] global collaboration of more than 170 computing centres in 36 countries ... to store, distribute and analyse the ~25 Petabytes (25 million Gigabytes) of data annually generated by the Large Hadron Collider"
56. "What is the Worldwide LHC Computing Grid?" (<https://web.archive.org/web/20120704015916/http://lcg-archive.web.cern.ch/lcg-archive/public/overview.htm>). *WLCG – Worldwide LHC Computing Grid*. 14 November 2012. Archived from the original (<http://lcg-archive.web.cern.ch/lcg-archive/public/overview.htm>) on 4 July 2012. "Currently WLCG is made up of more than 170 computing centers in 36 countries ... The WLCG is now the world's largest computing grid"
57. "First beam in the LHC – accelerating science" (<http://press.cern/press-releases/2008/09/first-beam-lhc-accelerating-science>). *Media and Press Relations* (Press release). CERN. 10 September 2008. Retrieved 9 October 2008.
58. Paul Rincon (23 September 2008). "Collider halted until next year" (<http://news.bbc.co.uk/2/hi/science/nature/7632408.stm>). BBC News. Retrieved 9 October 2008.
59. "Large Hadron Collider – Purdue Particle Physics" (<https://web.archive.org/web/20120717085441/http://www.physics.purdue.edu/particle/lhc/>). Physics.purdue.edu. Archived from the original (<http://www.physics.purdue.edu/particle/lhc/>) on 17 July 2012. Retrieved 5 July 2012.
50. Hadron Collider (<http://www.diffusion.ens.fr/index.php?idconf=2522&res=conf#Large>).
51. "The LHC is back" (<http://press.cern/press-releases/2009/11/lhc-back>). *Media and Press Relations* (Press release). CERN. 20 November 2009. Retrieved 13 November 2016.
52. "Two circulating beams bring first collisions in the LHC" (<http://press.cern/press-releases/2009/11/two-circulating-beams-bring-first-collisions-lhc>). *Media and Press Relations* (Press release). CERN. 23 November 2009. Retrieved 13 November 2016.
53. "What is LHCb" (<https://web.archive.org/web/20090326231649/http://cdsmedia.cern.ch/img/CERN-Brochure-2008-001-Eng.pdf>) (PDF). *CERN FAQ*. CERN Communication Group. January 2008. p. 44. Archived from the original (<http://cdsmedia.cern.ch/img/CERN-Brochure-2008-001-Eng.pdf>) (PDF) on 26 March 2009. Retrieved 2 April 2010.
54. Amina Khan (31 March 2010). "Large Hadron Collider rewards scientists watching at Caltech" (<http://articles.latimes.com/2010/mar/31/science/la-sci-hadron31-2010-mar31>). *Los Angeles Times*. Retrieved 2 April 2010.
55. M. Hogenboom (24 July 2013). "Ultra-rare decay confirmed in LHC" (<https://www.bbc.co.uk/news/science-environment-23431797>). BBC. Retrieved 18 August 2013.

56. "Challenges in accelerator physics" (<https://web.archive.org/web/20061005004318/http://lhc.web.cern.ch/lhc/general/acphys.htm>). CERN. 14 January 1999. Archived from the original (<http://lhc.web.cern.ch/lhc/general/acphys.htm>) on 5 October 2006. Retrieved 28 September 2009.
57. John Poole (2004). "Beam Parameters and Definitions" (https://edms.cern.ch/file/445830/5/Vol_1_Chapter_2.pdf) (PDF). *LHC Design Report*.
58. Agence Science-Presse (7 December 2009). "LHC: Un (très) petit Big Bang" (http://www.lienmultimedia.com/article.php3?id_article=22468) (in French). Lien Multimedia. Retrieved 29 October 2010. Google translation (https://translate.google.com/translate?sl=fr&tl=en&prev=_t&hl=en&u=http://www.lienmultimedia.com/article.php3?id_article%3D22468)
59. "How much does it cost?" (<https://web.archive.org/web/20110807103920/http://askanexpert.web.cern.ch/AskAnExpert/en/Accelerators/LHCgeneral-en.html#3>). CERN. 2007. Archived from the original (<http://askanexpert.web.cern.ch/AskAnExpert/en/Accelerators/LHCgeneral-en.html#3>) on 7 August 2011. Retrieved 28 September 2009.
70. Luciano Maiani (16 October 2001). "LHC Cost Review to Completion" (<https://web.archive.org/web/20081227135127/http://user.web.cern.ch/User/LHCCost/2001-10-16/LHCCostReview.html>). CERN. Archived from the original (<http://user.web.cern.ch/User/LHCCost/2001-10-16/LHCCostReview.html>) on 27 December 2008. Retrieved 15 January 2001.
71. Toni Feder (2001). "CERN Grapples with LHC Cost Hike" (<https://doi.org/10.1063%2F1.1445534>). *Physics Today*. **54** (12): 21–22. Bibcode:2001PhT....54l..21F (<https://ui.adsabs.harvard.edu/abs/2001PhT....54l..21F>). doi:10.1063/1.1445534 (<https://doi.org/10.1063%2F1.1445534>).
72. "Bursting magnets may delay CERN collider project" (<https://web.archive.org/web/20070503011021/https://www.reuters.com/article/scienceNews/idUSL054919720070405>). *Reuters*. 5 April 2007. Archived from the original (<https://www.reuters.com/article/scienceNews/idUSL054919720070405>) on 3 May 2007. Retrieved 28 September 2009.
73. Paul Rincon (23 September 2008). "Collider halted until next year" (<http://news.bbc.co.uk/1/hi/sci/tech/7632408.stm>). *BBC News*. Retrieved 28 September 2009.
74. Robert Aymar (26 October 2005). "Message from the Director-General" (<https://cds.cern.ch/record/901285?ln=en>). *Media and Press Relations* (Press release). CERN. Retrieved 12 June 2013.
75. "Fermilab 'Dumbfounded' by fiasco that broke magnet" (<https://www.photonics.com/Article.aspx?PID=6&VID=32&IID=230&AID=29203>). Photonics.com. 4 April 2007. Retrieved 28 September 2009.
76. "Fermilab update on inner triplet magnets at LHC: Magnet repairs underway at CERN" (https://web.archive.org/web/20090106233105/http://user.web.cern.ch/user/QuickLinks/Announcements/2007/LHCInnerTriplet_5.html). *Media and Press Relations* (Press release). CERN. 1 June 2007. Archived from the original (http://user.web.cern.ch/user/QuickLinks/Announcements/2007/LHCInnerTriplet_5.html) on 6 January 2009. Retrieved 28 September 2009.
77. "Updates on LHC inner triplet failure" (http://www.fnal.gov/pub/today/lhc_magnet_archive.html). *Fermilab Today*. Fermilab. 28 September 2007. Retrieved 28 September 2009.
78. Paul Rincon (23 September 2008). "Collider halted until next year" (http://news.bbc.co.uk/2/hi/in_depth/7632408.stm). *BBC News*. Retrieved 29 September 2009.

79. "LHC to restart in 2009" (<http://press.cern/press-releases/2008/12/lhc-restart-2009>) . *Media and Press Relations* (Press release). CERN. 5 December 2008. Retrieved 13 November 2016.
30. Dennis Overbye (5 December 2008). "After repairs, summer start-up planned for collider" (<https://www.nytimes.com/2008/12/06/science/06cern.html>). *New York Times*. Retrieved 8 December 2008.
31. "News on the LHC" (<http://user.web.cern.ch/user/news/2009/090716.html>). CERN. 16 July 2009. Retrieved 28 September 2009.
32. "Restarting the LHC: Why 13 TeV?" (<http://home.web.cern.ch/about/engineering/restarting-lhc-why-13-tev>). CERN. Retrieved 28 August 2015.
33. "First LHC magnets prepped for restart" (<http://www.symmetrymagazine.org/article/december-2014/first-lhc-magnets-prepped-for-restart>). *Symmetry Magazine*. Retrieved 28 August 2015.
34. Mark Henderson (10 September 2008). "Scientists cheer as protons complete first circuit of Large Hadron Collider" (<http://www.thetimes.co.uk/tto/news/world/article1967054.ece>). *Times Online*. London. Retrieved 6 October 2008.
35. "Interim Summary Report on the Analysis of the 19 September 2008 Incident at the LHC" (https://edms.cern.ch/file/973073/1/Report_on_080919_incident_at_LHC_2_.pdf) (PDF). CERN. 15 October 2008. EDMS 973073. Retrieved 28 September 2009.
36. "Incident in LHC sector 3-4" (<http://press.cern/press-releases/2008/09/incident-lhc-sector-3-4>). *Media and Press Relations* (Press release). CERN. 20 September 2008. Retrieved 13 November 2016.
37. "CERN releases analysis of LHC incident" (<http://press.cern/press-releases/2008/10/cern-releases-analysis-lhc-incident>). *Media and Press Relations* (Press release). CERN. 16 October 2008. Retrieved 13 November 2016.
38. "Final LHC magnet goes underground" (<http://press.cern/press-releases/2009/04/final-lhc-magnet-goes-underground>). *Media and Press Relations* (Press release). CERN. 30 April 2009. Retrieved 13 November 2016.
39. L. Rossi (2010). "Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN" (<https://cds.cern.ch/record/1235168/files/CERN-ATS-2010-006.pdf>) (PDF). *Superconductor Science and Technology*. **23** (3): 034001. Bibcode:2010SuScT..23c4001R (<https://ui.adsabs.harvard.edu/abs/2010SuScT..23c4001R>). doi:10.1088/0953-2048/23/3/034001 (<https://doi.org/10.1088%2F0953-2048%2F23%2F3%2F034001>).
30. "CERN announces start-up date for LHC" (<http://press.cern/press-releases/2008/08/cern-announces-start-date-lhc>). *Media and Press Relations* (Press release). CERN. 7 August 2008. Retrieved 13 November 2016.
31. "CERN management confirms new LHC restart schedule" (<http://press.cern/press-releases/2009/02/cern-management-confirms-new-lhc-restart-schedule>). *Media and Press Relations* (Press release). CERN. 9 February 2009. Retrieved 13 November 2016.
32. "CERN inaugurates the LHC" (<http://press.cern/press-releases/2008/10/cern-inaugurates-lhc>). *Media and Press Relations* (Press release). CERN. 21 October 2008. Retrieved 21 October 2008.
33. Seminar on the physics of LHC by John Iliopoulos, *École Normale Supérieure*, Paris, 2009.
34. "LHC sets new world record" (<http://press.cern/press-releases/2009/11/lhc-sets-new-world-record>). *Media and Press Relations* (Press release). CERN. 30 November 2009. Retrieved 13 November 2016.

95. "Big Bang Machine sets collision record" (<http://www.thehindu.com/sci-tech/science/article329160.ece>). *The Hindu*. Associated Press. 30 March 2010.
96. "CERN completes transition to lead-ion running at the LHC" (<http://press.cern/press-releases/2010/11/cern-completes-transition-lead-ion-running-lhc>). *Media and Press Relations* (Press release). CERN. 8 November 2010. Retrieved 28 February 2016.
97. "The Latest from the LHC : Last period of proton running for 2010. – CERN Bulletin" (<http://cdsweb.cern.ch/journal/CERNBulletin/2010/45/News%20Articles/1302710?ln=en>). Cdsweb.cern.ch. 1 November 2010. Retrieved 17 August 2011.
98. "The first LHC protons run ends with new milestone" (<http://press.cern/press-releases/2012/12/first-lhc-protons-run-ends-new-milestone>). *Media and Press Relations* (Press release). CERN. 17 December 2012.
99. "Long Shutdown 1: Exciting times ahead" (<http://home.web.cern.ch/about/updates/2013/02/long-shutdown-1-exciting-times-ahead>). *cern.ch*. Retrieved 28 August 2015.
100. "CERN" (<http://home.web.cern.ch/about/updates/2014/06/cern-announces-lhc-restart-schedule>). *cern.ch*. Retrieved 28 August 2015.
101. "LHC 2015 – latest news" (<http://lhc-commissioning.web.cern.ch/lhc-commissioning/news-2015/LHC-latest-news.html>). *cern.ch*. Retrieved 19 January 2016.
102. "LHC consolidations: A step-by-step guide" (<https://home.cern/about/updates/2013/03/lhc-consolidations-step-step-guide>). CERN.
103. O'Luanaigh, Cian. "First successful beam at record energy of 6.5 TeV" (<http://home.web.cern.ch/about/updates/2015/04/first-successful-beam-record-energy-65-tev>). CERN. Retrieved 24 April 2015.
104. O'Luanaigh, Cian (21 May 2015). "First images of collisions at 13 TeV" (<https://home.cern/about/updates/2015/05/first-images-collisions-13-tev>). CERN.
105. "Physicists eager for new high-energy Large Hadron Collider run" (<https://www.sciencedaily.com/releases/2015/06/150603181744.htm>). *Science Daily*. 3 June 2015. Retrieved 4 June 2015.
106. "LHC Report: end of 2016 proton-proton operation" (<https://home.cern/cern-people/updates/2016/10/lhc-report-end-2016-proton-proton-operation>). 31 October 2016. Retrieved 27 January 2017.
107. "LHC Report: far beyond expectations" (<https://home.cern/cern-people/updates/2016/12/lhc-report-far-beyond-expectations>). 13 December 2016. Retrieved 27 January 2017.
108. "LHC Schedule 2018" (https://beams.web.cern.ch/sites/beams.web.cern.ch/files/schedules/LHC_Schedule_2018.pdf) (PDF).
109. "LHC long term schedule" (<https://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm>). *lhc-commissioning.web.cern.ch*.
110. "LHC sets new world record" (<http://press.cern/press-releases/2009/11/lhc-sets-new-world-record>). *Media and Press Relations* (Press release). CERN. 30 November 2009. Retrieved 13 November 2016.
111. First Science Produced at LHC (<http://news.softpedia.com/news/First-Science-Produced-at-LHC-129833.shtml>) 2009-12-15
112. "LHC sees first stable-beam 3.5 TeV collisions of 2011" (<http://www.symmetrymagazine.org/breaking/2011/03/13/lhc-sees-first-3-5-tev-collisions-of-2011/>). *symmetry breaking*. 13 March 2011. Retrieved 15 March 2011.
113. "LHC sets world record beam intensity" (<http://press.cern/press-releases/2011/04/lhc-sets-world-record-beam-intensity>). *Media and Press Relations* (Press release). CERN. 22 April 2011. Retrieved 13 November 2016.

14. "Densest Matter Created in Big-Bang Machine" (<http://news.nationalgeographic.com/news/2011/05/110524-densest-matter-created-lhc-alice-big-bang-space-science/>). *nationalgeographic.com*. 26 May 2011.
15. "LHC achieves 2011 data milestone" (<http://press.cern/press-releases/2011/06/lhc-achieves-2011-data-milestone>). *Media and Press Relations* (Press release). CERN. 17 June 2011. Retrieved 20 June 2011.
16. Anna Phan. "One Recorded Inverse Femtobarn!!!" (<http://www.quantumdiaries.org/2011/10/18/one-recorded-inverse-femtobarn/>). *Quantum Diaries*.
17. Jonathan Amos (22 December 2011). "LHC reports discovery of its first new particle" (<https://www.bbc.co.uk/news/science-environment-16301908>). *BBC News*.
18. "LHC physics data taking gets underway at new record collision energy of 8TeV" (<http://press.cern/press-releases/2012/04/lhc-physics-data-taking-gets-underway-new-record-collision-energy-8tev>). *Media and Press Relations* (Press release). CERN. 5 April 2012. Retrieved 13 November 2016.
19. "New results indicate that new particle is a Higgs boson" (<http://home.web.cern.ch/about/updates/2013/03/new-results-indicate-new-particle-higgs-boson>). CERN. 14 March 2013. Retrieved 14 March 2013.
20. Ghosh, Pallab (12 November 2012). "Popular physics theory running out of hiding places" (<https://www.bbc.co.uk/news/science-environment-20300100>). *BBC News*. Retrieved 14 November 2012.
21. "The first LHC protons run ends with new milestone" (<http://press.cern/press-releases/2012/12/first-lhc-protons-run-ends-new-milestone>). *Media and Press Relations* (Press release). CERN. 17 December 2012. Retrieved 10 March 2014.
22. "First successful beam at record energy of 6.5 TeV" (<http://home.web.cern.ch/about/updates/2015/04/first-successful-beam-record-energy-65-tev>). CERN. 10 April 2015. Retrieved 5 May 2015.
23. *cds.cern.ch* <https://cds.cern.ch/journal/CERNBulletin/2015/49/News+Articles/2105084?ln=en> (<https://cds.cern.ch/journal/CERNBulletin/2015/49/News+Articles/2105084?ln=en>). Missing or empty |title= (help)
24. "LHC Report: Another run is over and LS2 has just begun..." (<https://home.cern/new/s/news/accelerators/lhc-report-another-run-over-and-ls2-has-just-begun>). *CERN*.
25. P. Rincon (17 May 2010). "LHC particle search 'nearing', says physicist" (<http://news.bbc.co.uk/1/hi/sci/tech/8685541.stm>). *BBC News*.
26. V. Khachatryan *et al.* (CMS collaboration) (2010). "Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV" (<https://doi.org/10.1007%2FJHEP02%282010%29041>). *Journal of High Energy Physics*. **2010** (2): 1–35. arXiv:1002.0621 (<https://arxiv.org/abs/1002.0621>). Bibcode:2010JHEP...02..041K (<https://ui.adsabs.harvard.edu/abs/2010JHEP...02..041K>). doi:10.1007/JHEP02(2010)041 (<https://doi.org/10.1007%2FJHEP02%282010%29041>).
27. V. Khachatryan *et al.* (CMS collaboration) (2011). "Search for Microscopic Black Hole Signatures at the Large Hadron Collider" (<https://doi.org/10.1016%2Fj.physletb.2011.02.032>). *Physics Letters B*. **697** (5): 434–453. arXiv:1012.3375 (<https://arxiv.org/abs/1012.3375>). Bibcode:2011PhLB..697..434C (<https://ui.adsabs.harvard.edu/abs/2011PhLB..697..434C>). doi:10.1016/j.physletb.2011.02.032 (<https://doi.org/10.1016%2Fj.physletb.2011.02.032>).

28. V. Khachatryan *et al.* (CMS collaboration) (2011). "Search for Supersymmetry in pp Collisions at 7 TeV in Events with Jets and Missing Transverse Energy" (<https://doi.org/10.1016%2Fj.physletb.2011.03.021>). *Physics Letters B*. **698** (3): 196–218. arXiv:1101.1628 (<https://arxiv.org/abs/1101.1628>). Bibcode:2011PhLB..698..196C (<https://ui.adsabs.harvard.edu/abs/2011PhLB..698..196C>). doi:10.1016/j.physletb.2011.03.021 (<https://doi.org/10.1016%2Fj.physletb.2011.03.021>).
29. G. Aad *et al.* (ATLAS collaboration) (2011). "Search for supersymmetry using final states with one lepton, jets, and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV pp" (<https://doi.org/10.1103%2FPhysRevLett.106.131802>). *Physical Review Letters*. **106** (13): 131802. arXiv:1102.2357 (<https://arxiv.org/abs/1102.2357>). Bibcode:2011PhRvL.106m1802A (<https://ui.adsabs.harvard.edu/abs/2011PhRvL.106m1802A>). doi:10.1103/PhysRevLett.106.131802 (<https://doi.org/10.1103%2FPhysRevLett.106.131802>). PMID 21517374 (<https://pubmed.ncbi.nlm.nih.gov/21517374>).
30. G. Aad *et al.* (ATLAS collaboration) (2011). "Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions" (<https://doi.org/10.1016%2Fj.physletb.2011.05.061>). *Physics Letters B*. **701** (2): 186–203. arXiv:1102.5290 (<https://arxiv.org/abs/1102.5290>). Bibcode:2011PhLB..701..186A (<https://ui.adsabs.harvard.edu/abs/2011PhLB..701..186A>). doi:10.1016/j.physletb.2011.05.061 (<https://doi.org/10.1016%2Fj.physletb.2011.05.061>).
31. Chalmers, M. Reality check at the LHC (<http://physicsworld.com/cws/article/indepth/44805>), physicsworld.com (<http://physicsworld.com/>), 18 January 2011
32. McAlpine, K. Will the LHC find supersymmetry? (<http://physicsworld.com/cws/article/news/45182>) Archived (<https://web.archive.org/web/20110225101256/http://physicsworld.com/cws/article/news/45182>) 25 February 2011 at the Wayback Machine, physicsworld.com (<http://physicsworld.com/>), 22 February 2011
33. Geoff Brumfiel (2011). "Beautiful theory collides with smashing particle data" (<https://doi.org/10.1038%2F471013a>). *Nature*. **471** (7336): 13–14. Bibcode:2011Natur.471...13B (<https://ui.adsabs.harvard.edu/abs/2011Natur.471...13B>). doi:10.1038/471013a (<https://doi.org/10.1038%2F471013a>). PMID 21368793 (<https://pubmed.ncbi.nlm.nih.gov/21368793>).
34. "LHC experiments present their latest results at Europhysics Conference on High Energy Physics" (<http://press.cern/press-releases/2011/07/lhc-experiments-present-their-latest-results-europhysics-conference-high>). *Media and Press Relations* (Press release). CERN. 21 July 2011. Retrieved 13 November 2016.
35. "LHC experiments present latest results at Mumbai conference" (<http://press.cern/press-releases/2011/08/lhc-experiments-present-latest-results-mumbai-conference>). *Media and Press Relations* (Press release). CERN. 22 August 2011. Retrieved 13 November 2016.
36. Pallab Ghosh (22 August 2011). "Higgs boson range narrows at European collider" (<https://www.bbc.co.uk/news/science-environment-14596367>). BBC News.
37. Pallab Ghosh (27 August 2011). "LHC results put supersymmetry theory 'on the spot' " (<https://www.bbc.co.uk/news/science-environment-14680570>). BBC News.
38. "LHCb experiment sees Standard Model physics" (<http://www.symmetrymagazine.org/breaking/2011/08/29/lhcb-experiment-sees-standard-model-physics/>). *Symmetry Magazine*. SLAC/Fermilab. 29 August 2011. Retrieved 1 September 2011.
39. "ATLAS and CMS experiments present Higgs search status" (<http://press.cern/press-releases/2011/12/atlas-and-cms-experiments-present-higgs-search-status>). *Media and Press Relations* (Press release). CERN. 13 December 2011. Retrieved 13 November 2016.


10. "CERN experiments observe particle consistent with long-sought Higgs boson" (<http://press.cern/press-releases/2012/07/cern-experiments-observe-particle-consistent-long-sought-higgs-boson>). *Media and Press Relations* (Press release). CERN. 4 July 2012. Retrieved 9 November 2016.
11. "Now confident: CERN physicists say new particle is Higgs boson (Update 3)" (<http://phys.org/news/2013-03-confident-cern-physicists-higgs-boson.html>). Phys Org. 14 March 2013. Retrieved 4 December 2019.
12. LHCb Collaboration (7 January 2013). "First Evidence for the Decay $B_s^0 \rightarrow \mu^+ \mu^-$ ". *Physical Review Letters*. **110** (2): 021801. arXiv:1211.2674 (<https://arxiv.org/abs/1211.2674>). Bibcode:2013PhRvL.110b1801A (<https://ui.adsabs.harvard.edu/abs/2013PhRvL.110b1801A>). doi:10.1103/PhysRevLett.110.021801 (<https://doi.org/10.1103%2FPhysRevLett.110.021801>). PMID 23383888 (<https://pubmed.ncbi.nlm.nih.gov/23383888>). S2CID 13103388 (<https://api.semanticscholar.org/CorpusID:13103388>).
13. CMS collaboration (5 September 2013). "Measurement of the $B_s^0 \rightarrow \mu^+ \mu^-$ Branching Fraction and Search for $B^0 \rightarrow \mu^+ \mu^-$ with the CMS Experiment" (<https://doi.org/10.1103%2FPhysRevLett.111.101804>). *Physical Review Letters*. **111** (10): 101804. arXiv:1307.5025 (<https://arxiv.org/abs/1307.5025>). Bibcode:2013PhRvL.111j1804C (<https://ui.adsabs.harvard.edu/abs/2013PhRvL.111j1804C>). doi:10.1103/PhysRevLett.111.101804 (<https://doi.org/10.1103%2FPhysRevLett.111.101804>). PMID 25166654 (<https://pubmed.ncbi.nlm.nih.gov/25166654>).
14. "Hints of New Physics Detected in the LHC?" (<http://news.discovery.com/space/hints-of-new-physics-detected-in-the-lhc-130802.htm>). 10 May 2017.
15. New subatomic particles predicted by Canadians found at CERN (<http://www.cbc.ca/news/technology/new-subatomic-particles-predicted-by-canadians-found-at-cern-1.2840199>), 19 November 2014
16. "LHCb experiment observes two new baryon particles never seen before" (<http://press.cern/press-releases/2014/11/lhcb-experiment-observes-two-new-baryon-particles-never-seen>). *Media and Press Relations* (Press release). CERN. 19 November 2014. Retrieved 19 November 2014.
17. O'Luanaigh, Cian (9 April 2014). "LHCb confirms existence of exotic hadrons" (<http://home.web.cern.ch/about/updates/2014/04/lhcb-confirms-existence-exotic-hadrons>). CERN. Retrieved 4 April 2016.
18. Aaij, R.; et al. (LHCb collaboration) (4 June 2014). "Observation of the resonant character of the $Z(4430)^-$ state" (<https://doi.org/10.1103%2FPhysRevLett.112.222002>). *Physical Review Letters*. **112** (21): 222002. arXiv:1404.1903 (<https://arxiv.org/abs/1404.1903>). Bibcode:2014PhRvL.112v2002A (<https://ui.adsabs.harvard.edu/abs/2014PhRvL.112v2002A>). doi:10.1103/PhysRevLett.112.222002 (<https://doi.org/10.1103%2FPhysRevLett.112.222002>). PMID 24949760 (<https://pubmed.ncbi.nlm.nih.gov/24949760>).
19. Aaij, R.; et al. (LHCb collaboration) (12 August 2015). "Observation of J/ψ resonances consistent with pentaquark states in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays" (<https://doi.org/10.1103%2FPhysRevLett.115.072001>). *Physical Review Letters*. **115** (7): 072001. arXiv:1507.03414 (<https://arxiv.org/abs/1507.03414>). Bibcode:2015PhRvL.115g2001A (<https://ui.adsabs.harvard.edu/abs/2015PhRvL.115g2001A>). doi:10.1103/PhysRevLett.115.072001 (<https://doi.org/10.1103%2FPhysRevLett.115.072001>). PMID 26317714 (<https://pubmed.ncbi.nlm.nih.gov/26317714>).
20. "CERN's LHCb experiment reports observation of exotic pentaquark particles" (<http://press.cern/press-releases/2015/07/cerns-lhcb-experiment-reports-observation-exotic-pentaquark-particles>). *Media and Press Relations* (Press release). CERN. Retrieved 28 August 2015.

51. Rincon, Paul (1 July 2015). "Large Hadron Collider discovers new pentaquark particle" (<https://www.bbc.com/news/science-environment-33517492>). *BBC News*. Retrieved 14 July 2015.
52. Aaij, R.; et al. (LHCb collaboration) (2017). "Observation of $J/\psi\phi$ structures consistent with exotic states from amplitude analysis of $B^+ \rightarrow J/\psi\phi K^+$ decays". *Physical Review Letters*. **118** (2): 022003. arXiv:1606.07895 (<https://arxiv.org/abs/1606.07895>). Bibcode:2017PhRvL.118b2003A (<https://ui.adsabs.harvard.edu/abs/2017PhRvL.118b2003A>). doi:10.1103/PhysRevLett.118.022003 (<https://doi.org/10.1103/PhysRevLett.118.022003>). PMID 28128595 (<https://pubmed.ncbi.nlm.nih.gov/28128595>). S2CID 206284149 (<https://api.semanticscholar.org/CorpusID:206284149>).
53. Aaij, R.; et al. (LHCb collaboration) (2017). "Amplitude analysis of $B^+ \rightarrow J/\psi\phi K^+$ decays". *Physical Review D*. **95** (1): 012002. arXiv:1606.07898 (<https://arxiv.org/abs/1606.07898>). Bibcode:2017PhRvD..95a2002A (<https://ui.adsabs.harvard.edu/abs/2017PhRvD..95a2002A>). doi:10.1103/PhysRevD.95.012002 (<https://doi.org/10.1103/PhysRevD.95.012002>). S2CID 73689011 (<https://api.semanticscholar.org/CorpusID:73689011>).
54. "ATLAS releases first measurement of the W mass using LHC data" (<http://atlas.cern/updates/physics-briefing/measuring-w-boson-mass>). 13 December 2016. Retrieved 27 January 2017.
55. Overbye, Dennis (15 December 2015). "Physicists in Europe Find Tantalizing Hints of a Mysterious New Particle" (<https://www.nytimes.com/2015/12/16/science/physicists-in-europe-find-tantalizing-hints-of-a-mysterious-new-particle.html>). *New York Times*. Retrieved 15 December 2015.
56. CMS Collaboration (15 December 2015). "Search for new physics in high mass diphoton events in proton-proton collisions at 13 TeV" (<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-15-004/index.html>). *Compact Muon Solenoid*. Retrieved 2 January 2016.
57. ATLAS Collaboration (15 December 2015). "Search for resonances decaying to photon pairs in 3.2 fb⁻¹ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector" (<http://cdsweb.cern.ch/record/2114853/files/ATLAS-CONF-2015-081.pdf>) (PDF). Retrieved 2 January 2016.
58. CMS Collaboration. "CMS Physics Analysis Summary" (<https://cds.cern.ch/record/2205245/files/EXO-16-027-pas.pdf>) (PDF). CERN. Retrieved 4 August 2016.
59. Overbye, Dennis (5 August 2016). "The Particle That Wasn't" (<https://www.nytimes.com/2016/08/05/science/cern-large-hadron-collider-particle.html>). *New York Times*. Retrieved 5 August 2016.
50. "Chicago sees floods of LHC data and new results at the ICHEP 2016 conference" (<https://press.cern/press-releases/2016/08/chicago-sees-floods-lhc-data-and-new-results-ichep-2016-conference>). *Media and Press Relations* (Press release). CERN. 5 August 2015. Retrieved 5 August 2015.
51. "LHC experiments delve deeper into precision" (<https://press.cern/update/2017/07/lhc-experiments-delve-deeper-precision>). *Media and Press Relations* (Press release). CERN. 11 July 2017. Retrieved 23 July 2017.
52. "A new schedule for the LHC and its successor" (<https://home.cern/news/news/accelerators/new-schedule-lhc-and-its-successor>). 13 December 2019.
53. Alan Boyle (2 September 2008). "Courts weigh doomsday claims" (http://cosmiclog.nbcnews.com/_news/2008/09/02/4350490-courts-weight-doomsday-claims). *Cosmic Log*. MSNBC. Retrieved 28 September 2009.

54. J.-P. Blaizot; J. Iliopoulos; J. Madsen; G.G. Ross; P. Sonderegger; H.-J. Specht (2003). "Study of Potentially Dangerous Events During Heavy-Ion Collisions at the LHC" (<https://cds.cern.ch/record/613175/files/CERN-2003-001.pdf>) (PDF). CERN. Retrieved 28 September 2009.
55. Ellis, J.; Giudice, G.; Mangano, M.L.; Tkachev, T.; Wiedemann, U. (2008). "Review of the Safety of LHC Collisions". *Journal of Physics G*. **35** (11): 115004. arXiv:0806.3414 (<https://arxiv.org/abs/0806.3414>). Bibcode:2008JPhG...35k5004E (<https://ui.adsabs.harvard.edu/abs/2008JPhG...35k5004E>). doi:10.1088/0954-3899/35/11/115004 (<https://doi.org/10.1088%2F0954-3899%2F35%2F11%2F115004>). S2CID 53370175 (<https://api.semanticscholar.org/CorpusID:53370175>).
56. "The safety of the LHC" (<http://press.cern/backgrounders/safety-lhc>). *Media and Press Relations* (Press release). CERN. 2008. Retrieved 28 September 2009.
57. Division of Particles & Fields (<http://www.aps.org/units/dpf/>). "Statement by the Executive Committee of the DPF on the Safety of Collisions at the Large Hadron Collider" (https://web.archive.org/web/20091024184048/http://www.aps.org/units/dpf/governance/reports/upload/lhc_saftey_statement.pdf) (PDF). American Physical Society. Archived from the original (http://www.aps.org/units/dpf/governance/reports/upload/lhc_saftey_statement.pdf) (PDF) on 24 October 2009. Retrieved 28 September 2009.
58. Katherine McAlpine (28 July 2008). "Large Hadron Rap" (<https://www.youtube.com/watch?v=j50ZssEojtM>). YouTube. Retrieved 8 May 2011.
59. Roger Highfield (6 September 2008). "Rap about world's largest science experiment becomes YouTube hit" (<https://www.telegraph.co.uk/earth/main.jhtml?xml=/earth/2008/08/26/scirap126.xml>). *Daily Telegraph*. London. Retrieved 28 September 2009.
70. Jennifer Bogo (1 August 2008). "Large Hadron Collider rap teaches particle physics in 4 minutes" (http://www.popularmechanics.com/blogs/science_news/4276090.html). *Popular Mechanics*. Retrieved 28 September 2009.
71. Malcolm W Brown (29 December 1998). "Physicists Discover Another Unifying Force: Doo-Wop" (<http://musicclub.web.cern.ch/MusiClub/bands/cernettes/Press/NYT.pdf>) (PDF). *New York Times*. Retrieved 21 September 2010.
72. Heather McCabe (10 February 1999). "Grrl Geeks Rock Out" (<http://musicclub.web.cern.ch/MusiClub/bands/cernettes/Press/Wired.pdf>) (PDF). *Wired News*. Retrieved 21 September 2010.
73. "Atom Smashers" (<https://web.archive.org/web/20140502010242/http://natgeotv.com.au/tv/world%27s-toughest-fixes/episode.aspx?id=100>). *World's Toughest Fixes*. Season 2. Episode 6. National Geographic Channel. Archived from the original (<http://natgeotv.com.au/tv/world%27s-toughest-fixes/episode.aspx?id=100>) on 2 May 2014. Retrieved 15 June 2014.
74. Boyle, Rebecca (31 October 2012). "Large Hadron Collider Unleashes Rampaging Zombies" (<http://www.popsci.com/science/article/2012-10/physics-students-film-zombie-movie-large-hadron-collider>). Retrieved 22 November 2012.
75. Taylor, Allen (2011). "Angels and Demons" (<http://angelsanddemons.web.cern.ch>). *New Scientist*. CERN. **214** (2871): 31. Bibcode:2012NewSc.214R..31T (<https://ui.adsabs.harvard.edu/abs/2012NewSc.214R..31T>). doi:10.1016/S0262-4079(12)61690-X (<https://doi.org/10.1016%2FS0262-4079%2812%2961690-X>). Retrieved 2 August 2015.
76. Ceri Perkins (2 June 2008). "ATLAS gets the Hollywood treatment" (http://atlas-service-enews.web.cern.ch/atlas-service-enews/2007-8/news_07-8/news_angelpphoto.php). *ATLAS e-News*. Retrieved 2 August 2015.

77. "FlashForward" (<http://flashforward.web.cern.ch/flashforward/>). CERN. September 2009. Retrieved 3 October 2009.

External links

- Official website (<http://home.cern/topics/large-hadron-collider>) 
- Overview of the LHC at CERN's public webpage (<http://public.web.cern.ch/public/en/LHC/LHC-en.html>)
- CERN Courier magazine (<http://www.cerncourier.com/>)
- 10 amazing facts about the LHC (https://meroli.web.cern.ch/blog_LHC_facts.html)
- LHC Portal (<http://www.lhcportal.com/>) Web portal
- Lyndon Evans and Philip Bryant (eds) (2008). "LHC Machine" (<https://doi.org/10.1088%2F1748-0221%2F3%2F08%2FS08001>). *Journal of Instrumentation*. **3** (8): S08001. Bibcode:2008JInst...3S8001E (<https://ui.adsabs.harvard.edu/abs/2008JInst...3S8001E>). doi:10.1088/1748-0221/3/08/S08001 (<https://doi.org/10.1088%2F1748-0221%2F3%2F08%2FS08001>). Full documentation for design and construction of the LHC and its six detectors (2008).

Video

- CERN, how LHC works (<https://www.youtube.com/watch?v=1sldBwvpvGFg>) on YouTube
- "Petabytes at the LHC" (http://www.sixtysymbols.com/videos/petabyte_LHC.htm). *Sixty Symbols*. Brady Haran for the University of Nottingham.
- Animation of LHC in collision production mode (June 2015) (<https://cds.cern.ch/reco rd/2021097>)

News

- Eight Things To Know As The Large Hadron Collider Breaks Energy Records (<https://www.forbes.com/sites/chadorzel/2015/05/21/things-to-know-as-the-large-hadron-collider-breaks-energy-records/>)

Retrieved from "https://en.wikipedia.org/w/index.php?title=Large_Hadron_Collider&oldid=1008405982"

This page was last edited on 23 February 2021, at 04:09 (UTC).

Text is available under the Creative Commons Attribution-ShareAlike License; additional terms may apply. By using this site, you agree to the Terms of Use and Privacy Policy. Wikipedia® is a registered trademark of the Wikimedia Foundation, Inc., a non-profit organization.