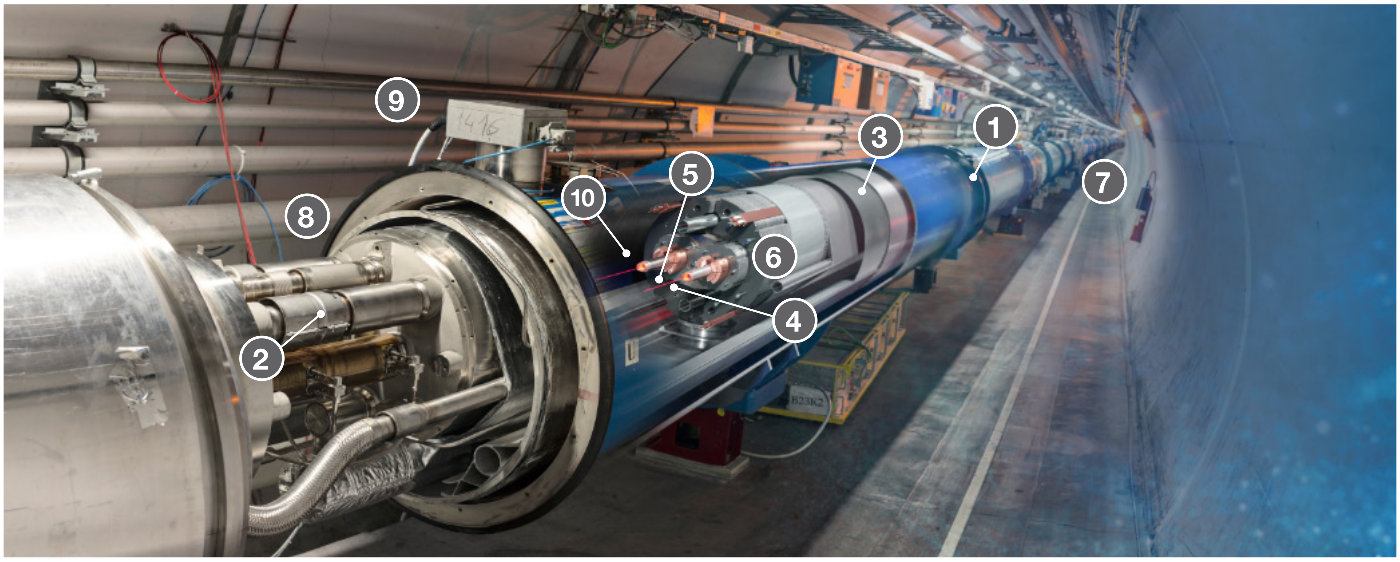
LHC Season 2: A stronger machine

In early 2013, after three years of running, the Large Hadron Collider (LHC) shut down for planned maintenance. Hundreds of engineers and technicians spent two years repairing and strengthening the accelerator in preparation for running at higher energy. Now the world's largest and most powerful particle collider is ready to start up again. So what's new?



1) NEW MAGNETS
Of the LHC's 1232 superconducting dipole magnets, which steer particle beams around the accelerator, 18 have been replaced owing to wear and tear.

2) STRONGER CONNECTIONS
More than 10,000 electrical interconnections between dipole magnets in the LHC have been fitted with shunts – pieces of metal that act as an alternative path for the 11,000 amp current, saving the interconnection if there is a fault.

3) SAFER MAGNETS
The LHC's superconducting magnets have an improved quench protection system. Superconducting magnets conduct electricity without losing energy to resistance, and so can achieve higher magnetic fields. In a quench, a magnet reverts back to a resistive state, releasing a large amount of energy. The quench-protection system in the LHC serves to dissipate this energy in a more controlled manner if it finds any abnormal voltage developing across a magnet.

4) HIGHER ENERGY BEAMS
The energy of collisions in the LHC in 2015 will be 13 TeV (or 6.5 TeV per beam) compared to 8 TeV (4 TeV per beam) in 2012.

Higher energy allows physicists to extend the search for new particles and to check previously untestable theories.

5) NARROWER BEAMS
Because transverse beam size – the width of the beam – decreases with increasing energy, beams in the LHC will be more tightly focused, which means more interactions and collisions for the experiments to study.

6) SMALLER BUT CLOSER PROTON PACKETS
There will be fewer protons per packet – or "bunch": 1.2 x 10^{11} compared to 1.7 x 10^{11} in 2012. When dozens of collisions occur at once, it becomes harder for a detector's computers to disentangle which particle comes from which collision. With fewer protons in each collision, this problem of "pileup" will be less severe. However, the bunches of protons will be separated in time by 25 nanoseconds compared to 50 nanoseconds. The LHC will thus deliver more particles per unit time as well as more collisions to the experiments.

7) HIGHER VOLTAGE
Radiofrequency cavities, which give particles little kicks of energy as they pass, will operate at higher voltages to give the beams higher energies.

8) SUPERIOR CRYOGENICS
The dipole magnets on the LHC must be kept at low temperature to be in their superconducting state. The cryogenics system has been fully consolidated, with complete maintenance of the cold compressors, as well as an upgrade of the control systems and renovation of the cooling plant.

9) RADIATION-RESISTANT ELECTRONICS
A full maintenance and upgrade of the electrical systems on the LHC included more than 400,000 electrical tests, and the addition of newer, more radiation-tolerant systems.

10) MORE SECURE VACUUM
The inside of the beam pipe is kept under vacuum so that the beam does not crash into molecules in its path. But charged beams can rip electrons from the inside surfaces of the pipe, forming an "electron cloud" that interferes with the beam. To dampen this effect the inside of the beam pipe has been coated with non-evaporable getter (NEG), a material that takes up the electrons. In places, solenoids have been wrapped around the beam pipe to keep electrons from deviating from the sides.

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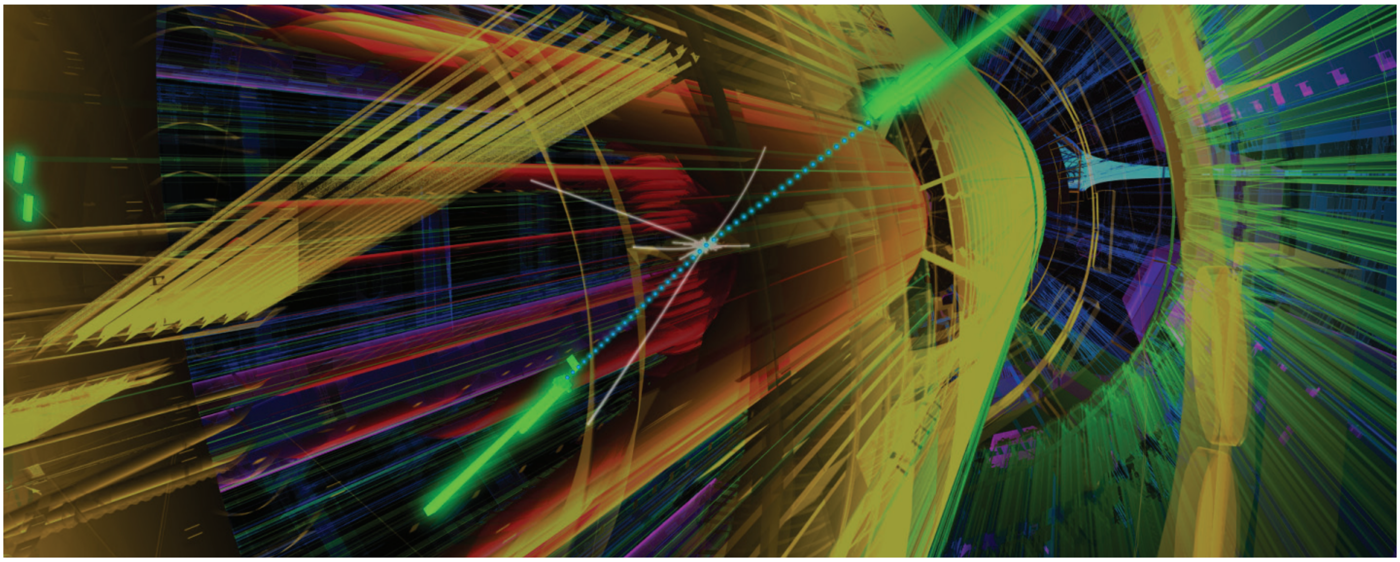
LHC Season 2:
New frontiers in physics

In early 2013, the Large Hadron Collider (LHC) shut down for two years of planned maintenance and repairs. Now the world's most powerful accelerator is ready to start up again, this time at 13 TeV — almost double its previous energy. This new energy frontier will allow researchers to probe new boundaries in our understanding of the fundamental structure of matter.



THE HIGGS BOSON
On 4 July 2012, the ATLAS and CMS experiments at CERN announced the discovery of a Higgs boson, a particle with a mass of 126 GeV. The Higgs is the simplest manifestation of the Brout-Englert-Higgs mechanism that gives particles mass. It is the final particle in the Standard Model – the theory that explains the fundamental particles and the forces between them – to be experimentally verified.

Increasing the energy of the LHC will increase the chance of creating Higgs bosons in collisions, which means more opportunity for researchers to measure the Higgs precisely and to probe its rarer decays. High-energy collisions could detect small, subtle differences between what the boson looks like in experiments, and what the Standard Model predicts.

EXOTIC PARTICLES
Some theories predict that there could be a whole new set of particles out there that physicists cannot detect because they don't interact through the electromagnetic force. But if these "dark sector" particles have mass, they will interact with the field associated with the Higgs boson. So the Higgs boson becomes a contact point between the Standard Model and new, more exotic particles.

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DARK MATTER
Invisible dark matter makes up most of the universe – but we can only detect it from its gravitational effects. But what is dark matter? One idea is that it could contain "supersymmetric particles" – hypothesized particles that are partners to those already known in the Standard Model. The data from higher-energy running at the LHC could provide more direct clues to resolve this mystery.

SUPERSYMMETRY
The Standard Model has worked beautifully to predict what experiments have shown so far about the basic building blocks of matter, but the theory is incomplete. Supersymmetry is an extension of the Standard Model that aims to fill some of the gaps. It predicts a partner particle for each particle in the Standard Model. These new particles would solve a major problem, fixing the mass of the Higgs boson. If the theory is correct, supersymmetric particles should appear in high-energy collisions at the LHC.

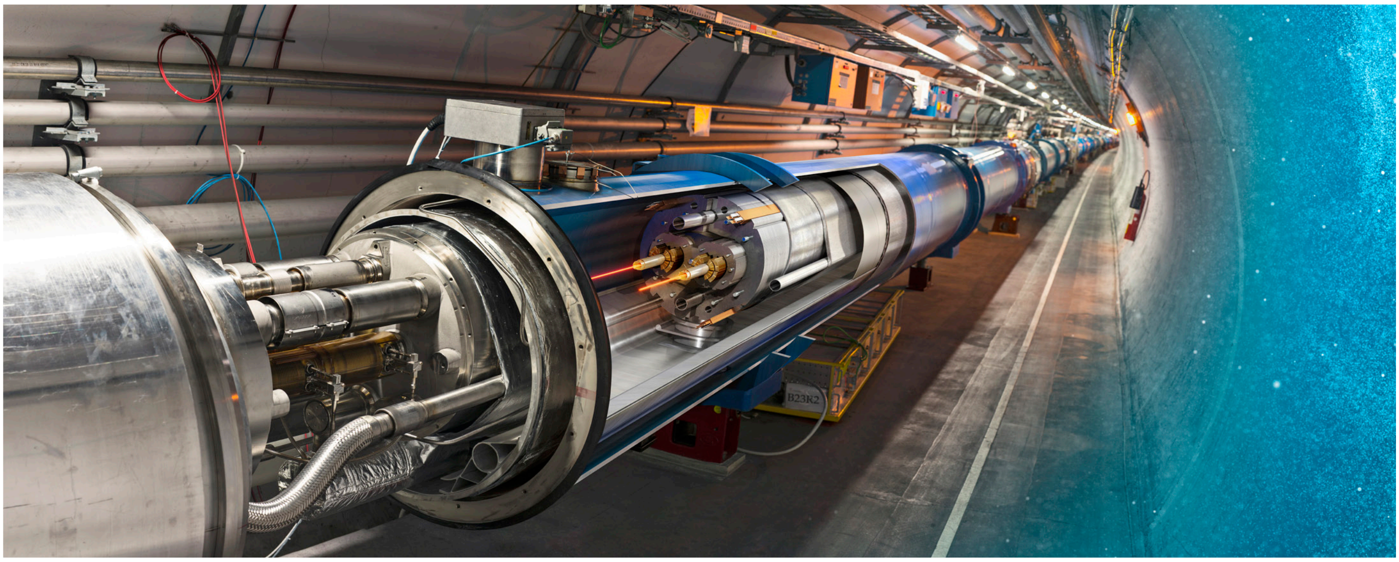
EXTRA DIMENSIONS
Why is gravity so much weaker than the other fundamental forces? Perhaps we don't feel the full effect of gravity because part of it spreads to extra dimensions. But how could we test for extra dimensions? One option is to find evidence of particles that can exist only if extra dimensions are real. Theories that require extra dimensions predict that, just as atoms have a low-energy ground state and excited high-energy states, there would be heavier versions of standard particles in other dimensions. Such heavy particles could be revealed at the high energies the LHC will reach in Run 2.

ANTIMATTER
Every particle of matter has a corresponding antiparticle, exactly matching the particle but with opposite charge. For the electron, for example, there is an "antielectron" called the positron – identical in every way but with a positive electric charge. But when matter and antimatter come into contact, they annihilate, disappearing in a flash of energy. The Big Bang should have created equal amounts of matter and antimatter. So why is there far more matter than antimatter in the universe? Running at higher energy will allow the production of more antiparticles for CERN's antimatter programme – helping physicists to check if the properties of antimatter differ from those of matter.

QUARK–GLUON PLASMA
For a few millionths of a second, shortly after the Big Bang, the universe was filled with an astonishingly hot, dense soup made of all kinds of particles moving at near light speed. This mixture was dominated by quarks – fundamental bits of matter – and by gluons, carriers of the strong force that normally "glue" quarks together into familiar protons, neutrons and other species. In those first evanescent moments of extreme temperature, however, quarks and gluons were bound only weakly, free to move on their own in what's called a quark–gluon plasma. The higher energy collisions at the LHC will allow new and more detailed characterization of this quark-gluon plasma.

LHC Season 2
facts & figures

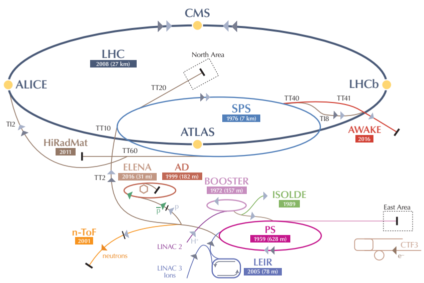
The Large Hadron Collider (LHC) is the most powerful particle accelerator ever built. The accelerator sits in a tunnel 100 metres underground at CERN, the European Organization for Nuclear Research, on the Franco-Swiss border near Geneva, Switzerland.



WHAT IS THE LHC?
The LHC is a particle accelerator that pushes protons or ions to near the speed of light. It consists of a 27-kilometre ring of superconducting magnets with a number of accelerating structures that boost the energy of the particles along the way.

WHY IS IT CALLED THE “LARGE HADRON COLLIDER”?
• "Large" refers to its size, approximately 27km in circumference.
• "Hadron" because it accelerates protons or ions, which belong to the group of particles called hadrons.
• "Collider" because the particles form two beams travelling in opposite directions, which are made to collide at four points around the machine.

HOW DOES THE LHC WORK?
• The CERN accelerator complex is a succession of machines with increasingly higher energies. Each machine accelerates a beam of particles to a given energy before injecting the beam into the next machine in the chain. This next machine brings the beam to an even higher energy and so on. The LHC is the last element of this chain, in which the beams reach their highest energies.



• Inside the LHC, two particle beams travel at close to the speed of light before they are made to collide. The beams travel in opposite directions in separate beam pipes – two tubes kept at ultrahigh vacuum. They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. Below a certain characteristic temperature, some materials enter a superconducting state and offer no resistance to the passage of electrical current. The electromagnets in the LHC are therefore chilled to -271.3°C (1.9K) – a temperature colder than outer space – to take advantage of this effect. The accelerator is connected to a vast distribution system of liquid helium, which cools the magnets, as well as to other supply services.

WHAT ARE THE MAIN GOALS OF THE LHC?
The Standard Model of particle physics – a theory developed in the early 1970s that describes the fundamental particles and their interactions – has precisely predicted a wide variety of phenomena and so far successfully explained almost all experimental results in particle physics. But the Standard Model is incomplete. It leaves many questions open, which the LHC will help to answer.

• **What is the origin of mass?** The Standard Model does not explain the origins of mass, nor why some particles are very heavy while others have no mass at all. However, theorists Robert Brout, François Englert and Peter Higgs made a proposal that was to solve this problem. The Brout-Englert-Higgs mechanism gives a mass to particles when they interact with an invisible field, now called the “Higgs field”, which pervades the universe. Particles that interact intensely with the Higgs field are heavy, while those that have feeble interactions are light. In the late 1980s, physicists started the search for the Higgs boson, the particle associated with the Higgs field. In July 2012, CERN announced the discovery of the Higgs boson, which confirmed the Brout-Englert-Higgs mechanism. However, finding it is not the end of the story, and researchers have to study the Higgs boson in detail to measure its properties and pin down its rarer decays.

• **Will we discover evidence for supersymmetry?** The Standard Model does not offer a unified description of all the fundamental forces, as it remains difficult to construct a theory of gravity similar to those for the other forces. Supersymmetry – a theory that hypothesises the existence of more massive partners of the standard particles we know – could facilitate the unification of fundamental forces.

• **What are dark matter and dark energy?** The matter we know and that makes up all stars and galaxies only accounts for 4% of the content of the universe. The search is then still open for particles or phenomena responsible for dark matter (23%) and dark energy (73%).

• **Why is there far more matter than antimatter in the universe?** Matter and antimatter must have been produced in the same amounts at the time of the Big Bang, but from what we have observed so far, our Universe is made only of matter.

• **How does the quark-gluon plasma give rise to the particles that constitute the matter of our Universe?** For part of each year, the LHC provides collisions between lead ions, recreating conditions similar to those just after the Big Bang. When heavy ions collide at high energies they form for an instant the quark-gluon plasma, a "fireball" of hot and dense matter that can be studied by the experiments.

HOW WAS THE LHC DESIGNED?
Scientists started thinking about the LHC in the early 1980s, when the previous accelerator, the LEP, was not yet running. In December 1994, CERN Council voted to approve the construction of the LHC and in October 1995, the LHC technical design report was published.
Contributions from Japan, the USA, India and other non-Member States accelerated the process and between 1996 and 1998, four experiments (ALICE, ATLAS, CMS and LHCb) received official approval and construction work started on the four sites.

IMPORTANT FIGURES: THE ENERGY OF THE LHC FOR RUN 2

Quantity	Number
Circumference	26659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	6.5 TeV
Nominal energy, ions	2.56 TeV/u (energy per nucleon)
Nominal energy, protons collisions	13 TeV
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11245
Number of collisions per second	1 billion

WHAT ARE THE DETECTORS AT THE LHC?
There are seven experiments installed at the LHC: ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM and MoEDAL. They use detectors to analyse the myriad of particles produced by collisions in the accelerator. These experiments are run by collaborations of scientists from institutes all over the world. Each experiment is distinct, and characterized by its detectors.

HOW MUCH DOES THE LHC COST?
• Construction costs (MCHF)

	Personnel	Materials	Total
LHC machine and areas*	1224	3756	4980
CERN share to detectors	869	493	1362
LHC computing (CERN share)	85	83	168
Total	2178	4332	6510

**Includes: Machine R&D and injectors, tests and pre-operation*

• Costs for Run 1
Exploitation costs of the LHC when running (direct and indirect costs) represent about 80% of the CERN annual budget for operation, maintenance, technical stops, repairs and consolidation work in personnel and materials (for machine, injectors, computing, experiments).
The directly allocated resources for the years 2009-2012 were about 1.1 billion CHF.

• Costs for LS1
The cost of the Long Shutdown 1 (22 months) is estimated at 150 Million CHF.
The maintenance and upgrade works represent about 100 MCHF for the LHC and 50 MCHF for the accelerator complex without the LHC.

WHAT IS THE DATA FLOW FROM THE LHC EXPERIMENTS?
The CERN Data Centre stores more than 30 petabytes of data per year from the LHC experiments, enough to fill about 1.2 million Blu-ray discs, i.e. 250 years of HD video.
Over 100 petabytes of data are permanently archived, on tape.

WHAT IS THE LHC POWER CONSUMPTION?
The total power consumption of the LHC (and experiments) is equivalent to 600 GWh per year, with a maximum of 650 GWh in 2012 when the LHC was running at 4 TeV. For Run 2, the estimated power consumption is 750 GWh per year.
The total CERN energy consumption is 1.3 TWh per year while the total electrical energy production in the world is around 20000 TWh, in the European Union 3400 TWh, in France around 500 TWh, and in Geneva canton 3 TWh.

WHAT ARE THE MAIN ACHIEVEMENTS OF THE LHC SO FAR?

• **10 September 2008:** LHC first beam

• **23 November 2009:** LHC first collisions

• **30 November 2009**: world record with beam energy of 1.18 TeV

• **16 December 2009:** world record with collisions at 2.36 TeV and significant quantities of data recorded

• **March 2010**: first beams at 3.5 TeV (19 March) and first high energy collisions at 7 TeV (30 March)

• **8 November 2010:** LHC first lead-ion beams
• **22 April 2011:** LHC sets new world record beam intensity

• **5 April 2012:** First collisions at 8 TeV

• **4 July 2012:** Announcement of the discovery of a Higgs-like particle at CERN

• **28 September 2012:** Tweet from CERN: "The LHC has reached its target for 2012 by delivering 15 fb-1 (around a million billion collisions) to ATLAS and CMS"

• **14 February 2013:** At 7.24 a.m, the last beams for physics were absorbed into the LHC, marking the end of Run 1 and the beginning of the Long Shutdown 1

• **8 October 2013:** Physics Nobel prize to François Englert and Peter Higgs for "the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

WHAT ARE THE MAIN GOALS FOR THE SECOND RUN OF THE LHC?
The discovery of the Higgs boson was only the first chapter of the LHC story. Indeed, the restart of the machine this year marks the beginning of a new adventure, as it will operate at almost double the energy of its first run. Thanks to the work that has been done during the Long Shutdown 1, the LHC will now be able to produce 13 TeV collisions (6.5 TeV per beam), which will allow physicists to further explore the nature of our Universe.

HOW LONG WILL THE LHC RUN?
The LHC is planned to run over the next 20 years, with several stops scheduled for upgrades and maintenance work.

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