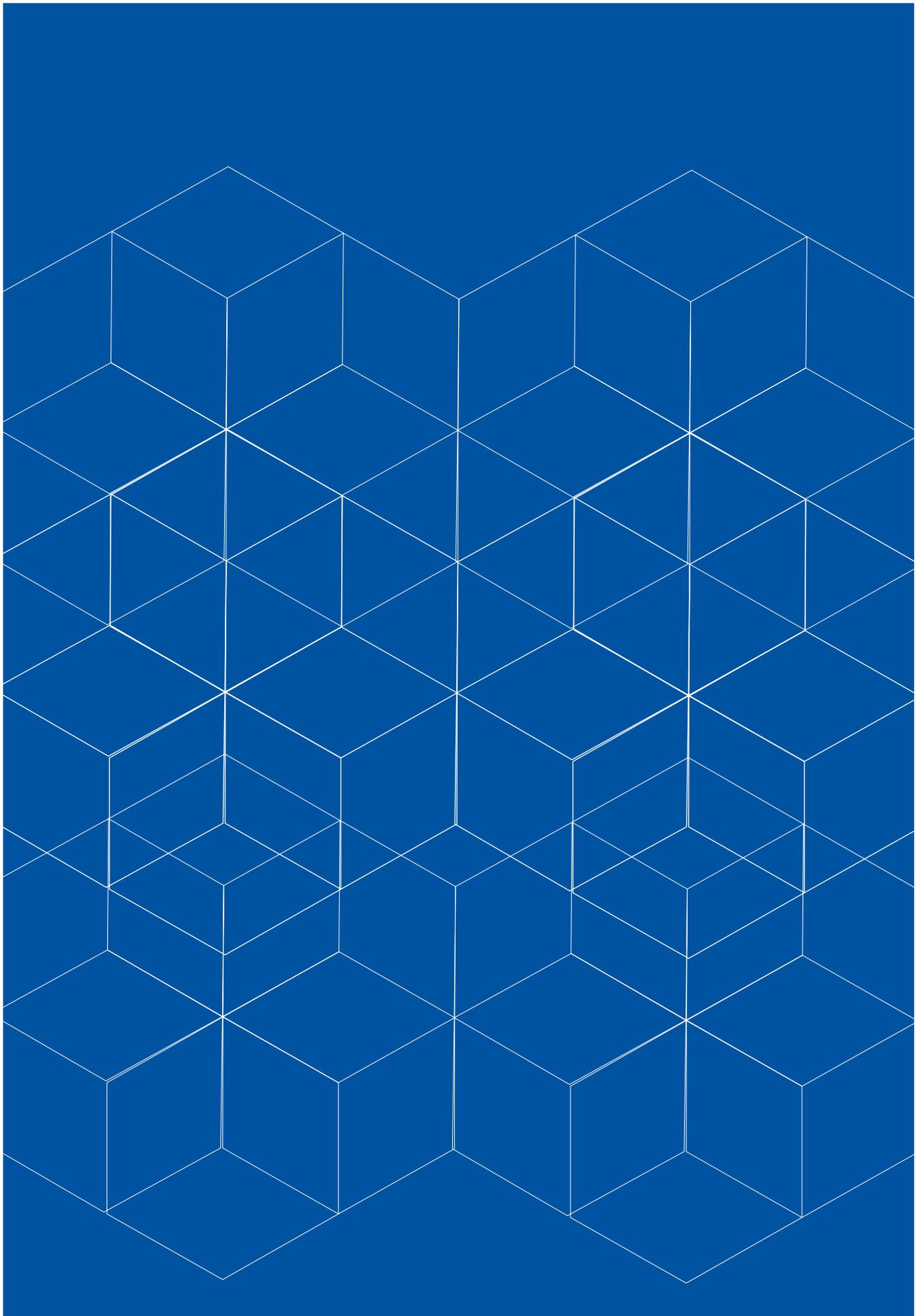


Annual Report **2019**

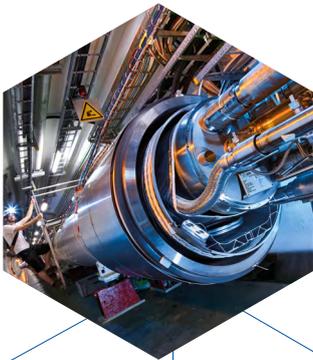




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CERN, the European Organization for Nuclear Research, is the world's leading laboratory for particle physics. It provides a unique range of particle-accelerator facilities enabling research at the forefront of human knowledge. Its business is fundamental physics, finding out what the universe is made of and how it works.

Founded in 1954, CERN has 23 Member States, with other nations from around the globe contributing to and participating in its research programmes. The Laboratory has become a prime example of international collaboration, uniting people from all over the world in the quest to push the frontiers of science and technology for the benefit of all.



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MESSAGE FROM THE PRESIDENT OF THE COUNCIL

Preparing the future of CERN was the overriding theme of 2019, a year devoted to enhancing the LHC's capabilities, updating the European Strategy for Particle Physics and designating the next Director-General.

Throughout 2019, the LHC was in its second long shutdown, which will continue into 2020 and is dedicated to upgrading the LHC experiments, in particular ALICE and LHCb, finalising the LHC Injector Upgrade and preparing the High-Luminosity LHC, which will be CERN's major particle physics programme during the second half of the decade and beyond. The necessary financial flexibility had to be found to realise these important investments in LHC infrastructure while maintaining scientific diversity, pursuing technology developments and ensuring the necessary investments in computing infrastructure and site consolidation over the coming years.

However, the time has come to look beyond the LHC and pave the way for particle physics after 2040. Input for the update of the European Strategy for Particle Physics had been gathered from the whole community by the end of 2018 and was debated during an Open Symposium held in Granada in May. During this crucial meeting, a large variety of projects and visions for the future were discussed, addressing the major scientific questions of the field. The post-LHC infrastructures may operate until the end of the century, but to investigate their feasibility and lay the groundwork for their possible realisation is the task of today. The Physics Briefing Book, published in September and summarising the outcome of this work, gives us today's tantalising vision of the future of the field and is the basis for the strategy scheduled to be adopted by the CERN Council in May 2020.

Overseeing the implementation of the strategy is the role of CERN's Director-General and will be a major point of the upcoming mandate. Possible candidates for the post of the next Director-General were scrutinised by a dedicated and diligent search committee. The CERN Council had the challenge of making its selection from among several outstanding candidates, and ultimately entrusted this crucial work to Dr Fabiola Gianotti, who will serve a second term.

It was a particular pleasure in 2019 to welcome Serbia to the family of CERN's Member States, and Croatia as a new Associate Member, testifying to the continuing interest in joining this unique organisation. The definition of CERN's future scientific goals has to be accompanied by an assessment of the Organization's international relations and institutional structure. With this in mind, the review of certain aspects of the geographical enlargement of CERN reached a conclusion this year, and will be followed by a review of aspects of governance.

My first year as Council President has been very intense and rich. I would like to express my deep gratitude to the former Council President, Sijbrand De Jong, for his precious advice, as well as to the CERN staff and the Directorate for their invaluable support and cooperation.

Ursula Bassler

A handwritten signature in black ink, appearing to read 'U. Bassler'.



MESSAGE FROM THE DIRECTOR-GENERAL

One of the main focuses of 2019 was the start of the second long shutdown (LS2) of CERN's accelerator complex. This saw a range of demanding maintenance and upgrade activities performed on the injectors, the LHC and the experiments. LS2 performed according to the principle of prioritising safety first, then quality and then the schedule, and all of these criteria were met. By the end of 2019, the LHC Injectors Upgrade (LIU) project was more than 80% complete, and the vastly improved injectors will gradually start to be commissioned in 2020.

Preparations for the High-Luminosity LHC (HL-LHC) were also a major feature of 2019, encompassing everything from civil engineering to magnets. Major accomplishments were the successful construction and qualification for installation of the first 11-tesla dipole magnet at CERN and the successful test in the United States of the first full-size quadrupole magnet, both using niobium-tin (Nb_3Sn) superconductors. By the end of 2019, the civil-engineering work at Points 1 and 5 to excavate the underground tunnels and service caverns needed to host the HL-LHC components was 80–90% complete.

A long shutdown does not mean no physics activity: 2019 saw the release of many beautiful results covering CERN's full scientific programme, from the LHC to the fixed-target experiments. At the LHC, a highlight from ATLAS was the observation and measurement of Z-boson pair production in vector-boson fusion, while CMS substantially extended its limits on new physics up to particle masses of about 8 TeV through the search for high-mass di-jet resonances. The LHCb experiment scored a first with the observation of CP violation in the decay of charmed hadrons, while ALICE measured the lifetime of an exotic particle, called the hypertriton, whose study may give insight into the interactions occurring in the core of neutron stars. Highlights from the fixed-target programme include progress in the study of the extremely rare $K^+ \rightarrow \pi^+ \bar{\nu}$ decay from NA62, and new results on searches for dark photons from the NA64 beam-dump experiment. Both are promising avenues to search for new physics in ways that are complementary to high-energy colliders. These are just a few examples from a

scientifically very productive year, which was possible only thanks to the excellent performance of the WLCG computing infrastructure, which broke new records.

Among other highlights from 2019, preparations for the update of the European Strategy for Particle Physics proceeded apace, with significant contributions from CERN's community. The CERN Environmental Protection Steering board oversaw excellent progress in the implementation of its recommendations for high-priority measures to minimise CERN's impact on the environment. By the end of 2019, about 84% of the external funding required for the Science Gateway project aimed at building a scientific education and outreach facility for the general public had been secured through donations. On 14–15 September 2019, CERN welcomed some 75 000 visitors in the framework of its very successful Open Days.

Details of these and other achievements can be found in the pages of this report. They were possible thanks to the competence, hard work and commitment of CERN's personnel, and to the strong and sustained support of our Member and Associate Member States. My deep thanks, along with those of the entire CERN Directorate, go to them all.

Fabiola Gianotti

A handwritten signature of Fabiola Gianotti in black ink.

2019 IN PICTURES

With infrastructure improvements in progress across the Laboratory as part of CERN's second long shutdown, CERN opens its doors to the public, marks 30 years of the World Wide Web and welcomes new Member and Associate Member States. These are just some of the highlights of 2019. Discover more in pictures.



25 JANUARY

Excavation of two new shafts marks the first civil-engineering milestone for the High-Luminosity LHC.



28 FEBRUARY

An agreement is signed in order to admit Croatia as an Associate Member of CERN. On 10 October, Croatia officially becomes an Associate Member of CERN. Ambassador Vesna Batistić Kos, Permanent Representative of Croatia to the United Nations Office and other international organisations in Geneva, hands over the official notification to CERN's Director-General.

(CERN-PHOTO-201910-336-3)



12 MARCH

Sir Tim Berners-Lee celebrates 30 years of his invention, the World Wide Web (see p. 30).

(CERN-PHOTO-201903-059-1)

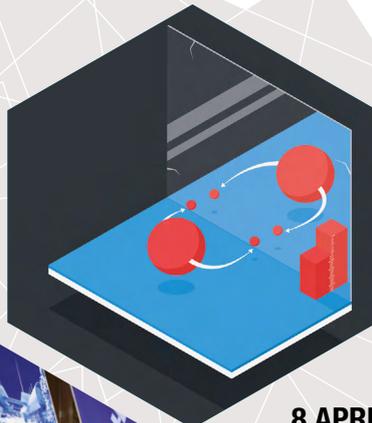
13 MARCH

Roger Waters, former member of the band Pink Floyd, visits CERN.
(CERN-PHOTO-201903-062-2)



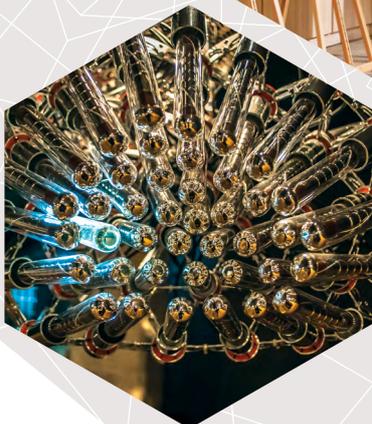
21 MARCH

The LHCb collaboration observes a new flavour of matter–antimatter asymmetry (see p. 17).
(CERN-HOMEWEB-PHO-2019-019-1)



8 APRIL

CERN unveils the Science Gateway project, a new education and outreach centre designed by world-renowned architect Renzo Piano.
(CERN-PHOTO-201904-084-13)



9 APRIL

The Quàntica exhibition in Barcelona brings together ten artworks from art residencies at CERN.
(OPEN-PHO-MISC-2019-002-28)

9 APRIL

German film-maker and artist Werner Herzog visits CERN.
(CERN-PHOTO-201904-086-1)

23 APRIL

Ana Brnabić, Prime Minister of the Republic of Serbia, joins the flag-raising ceremony to officially mark Serbia joining CERN as its 23rd Member State on 24 March.

(CERN-PHOTO-201904-101-83)



13 MAY

The European particle physics community meets in Granada, Spain, to discuss the future of the field (see p. 46).



21 MAY

The CERN-led and EU-funded initiative ATTRACT awards funding to 170 breakthrough projects in detection and imaging.



10 JUNE

Sergio Mattarella, President of the Italian Republic (on the left), and Dmitry Medvedev, Prime Minister of the Russian Federation (on the right), visit CERN.

(CERN-PHOTO-201906-152-27)

(CERN-PHOTO-201906-153-1)

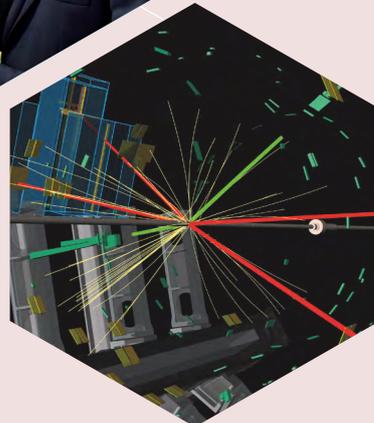
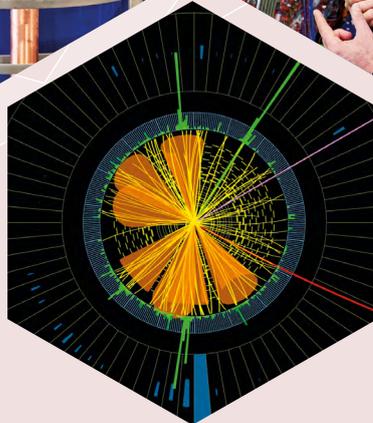
11 JUNE

Marjan Šarec, Prime Minister of the Republic of Slovenia, visits CERN.
(CERN-PHOTO-201906-154-22)



25 JUNE

Rumen Radev, President of the Republic of Bulgaria, visits CERN.
(CERN-PHOTO-201906-175-10)



15 JULY

ATLAS and CMS present new precision measurements of Higgs properties (see p. 16).
(CMS-PHO-EVENTS-2019-002-6)
(ATLAS-PHOTO-2019-026-1)

16 JULY

ALICE measures the elliptic flow of bottomonium particles, shedding new light on the early universe.

(ALICE-PHO-GEN-2012-001-12)



21 AUGUST

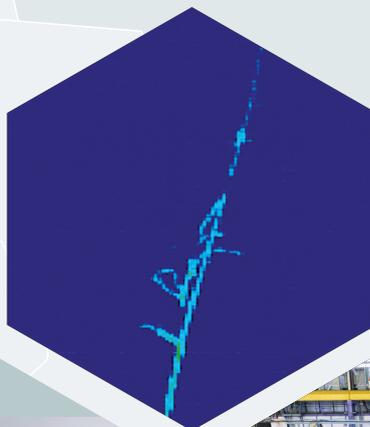
World-famous cellist Yo-Yo Ma performs in the LHC tunnel.

(CERN-PHOTO-201909-233-2)



13 SEPTEMBER

First particle tracks emerge from the dual-phase ProtoDUNE detector, a prototype for an international neutrino experiment.



14–15 SEPTEMBER

CERN opens its doors to the public for two days, welcoming more than 75 000 visitors curious to explore the future (see p. 37).

(CERN-PHOTO-201909-239-3)

18 SEPTEMBER

Medipix celebrates 20 years of turning detector technology into applications for medical imaging, art restoration and more.

(CERN-PHOTO-201702-048-3)

23 SEPTEMBER

A new run of the CLOUD experiment examines the direct effect of cosmic rays on clouds.

(CERN-PHOTO-201909-278-4)

6 NOVEMBER

At its 195th Session, the CERN Council appoints Fabiola Gianotti (here, on the right, with Ursula Bassler, President of the CERN Council) for a second term of office as CERN's Director-General.

(CERN-PHOTO-201911-367-2)



15 NOVEMBER

European Space Agency (ESA) astronaut Luca Parmitano and NASA astronaut Andrew Morgan begin a series of spacewalks to service the Alpha Magnetic Spectrometer.



13 DECEMBER

CERN successfully connects the underground structures of the High-Luminosity LHC to the LHC tunnel.

(CERN-PHOTO-201912-418-11)

A LABORATORY FOR THE WORLD

International cooperation is at the heart of all of CERN's activities: in 2019, over 17 600 people from institutes, universities and companies all over the world took part in the Laboratory's work. At all levels, from nations down to universities and individual scientists, the goal is the same: to push forward the boundaries of knowledge. At CERN, around 2600 staff members develop, build and operate the Laboratory's research infrastructure. They also contribute to the design and operation of the experiments, as well as to the analysis of the data they produce. In 2019, the infrastructure and the data gathered at CERN were made available to a community of over 12 400 scientific users of 110 nationalities from institutions in more than 70 countries.



BREAKDOWN OF CERN USERS ACCORDING TO THE COUNTRY OF THEIR HOME INSTITUTE, AS OF 31 DECEMBER 2019

NUMBER OF USERS: 12 427

MEMBER STATES (7262)

Austria 93 – Belgium 147 – Bulgaria 41 – Czech Republic 248 – Denmark 46 – Finland 87 – France 821 – Germany 1282 – Greece 154 – Hungary 75 – Israel 70 – Italy 1531 – Netherlands 179 – Norway 90 – Poland 300 – Portugal 92 – Romania 116 – Serbia 38 – Slovakia 75 – Spain 356 – Sweden 100 – Switzerland 370 – United Kingdom 951

ASSOCIATE MEMBER STATES IN THE PRE-STAGE TO MEMBERSHIP (34)

Cyprus 13 – Slovenia 21

ASSOCIATE MEMBER STATES (450)

Croatia 41 – India 186 – Lithuania 19 – Pakistan 39 – Turkey 129 – Ukraine 36

OBSERVERS (3283)

Japan 244 – Russia 1071 – United States of America 1968

OTHER COUNTRIES (1398)

Algeria 3 – Argentina 16 – Armenia 13 – Australia 24 – Azerbaijan 3 – Bahrain 3 – Belarus 27 – Brazil 112 – Canada 210 – Chile 22 – Colombia 23 – Cuba 3 – Ecuador 4 – Egypt 16 – Estonia 24 – Georgia 36 – Hong Kong 21 – Iceland 3 – Indonesia 8 – Iran 12 – Ireland 7 – Kuwait 2 – Latvia 2 – Lebanon 15 – Malaysia 9 – Malta 4 – Mexico 55 – Montenegro 5 – Morocco 16 – New Zealand 11 – Oman 1 – People's Republic of China 367 – Peru 3 – Puerto Rico 1 – Republic of Korea 144 – Singapore 3 – South Africa 87 – Sri Lanka 8 – Taiwan 55 – Thailand 18 – United Arab Emirates 2



(CERN-PHOTO-202001-011-4)

GLOBAL SCIENTIFIC ENGAGEMENT

At the end of 2019, CERN had 23 Member States, two Associate Member States in the pre-stage to Membership and six Associate Member States. Serbia became a Member State in March and Croatia became an Associate Member State in October.

The Laboratory also maintains strong links with many other countries and territories that participate in its activities and thus actively supports the development of particle physics in Europe and around the world. In 2019, CERN signed cooperation agreements with Paraguay and Russia and several implementing agreements (protocols and addenda). CERN's big multicultural family is one of its main assets. Its diversity gives rise to new ideas that are essential for advancing knowledge.

A HIGH-ENERGY NETWORK

Less than three years after it was set up, the CERN Alumni programme already has 5800 members from over 100 countries. It allows alumni pursuing careers in a wide variety of fields, ranging from academia to industry, economics, information technology and medicine, to maintain links with CERN, to benefit from the wealth and diversity of their large community, and to leverage the experience and support of the network's members.

By the end of 2019, the network had nine regional groups, in Austria, Greece, Italy, the Netherlands, Switzerland, the United Kingdom and the United States. At CERN, the success of the "Moving Out of Academia to..." series of workshops was confirmed with two new seminars: "Moving Out of Academia to... Industrial Engineering" and "Moving Out of Academia to... Entrepreneurship". These workshops are designed to support future alumni in their transition from the academic world to other professional sectors. Over 60 events were announced via the High-Energy Network, confirming the CERN Alumni platform as the ideal place to share experiences and forge new professional relationships.



(ALUMNI-PHO--2018-003-42)

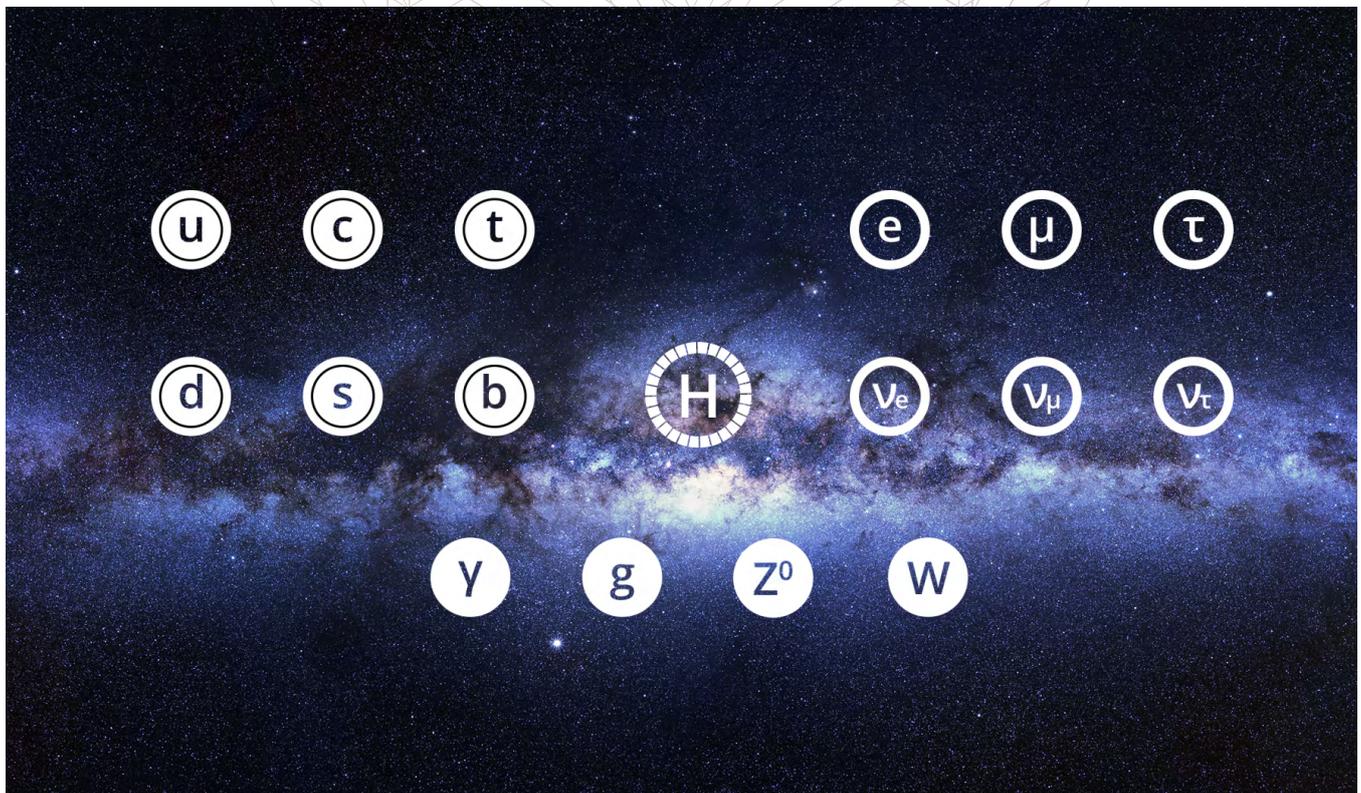
EXPLORING THE NATURE OF THE UNIVERSE

To understand what the universe is made of and how it works, CERN operates a unique network of accelerators that collide particle beams head on or direct them onto fixed targets. The products of these collisions are recorded by state-of-the-art detectors and studied by collaborations of scientists at CERN and beyond.

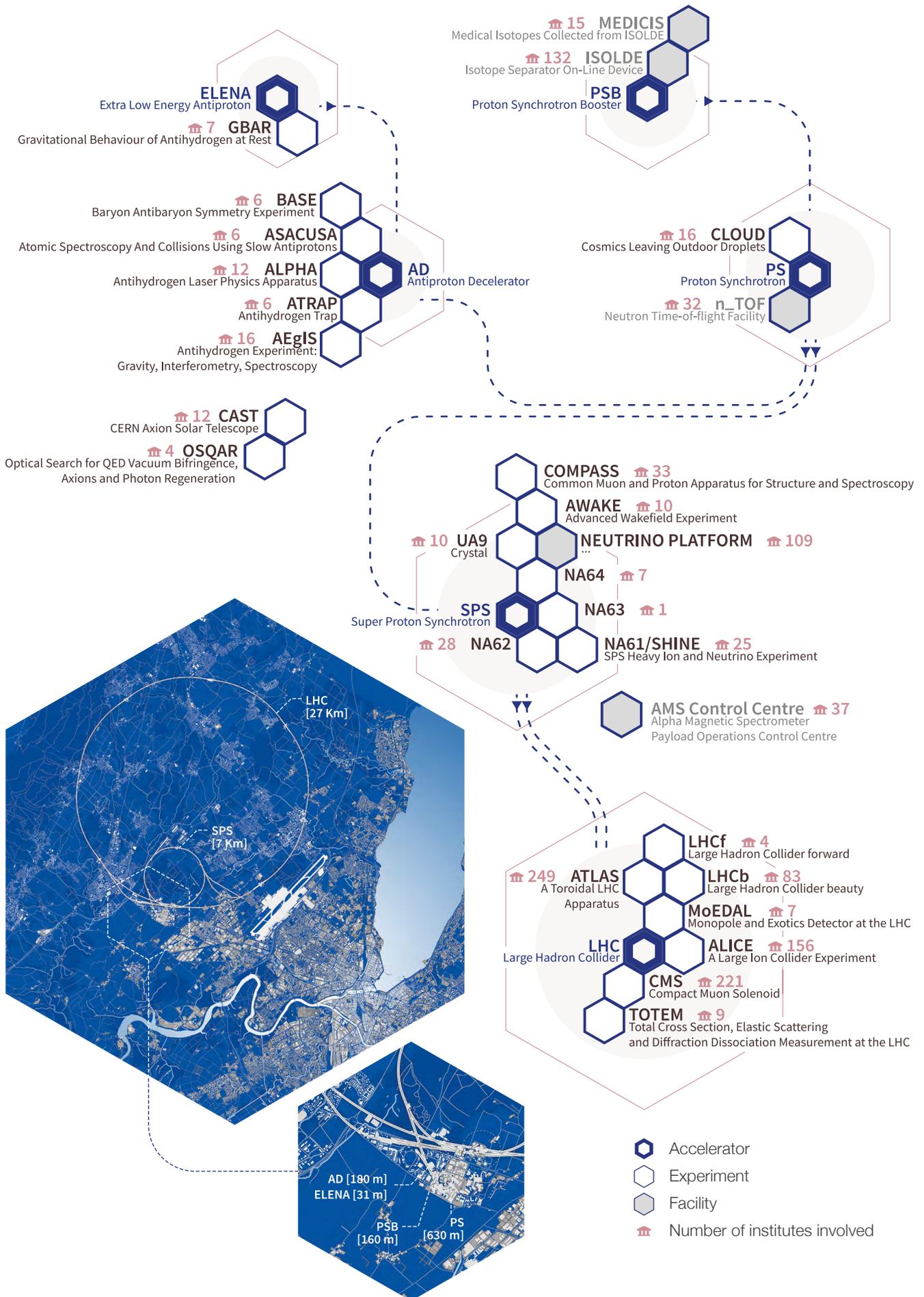
GERN'S ACCELERATOR COMPLEX AND THE EXPERIMENTS THAT IT FEEDS

The Large Hadron Collider (LHC) is the Laboratory's flagship machine and the world's most powerful particle accelerator. It collides beams of protons and heavy ions, and the results of the collisions are recorded inside seven experiments: ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL and TOTEM. The collider and the whole of CERN's accelerator complex entered a two-year upgrade programme known as Long Shutdown 2 at the end of 2018. Nonetheless, the year saw the

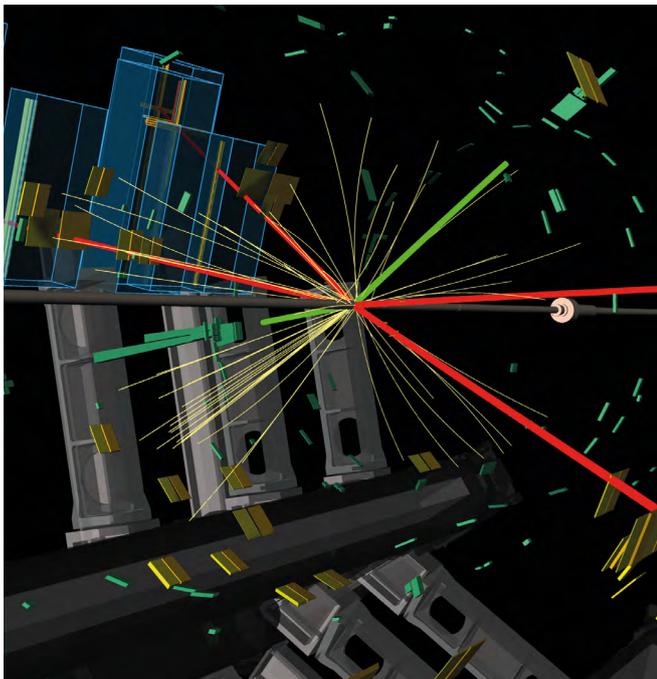
release of many physics results based on the analysis of data taken before the shutdown by the LHC experiments as well as experiments at other machines at the Laboratory. The results extended scientists' knowledge of the building blocks of matter and informed discussions and work for the forthcoming update of the European Strategy for Particle Physics (see p. 46). They include new or more precise measurements of the Higgs boson, in particular the production of the boson in so-called electroweak processes, detailed scrutiny of the Standard Model of particle physics, and more sensitive searches for unknown particles.



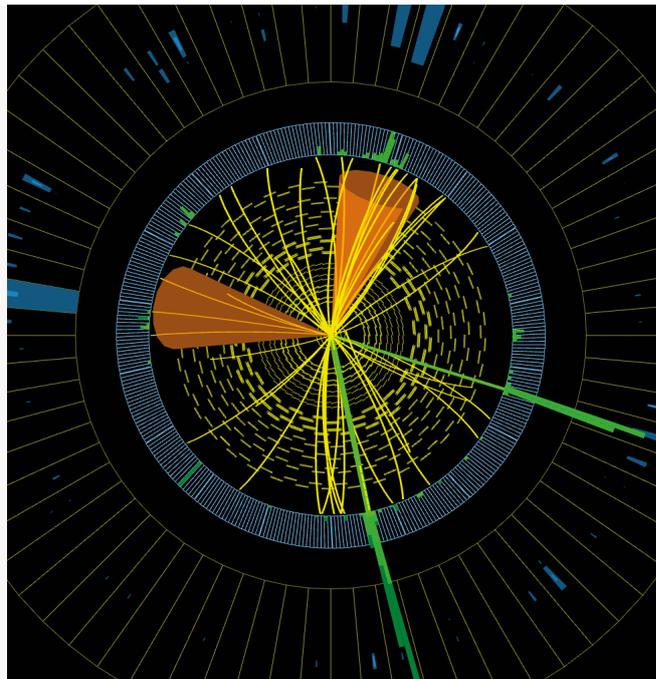
Particles of the Standard Model of particle physics, which currently provides the best description of the subatomic world but does not explain the complete picture.



CERN's accelerators serve many experiments and facilities that are used by researchers across the globe.



ATLAS candidate for a Higgs boson produced with a Z boson. Both ultimately decay to leptons, leaving two electrons (green) and four muons (red). (ATLAS-PHOTO-2019-026-1)



CMS candidate for a Higgs boson produced with a Z boson. The Higgs boson decays to two charm quarks, forming jets (cones); the Z boson decays to electrons (green). (CMS-PHO-EVENTS-2019-006-10)

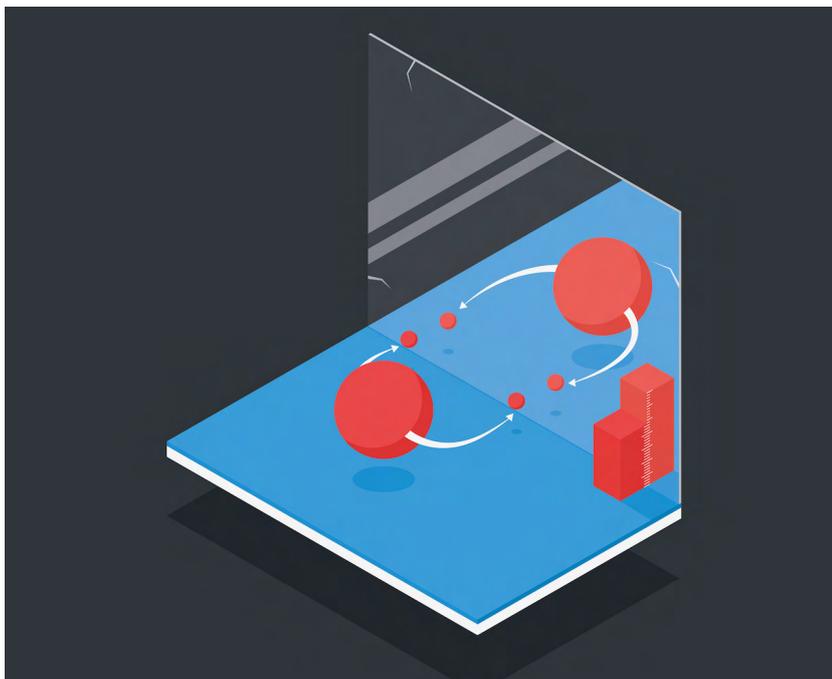
HOMING IN ON THE HIGGS BOSON

The Standard Model predicts how the Higgs boson interacts with other particles. Testing these predictions is a major research endeavour at the LHC and a goal of proposed future colliders, as any deviation from the predictions could signal new physics phenomena. This investigation can be done by looking at how the Higgs boson transforms, or decays, into lighter particles. In the LHC's Run 1 (2009–2013), decays of the Higgs boson involving pairs of so-called electroweak bosons were observed. The complete dataset from Run 2 (2015–2018) provides a much larger sample of Higgs bosons to study, allowing measurements of the particle's properties to be made with unprecedented precision. In 2019, the ATLAS and CMS collaborations presented measurements of the differential cross-sections of the bosonic decay processes, which look at not just the production rate of Higgs bosons but also the distribution and orientation of the decay products relative to the colliding proton beams. These differential measurements provide insights into the underlying mechanism that produces the Higgs bosons. Both collaborations determined that the observed rates and distributions are compatible with those predicted by the Standard Model, at the current rate of statistical uncertainty.

The strength of the Higgs boson's interaction with an elementary particle is proportional to its mass, so the Higgs interacts most strongly with the third and heaviest generation of fermions, which comprises the top quark, bottom quark and tau lepton. Interactions with the lighter second-generation fermions – muons, charm quarks and strange

quarks – are considerably rarer. In 2019, both collaborations reported on their searches for the elusive second-generation interactions. ATLAS obtained its first result from searches for Higgs bosons decaying to pairs of muons using the full Run 2 dataset, showing that the collaboration is close to the sensitivity required to test the Standard Model's predictions for this very rare decay. CMS obtained its first result from searches for decays of Higgs bosons to pairs of charm quarks, demonstrating that the collaboration can tackle the difficult task of identifying the jets of particles produced by the quarks with the help of novel machine-learning techniques. Both results confirm the experiments' ability to measure second-generation decays once a sufficiently large data sample becomes available.

The Higgs boson also acts as a mediator of physics processes in which electroweak bosons scatter or bounce off each other. Studies of these processes with very high statistics serve as powerful tests of the Standard Model. ATLAS presented the first ever measurement of the scattering of two Z bosons. Observing this scattering completed the picture for the W and Z bosons, as ATLAS had previously observed the WZ scattering process and both collaborations the WW process. CMS presented the first observation of electroweak-boson scattering that results in the production of a Z boson and a photon. Other highlights of the year include CMS's most precise measurement to date of the Higgs boson mass and ATLAS's new constraints on the interaction of the Higgs with itself.



A CP-symmetry transformation swaps a particle with the mirror image of its antiparticle. LHCb has observed a breakdown of this symmetry in the decays of the D^0 meson (illustrated by the large right-hand sphere) and its antimatter counterpart, the anti- D^0 (large left-hand sphere), into other particles (smaller spheres). The extent of the breakdown was deduced from the difference in the number of decays in each case (vertical bars, for illustration only).

(CERN-HOMEWEB-PHO-2019-019-1)

TESTING THE STANDARD MODEL AND BEYOND

The LHC experiments continue to test the Standard Model to increased levels of precision and sensitivity. In 2019, LHCb achieved a breakthrough with the observation of the matter–antimatter asymmetry known as CP violation in the decay of the charmed hadron D^0 and its antimatter counterpart. Until this result, CP violation had only been observed in particles containing a strange or a bottom quark. These previous observations had confirmed the pattern of CP violation described in the Standard Model by the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix, which characterises how quarks of different types transform into each other via weak interactions. The deep origin of the CKM matrix, and the quest for additional sources and manifestations of CP violation, are among the big open questions of particle physics. The new LHCb result is the first evidence of this asymmetry for the charm quark, which had long been looked for. The result is a beautiful testimony to the sensitivity of the LHC to rare phenomena.

In addition, in 2019 LHCb discovered new five-quark hadrons, or “pentaquarks”, which have long been predicted to exist but have been discovered only relatively recently. In a 2015 study, LHCb analysed data from the decay of the beauty baryon Λ_b^0 into a J/ψ particle, a proton and a charged kaon and were able to see two new pentaquarks in intermediate decay states. After analysing a sample of nine times more Λ_b^0 decays than in the 2015 study, LHCb observed a new pentaquark and showed that one of the previously observed pentaquarks is in fact two particles. LHCb also made a further test of lepton universality, a key principle of the Standard Model, using decays of the Λ_b^0 . The collaboration further presented a much anticipated update on its lepton-universality test using decays of a B^+ meson. Both results still need to reach statistical significance, but they are important additions to lepton-universality studies, not least since hints of a difference have been popping up in different particle decays and experiments.

Highlights from ATLAS, other than the Higgs results, included strong evidence of charge asymmetry in the production of top and antitop quarks. This asymmetry results from the unequal production of top and antitop quarks with respect to the proton-beam direction, which is caused by the uneven distribution of quarks and antiquarks in the proton. Other achievements included searches for new phenomena in the area of supersymmetry, where the large dataset enables significant limits to be obtained on supersymmetric particles that only interact through the electroweak force. ATLAS also tested the Standard Model through a search for Higgs-boson pairs produced via the rare process where two so-called vector bosons fuse, and found no hints of deviations from the Standard Model. In addition, the experiment searched for unconventional signatures of new physics, such as heavy neutral leptons that decay either very close to or at some distance from the primary production vertex.

Early in 2019, CMS obtained its first result based on the full LHC dataset collected in 2018 and data collected in 2016 and 2017, observing two B mesons. After this, the collaboration conducted studies on a wide range of topics based on this or partial Run 2 data. Examples of results on rare processes predicted by the Standard Model were the first observation of a top quark produced in association with a Z boson, and evidence of the production of a W boson pair via the double-parton process, in which more than one parton (quark or gluon) from each colliding hadron participates. On the beyond-the-Standard-Model front, CMS highlights included searches for new particles decaying to muons, using both standard data-taking and data-taking with compact collision-event content. CMS also achieved major progress in the measurement and identification of leptons and jets, and in the identification and mass resolution of heavy objects decaying to jets, based on the application of advanced machine-learning techniques.

The year 2019 also saw results from the smaller LHC experiments, TOTEM, LHCf and MoEDAL. Achievements included TOTEM's publication of measurements of proton–proton cross-sections from energies between 2.7 and 13 TeV; LHCf's preliminary results from the analysis of the neutral pion production cross-section and the so-called neutron energy flow in 13 TeV proton–proton collisions; and MoEDAL's limits on the photon–photon production of pairs of monopoles – hypothetical particles with magnetic charge.

LHCB SCORED A FIRST WITH THE OBSERVATION OF CP VIOLATION IN THE DECAY OF PARTICLES CONTAINING CHARM QUARKS.

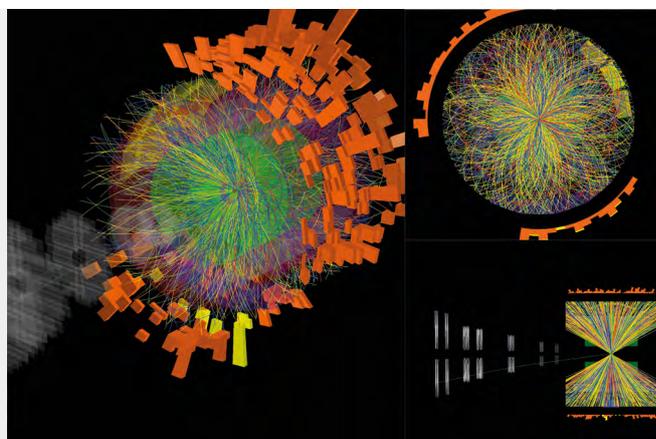
HEAVY-ION INSPECTIONS

As well as protons, the LHC collides heavy ions such as lead nuclei. These heavy-ion collisions effectively recreate the quark-gluon plasma (QGP), a dense state of free quarks and gluons that is thought to have occurred shortly after the Big Bang. However, the presence and properties of the recreated QGP can only be deduced from the signatures it leaves on the particles produced in the collisions. The ALICE experiment, which specialises in these collisions, reported the first measurement of one such signature – the elliptic flow – for upsilon (Υ) particles produced in lead–lead collisions. The Υ particles, as well as other particles consisting of a bottom quark and its antiquark, are excellent probes of the QGP as they are created in the initial stages of a heavy-ion collision and experience the entire evolution of the QGP. The elliptic flow results from the initial elliptic shape of non-central collisions. ALICE found that the magnitude of the Υ elliptic flow is small for a range of momenta and collision centralities, making Υ the first hadrons that do not seem to exhibit a significant elliptic flow in heavy-ion collisions at the LHC; other hadrons observed in heavy-ion collisions at the LHC and other colliders display significant flow.

ALICE also obtained the first measurement of the triangle-shaped flow of J/ψ particles, which contain charm quarks, in lead–lead collisions. This measurement shows that even heavy quarks are affected by the quarks and gluons in the QGP and retain some memory of the collisions' initial geometry. In addition, the collaboration presented measurements of another type of flow (called “directed flow”) for charged hadrons and D^0 mesons that provide insights into the effects on the dynamics of light and heavy quarks of the strong electromagnetic field and the initial tilt of matter created in non-central heavy-ion collisions.

Another noteworthy ALICE result was the measurement of the lifetime of a “hypernucleus” called the hypertriton. Hypernuclei, which are bound states of nucleons and

Another LHC experiment, FASER, was approved in 2019 and is in preparation, bringing the number of LHC experiments to eight. FASER will be located about 480 metres downstream of ATLAS and will search for light and weakly interacting particles such as dark photons. In addition, FASERv, a small subdetector of FASER that was also approved in 2019, could, according to estimations by the FASER team, detect more than 20 000 neutrinos of all flavours produced in LHC collisions. No neutrino produced at a particle collider has ever been detected, even though colliders create them in huge numbers.



Particle trajectories and energy deposition in the ALICE detector during the last lead–lead collisions of Run 2. (ALICE-EVENTDISPLAY-2018-004-1)

hyperons, are abundantly produced in heavy-ion collisions and can provide insight into the particle interactions that occur in the cores of neutron stars. The lifetime of the hypertriton had been measured previously, but lifetimes measured in the last decade were systematically below theoretical predictions, hence the so-called “lifetime puzzle”. Based on a large dataset, ALICE’s measured lifetime, $242^{+34}_{-38}(\text{stat}) \pm 17(\text{syst})$ ps, is the first statistically significant result that is close to predictions, representing an important step forward in solving the puzzle. The collaboration also presented the first observation, based on proton–lead collision data, of the attractive strong interaction between a proton and the hyperon Ξ^- , which contains two strange quarks.

The other main LHC experiments also made progress in heavy-ion physics. To mention just a couple of results, CMS obtained evidence of top-quark pair production in lead–lead collisions, and ATLAS observed in lead-ion collisions the very rare light-by-light scattering process in which two photons interact, confirming a key prediction of the quantum theory of electromagnetism.



Using a reservoir of antiprotons trapped in October 2018, the BASE experiment continued running until June 2019.
(CERN-PHOTO-201710-255-6)

THEORY ADVANCES

In 2019, CERN's Theoretical Physics (TH) department produced cutting-edge research supporting the Laboratory's activities and serving the international theoretical physics community. The research covered many areas, from quantum field theory to collider physics, cosmology and astroparticle physics, to name just a few.

This research led to the submission of 315 papers to the arXiv preprint server. Highlights included precise calculations of processes in the Standard Model; an improved version of Herwig, a multipurpose particle-physics event generator; contributions to the community report on the physics of the High-Luminosity LHC and the High-Energy LHC and to the Briefing Book for the European Strategy for Particle Physics; the development of a new method based on machine learning to identify signals of physics beyond the Standard Model; proposals to search for ultralight dark matter in the surroundings of supermassive black holes and for massive compact objects in the spectra of fast radio bursts; and a comprehensive analysis to extract cosmological information from a survey of galaxies.

The TH department also made fundamental contributions to the LHC Physics Centre at CERN (LPCC) and to all working groups on the physics of the LHC and on the proposed colliders CLIC and FCC. It also played a leading role in new physics research initiatives in the context of the Neutrino Platform (see p. 21) and Physics Beyond Colliders (see p. 48).

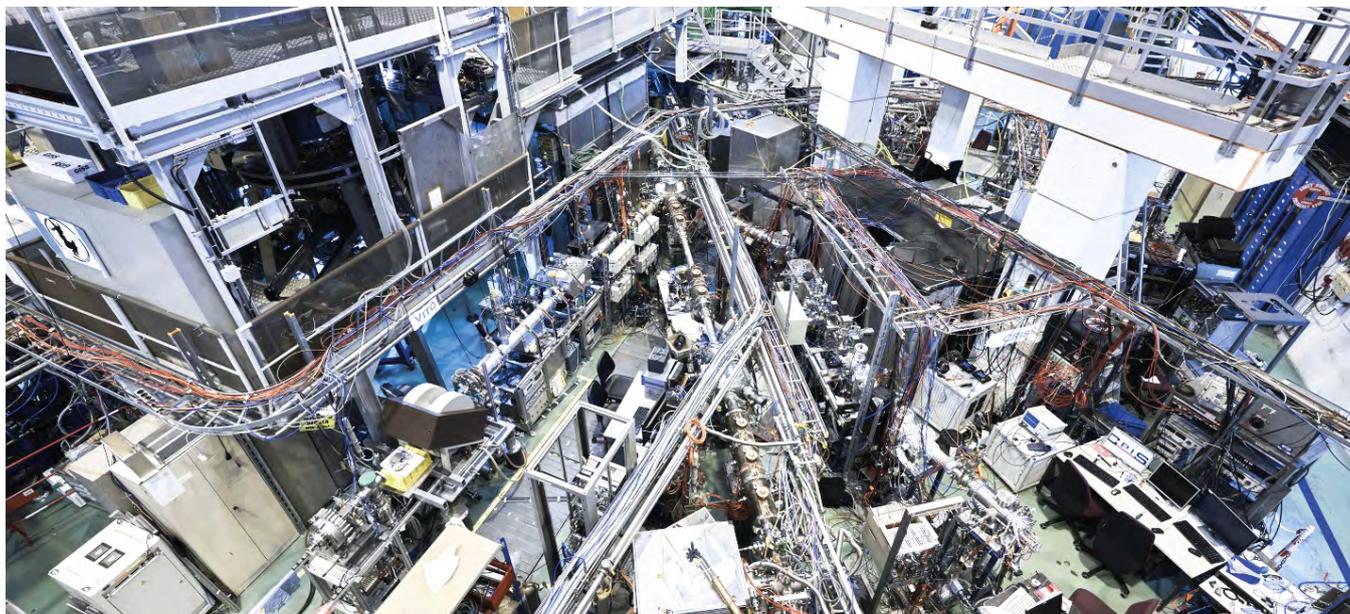
The department hosted 804 scientists (25 associates, 555 paid visitors, 224 unpaid visitors) and 59 fellows. It also arranged between five and eight seminars per week, and hosted nine theory institutes and 11 workshops and schools.

ANTIMATTER ANALYSES

CERN's unique Antiproton Decelerator (AD) provides experiments with low-energy antiprotons for precise spectroscopy, as well as gravitational and other measurements, allowing ever more precise comparisons of the behaviour of matter with antimatter. The AD currently hosts five experiments: ALPHA, AEGIS, ASACUSA, BASE and GBAR; a sixth experiment, ATRAP, completed operation in 2019. The new ELENA ring slows down antiprotons even further than the existing AD so that they are more easily trapped by the experiments. GBAR was the first experiment to be connected to ELENA and received its first antiprotons from the ring before the start of the ongoing shutdown. The other AD experiments will follow suit.

In 2019, the AEGIS team achieved the first pulsed production of antihydrogen and the first pulsed (metastable) positronium beam. The ALPHA collaboration demonstrated the cooling of positrons using laser-cooled beryllium ions, with a view to increasing the yield of trapped antihydrogen. It also made progress towards the upgrades of ALPHA and of ALPHA-g, which is essentially a vertical version of ALPHA. ASACUSA developed a way to measure the temperature of positrons, and is now working on a proton source, lasers and other equipment. The GBAR collaboration achieved a slow-positron production rate of 5×10^7 positrons per second, using the experiment's linear accelerator. All of these technical achievements will allow these experiments to make new antimatter measurements in 2021 and beyond.

Meanwhile, using a reservoir of antiprotons trapped in October 2018, the BASE experiment continued running until June 2019 and completed another campaign to compare the charge-to-mass ratio of the proton to that of the antiproton. Under various model assumptions, the BASE team also placed the first direct constraints on the interaction of antiprotons with a dark-matter candidate, the hypothetical axion.



The ISOLDE experimental hall. (CERN-PHOTO-201911-394-13)

INVESTIGATIONS AT ISOLDE

CERN's nuclear-physics facility, ISOLDE, directs a 1.4 GeV proton beam from the PS Booster (see p. 24) to a target station in order to generate exotic radioactive-ion beams for studies in the fields of nuclear and atomic physics, solid-state physics, materials science and life sciences. These beams can be re-accelerated using the recently completed REX/HIE-ISOLDE linear accelerator, which allows radioactive isotopes to be accelerated to energies close to 10 MeV per nucleon (proton or neutron), even for the most neutron-rich ions. No experiments were carried out at ISOLDE in 2019, due to the ongoing long shutdown, but several upgrades were made to the experiments, and various results were obtained from analyses of data taken in 2018.

An example was the demonstration that the radon isotopes ^{224}Rn and ^{226}Rn do not possess static pear shapes in their lowest-energy states. Static pear shapes and their so-called electric dipole moments could be used to probe physics beyond the Standard Model, so it is important to identify which nuclei exhibit them. The facility also saw the

first ever laser-spectroscopy measurements of short-lived radioactive molecules, using the state-of-the-art Collinear Resonance Ionisation Spectroscopy (CRIS) experiment. The measurements were made on radium monofluoride (RaF) molecules, which can contain pear-shaped radium isotopes and are predicted to offer a superior means of searching for new physics phenomena. The results are in agreement with theoretical calculations and represent an important step towards high-precision studies of short-lived radioactive molecules.

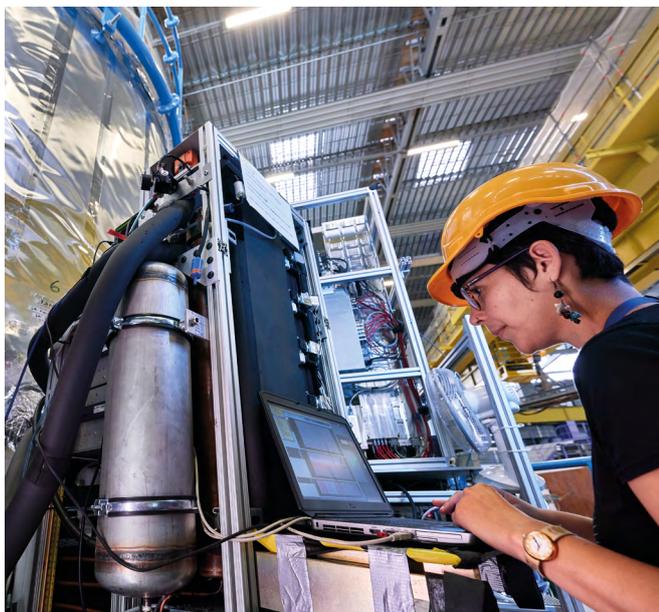
Another highlight was the very precise measurement, also using CRIS, of the charge radii of exotic copper isotopes up to ^{78}Cu . The results revealed an unexpected disappearance of the odd-even staggering in the radii when more than 46 neutrons are added to the 29 protons of the Cu isotopes; in this form of staggering, isotopes with an even number of neutrons have a slightly larger radius than those with an odd number. However, the researchers were able to explain the data using sophisticated models.

TARGETED EXPERIMENTS

Other CERN-based experiments, many of which are fed by beams from the PS Booster and the PS and SPS accelerators, have also made great advances. These include particle measurements for neutrino and cosmic-ray experiments and investigation of the QGP in heavy-ion collisions in fixed-target mode (NA61/SHINE); studies of rare kaon decays and searches for new heavy neutral leptons (NA62), with the detection of two candidate events for the ultra-rare decay of a positively charged kaon into a pion and a neutrino-antineutrino pair; studies of radiation processes in strong electromagnetic fields (NA63); searches for dark-sector particles (NA64), one of which resulted in some of



The NA64 experiment in CERN's North Area. (CERN-PHOTO-201611-278-3)



the most stringent bounds yet to be placed on the strength of the interaction between a photon and a dark photon; measurements of neutron-induced processes relevant to nuclear physics and astrophysics (n_TOF); studies of the hadron structure (COMPASS); searches for chameleon particles and axion particles (CAST), with the first results from the KWISP detector's chameleon search; and further studies of cloud formation in the ultra-pure chamber of the CLOUD experiment, which ran in 2019 using natural cosmic rays emitted by cosmic objects as opposed to the artificial cosmic rays that are usually provided by the PS but were not available due to the ongoing shutdown.

The CLOUD experiment ran in 2019 using natural cosmic rays emitted by cosmic objects. (CERN-PHOTO-201909-278-6)

NURTURING NEUTRINOS

Neutrinos are the lightest known massive particles, yet they could hold the key to some of the greatest puzzles of physics, such as the imbalance between matter and antimatter in the present-day universe. CERN's Neutrino Platform was established to support European participation in accelerator-based neutrino projects in the US and Japan, and provides charged beams and test space for large neutrino detectors. The developments in 2019 included the start of tests of the second prototype for the DUNE detector at the US Long Baseline Neutrino Facility. The first prototype, the single-phase ProtoDUNE detector, which is

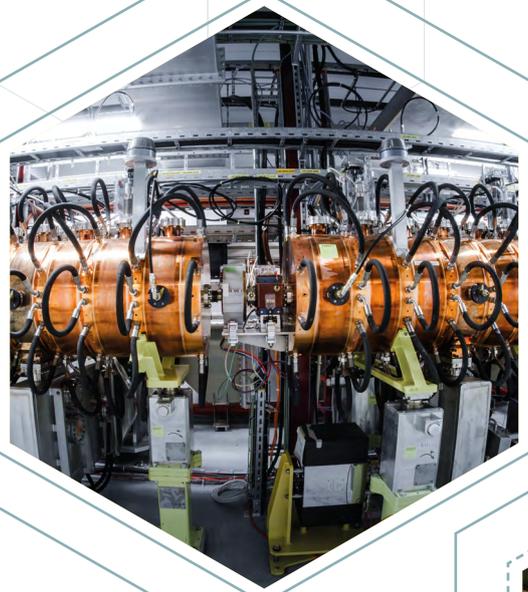
filled entirely with liquid argon, began taking data in 2018 and continued running in 2019, proving its robustness; sensors submerged in the liquid argon record the faint signals generated when a neutrino smashes into an argon atom. The second prototype is a dual-phase version: it uses liquid argon as the target material and a layer of gaseous argon above the liquid to amplify faint particle signals before they arrive at sensors located at the top of the detector, inside the argon gas. The dual-phase set-up could yield stronger signals and would enable scientists to look for lower-energy neutrino interactions.

Inside the dual-phase protoDUNE detector, which started to be tested in 2019. (CERN-PHOTO-201902-023-1)



DISCOVERY MACHINES

2019 was noteworthy for being the start of Long Shutdown 2 (LS2) of the CERN accelerator complex. Across all the machines, teams began the tasks of maintaining or renovating numerous items of equipment or replacing them with new, innovative systems. These major upgrades are being carried out in preparation for the third run of the LHC and for the High-Luminosity LHC (HL-LHC). What's more, they will benefit the users of all the accelerators as many aspects of the work are being carried out as part of the LHC Injectors Upgrade (LIU) project.



LINEAR ACCELERATOR 4 (LINAC4)

Linac4 is now connected to the LHC accelerator chain. A nominal beam of 160 MeV reached the Linac4 beam dump in October.

(CERN-PHOTO-201704-093-27)



ISOLDE

The front-ends for the isotope separator targets have been built, tested and partially installed. The new Offline2 test facility, equipped with a laser ion source, was commissioned.

(CERN-PHOTO-201911-394-28)



PS BOOSTER (PSB)

Seventy of the 215 metres of the PSB's beam lines have been removed to allow the installation of new equipment. More than 60 magnets have been renovated or replaced in the accelerator. A new RF acceleration system has been installed. After LS2, the energy of the PS Booster will increase from 1.4 to 2 GeV. (CERN-PHOTO-201906-149-11)

SUPER PROTON SYNCHROTRON (SPS)

A new RF acceleration system is under construction. The SPS beam dump is being replaced. A new fire safety system has been installed.

(CERN-PHOTO-201902-032-9)



LARGE HADRON COLLIDER (LHC)

The electrical insulation of the diodes has been completed on 94% of the accelerator's 1232 dipole magnets. Nineteen dipole magnets and three quadrupoles have been replaced.

(CERN-PHOTO-201905-117-9)



PROTON SYNCHROTRON (PS)

Forty of the 100 main magnets have been renovated. A new set of quadrupole magnets has been installed in the injection line and connected to new power converters.

(CERN-PHOTO-201902-028-14)



ANTIPROTON DECELERATOR (AD) AND ELENA

Twenty of the AD's 84 magnets have been renovated. The target area supplying the AD with antiprotons is being renovated. ELENA is now connected to all of the antimatter experiments.

(CERN-PHOTO-201611-300-1)



One of the PS Booster's main magnets is dismantled and removed from the accelerator. (CERN-PHOTO-201901-019-1)



A new kicker magnet is installed in the PS injection line. (CERN-PHOTO-202001-028-23)

FOUR INJECTORS UNDERGO A COMPLETE TRANSFORMATION

Long Shutdown 2 has brought a wind of change to CERN's vast accelerator complex. As part of the LHC Injectors Upgrade (LIU) project, the injectors are undergoing extensive renovation and upgrade work, for which new equipment has been constructed.

The first link in CERN's accelerator chain, the brand new **Linear Accelerator 4** (Linac4), officially replaced its predecessor, Linac2. Linac4 thus becomes the new and only source of proton beams for the LHC. During this first year of the shutdown, it was connected to the LHC injector chain via new transfer lines. No fewer than 160 metres of transfer lines have also been renovated and reinstalled. In order to prepare Linac4 to provide reliable high-quality beams to the PS Booster, the second link in the chain, a special run with beam took place at the end of the year. Beams travelled the 86-metre length of Linac4 before being sent along the new and the renovated transfer lines to the emittance measurement line (LBE) and then ended their journey at a beam dump located next to the wall of the Booster. In October, a nominal beam of 160 MeV reached the beam dump.

So that the **PS Booster** (PSB) is able to receive beams from Linac4 at 160 MeV, as against 50 MeV in the case of Linac2, the system that injects the beams into the PSB has been replaced, particularly since Linac4 will accelerate H^- ions (formed of an atom of hydrogen with an additional electron). These ions are stripped of their electrons – thus becoming protons – using an ingenious injection system, before being accelerated to 2 GeV in the Booster. Of the 215 metres of beam lines in the PSB complex, 70 metres have been dismantled to allow the installation of new injection and extraction equipment. In particular, magnets have been replaced in the transfer lines. Sixty magnets in the PSB itself have also been replaced or renovated. The new radiofrequency acceleration system of the Booster has been installed. Three structures, each housing eight cavities based

on a composite magnetic material known as FineMet and 48 power amplifiers, have been put in place. The installation of the cavities was completed in October and was followed by the commissioning of the new acceleration system, which has a new power supply: 24 racks containing 144 power converters, along with 18 racks of control modules, were installed in the spring. On the infrastructure side, the PSB's cooling system was replaced and new cooling towers were installed.

The **Proton Synchrotron** (PS) celebrated its 60th birthday in 2019. Alongside its main job today of supplying protons at 26 GeV to the Super Proton Synchrotron (SPS), it also supplies particles to several experimental areas. During LS2, the PS is undergoing a major service to prepare it for higher beam intensity during Run 3 of the LHC and for the HL-LHC later on. Of the 100 main magnets in the PS, 40 were renovated and reinstalled in the machine in 2019. The injection line into the PS is also being renovated; a new set of quadrupole magnets has already been installed. The power converters that supply this line have been installed in completely renovated buildings. Equipment will continue to be installed in 2020.

A new cooling system is also being installed and will double the flow rate while also reducing operating costs. At the same time, the pumps and heat exchangers have been replaced, as well as three kilometres of pipes. The cooling system of the injection line between the PS and the SPS has been separated from that of the PSB, which will allow the PS to operate independently.

At the **Super Proton Synchrotron** (SPS), the machine's acceleration system is undergoing significant modifications. With the increase in beam intensity, the accelerating cavities will require more radiofrequency (RF) power. The original power amplifiers, which are based on electronic vacuum tubes, will be joined by an innovative system that

WORK CONTINUES ON THE SM18 TESTING HALL

Building SM18 is a unique hall for testing very-low-temperature magnets and cavities with very high current intensities. To meet the needs of the HL-LHC project, a major upgrade campaign has been underway there since several years. In 2019, a new helium liquefier was installed. This new system will more than double the production of liquid helium in the hall from 25 to 60 grams per second.



The SM18 hall, a unique facility for testing superconducting magnets and cavities, is undergoing an upgrade campaign. (CERN-PHOTO-201910-361-92)

uses RF power transistors. Thirty-two towers containing 10 240 transistors are being installed in this framework. The whole system will provide RF power of two times 1.6 megawatts, thus virtually doubling the existing capacity. The modules were all tested on a specially designed test bench and 20 towers had been validated by the end of 2019. In parallel, the RF accelerating cavities were removed from the tunnel and are now being prepared to accelerate more intense beams.

The Faraday cage, which houses the electronic racks for the beam control system, was completely emptied, ready to be fitted with the latest electronics and new infrastructure. Several other devices are also being installed in the SPS to allow operation with beams of an unprecedented intensity.

In order to reduce the electromagnetic interaction of the beam with its surroundings and thus make it more stable, the flanges connecting the focusing quadrupoles to one another in the short straight sections are gradually having shielding added. At the same time, the internal walls of the vacuum

chambers of these quadrupoles are being coated with a thin layer of amorphous carbon, with the aim of reducing the emission of secondary electrons and thus preventing the formation of electron clouds. The ionic pumps, which suck out the residual gases present in the machine, are gradually being replaced. Improved pumping systems are also being installed in the injection and extraction regions.

The SPS beam dump, located at Point 1 of the accelerator, will be replaced by a new dump at Point 5. Significant civil-engineering work was carried out in 2019 so that this new device could be installed. The fire-safety systems in the SPS have also been consolidated and modernised as part of a project launched in 2016. A new aspirating smoke-detection system has been installed in the SPS tunnel, along with a partitioning system to prevent fire from propagating. In the long straight sections, the service tunnels and the access shafts, fixed automatic water extinguishing systems were installed.



Major civil-engineering work has been carried out in one of the underground SPS halls to prepare it for the installation of the accelerator's new beam dump.

(CERN-HOMEWEB-PHO-2019-037-1)



One of the Antiproton Decelerator's dipole magnets is extracted for renovation. (CERN-HOMEWEB-PHO-2020-044-1)



Electrical quality-assurance tests are performed in the LHC in the context of the superconducting-magnet diode-consolidation project. (CERN-HOMEWEB-PHO-2020-048-11)

A NEW LOOK FOR THE NUCLEAR PHYSICS FACILITIES

The **ISOLDE** facility is used to study the properties of atomic nuclei for a large range of applications. In 2019, the front-ends for the targets of the two isotope separators were built, tested and, in one case, installed (the second will be installed in 2020). ISOLDE's new Offline2 test facility, equipped with a laser ion source, was also commissioned. One of the four cryomodules of the new HIE-ISOLDE (High-Intensity and Energy upgrade of ISOLDE) linear accelerator underwent repairs and a series of tests. It will be reinstalled in early 2020. New beam-diagnostics systems have also been developed for the accelerator.

The target of the **neutron time-of-flight** (n_TOF) facility, which studies nucleus–neutron interactions, was removed. Construction of a new target, made from pure lead and cooled with nitrogen, began in 2019.

TWO ANTIMATTER DECELERATORS

The beamlines that carried particles from the **Antiproton Decelerator** (AD) to the antimatter experiments have been dismantled to make way for the injection lines of the new **ELENA** (Extra Low Energy Antiproton) deceleration ring. ELENA will slow down the antiprotons coming from the AD even further, allowing the experiments to trap almost 100 times more antiprotons than before. The new ring is now connected to all of the antimatter experiments. The machine's testing and commissioning period will begin in mid-2020.

During the first phase of LS2, 20 of the AD's 84 magnets were renovated. Most of them were recycled from previous facilities and are much older than the AD itself. Work is also underway to consolidate other components of the AD, including the kicker magnets, septum magnets and radiofrequency cavities. The area housing the target that supplies the AD with antiprotons is currently being renovated and a new target will be installed there. Building 196, which was home to the target area's cooling system, has been demolished to make room for a new building that will host a fully renovated cooling system. The target, which was previously cooled using water, will now be cooled using air.

THE LHC PREPARES FOR RUN 3

In April, the teams involved in the Diode Insulation and Superconducting Magnets Consolidation (DISMAC) project began working in the tunnel of the **Large Hadron Collider**. Their task is to improve the electrical insulation of the diodes of the accelerator's 1232 dipole magnets, replace 22 of the main superconducting magnets and carry out a series of other activities. Each dipole magnet is fitted with a diode, a parallel circuit allowing the current to be diverted in the event of a quench. This diode is connected to the associated magnet via a copper busbar. During LS2, the electrical insulation of these connections has been improved using made-to-measure insulating parts. To complete this project, a team of no fewer than 150 people are working in turns according to a carefully orchestrated schedule. By the end of 2019, more than 90% of the 1232 diode boxes had been cleaned and insulated. In addition, 19 dipole magnets and three quadrupole magnets were replaced and instrumentation systems to study the heat loads caused by the beam were installed.



One of the LHC's cold boxes, a key component of the accelerator's cryogenics system, on which numerous maintenance and upgrade operations have been performed. (CERN-PHOTO-201904-107-2)



One of the East Area's magnets undergoing renovation work at CERN. (CERN-PHOTO-201903-057-9)

The maintenance of the LHC's current leads, which provide the link between the copper cables at room temperature and the superconducting cables at 1.9 K ($-271.3\text{ }^{\circ}\text{C}$) was also completed, with some necessary repairs made. Maintenance and upgrade activities were also carried out on the energy-extraction systems that provide protection against quenches of the LHC's superconducting magnets, notably on the 13 kA systems. A component known as the secondary arcing contact was replaced in each of the 256 electromechanical switches of the energy-extraction systems.

A major maintenance campaign is also underway on the 70 helium compressors that form the first links in the LHC's cryogenic chain. The compressors are sent to specialised workshops, mainly in Germany and Sweden, where they are taken apart and then reassembled in order to check the condition of all of the parts and make replacements if necessary. The compressors' 70 electric motors are being serviced in Italy, and six of the 28 cold compressors have travelled all the way to Japan. No fewer than 4000 maintenance operations have already been carried out on the LHC's eight cold boxes. The sensors, thermometers, valves, turbines, filters, etc. are being checked and either validated or replaced.

HEADING EAST

The East Area, which is supplied by the PS, is in the midst of a major overhaul. Dismantling activities and civil-engineering work were completed this year. The main challenge was to dismantle the T9 and T10 experiment areas and carry out a major cable-removal campaign while keeping the CLOUD experiment running. Approximately 250 metres of beamlines

supplying the CLOUD, CHARM and IRRAD experiments and the associated experiment areas were dismantled. Thirty dipole and quadrupole magnets were renovated and a further thirty will be replaced; the new ones are currently in production. Power will be supplied to the new magnets on a cyclical basis, with an energy recovery stage between each cycle. Electricity consumption should therefore fall from 11 GWh/year to around 0.6 GWh/year. Once renovated, the beamlines will be arranged in a new configuration, with flexible optics. The old extraction line from the PS was dismantled and the installation of the new line began in November.

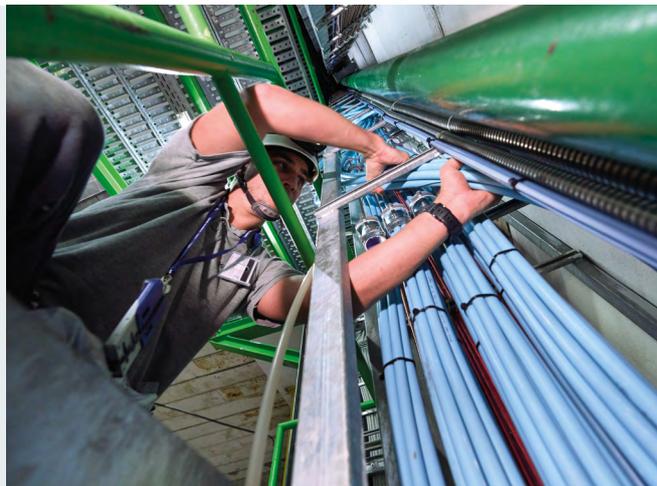
New beam-profile control monitors are also being manufactured. These scintillating-fibre detectors were developed at CERN to replace the less powerful delay-wire chambers that were used in the past.

TURNING TO THE NORTH

The SPS supplies the North Area's 60 experiments and areas via six beamlines. Most of this equipment dates from 1976, when the SPS started up. Several upgrades are on the agenda for LS2, mainly aiming to improve the safety of the installations. The gas-supply system is being renovated, which involves replacing several hundred metres of pipes. The radiation-detection system has also been renovated. In addition, the layout of the largest hall of the North Area will be modified in order to extend the test area for new detectors. The LHC experiments, in particular, need facilities to test the new subdetectors that they will use in the HL-LHC era.



One of the two input substations, on which major maintenance and consolidation work was performed in 2019. (OPEN-PHO-CIVIL-2019-002-2)



In 2019, 20 000 optical fibres contained within 220 cables were installed inside the ALICE experiment. (CERN-PHOTO-201906-164-12)

REINFORCEMENT OF CERN'S INFRASTRUCTURE

GUARANTEEING A RELIABLE POWER SUPPLY

The electrical infrastructure must be reliable in order to ensure the proper functioning of the installations, experiments and accelerators. In its nominal configuration, it comprises two substations with an input voltage of 400 kilovolts (kV), which is supplied by the French electrical grid. Downstream, these substations are connected to another substation that lowers the voltage to 66 kV. Part of this network supplies facilities several kilometres away (notably those of the LHC), while, following a conversion to 18 kV, the other part supplies the Meyrin and Prévessin sites and the SPS. At the beginning of July, one of the two input substations, some of whose equipment had come to the end of its life, was switched off so that major consolidation work could be carried out on its protection system. Most of this work was completed in November.

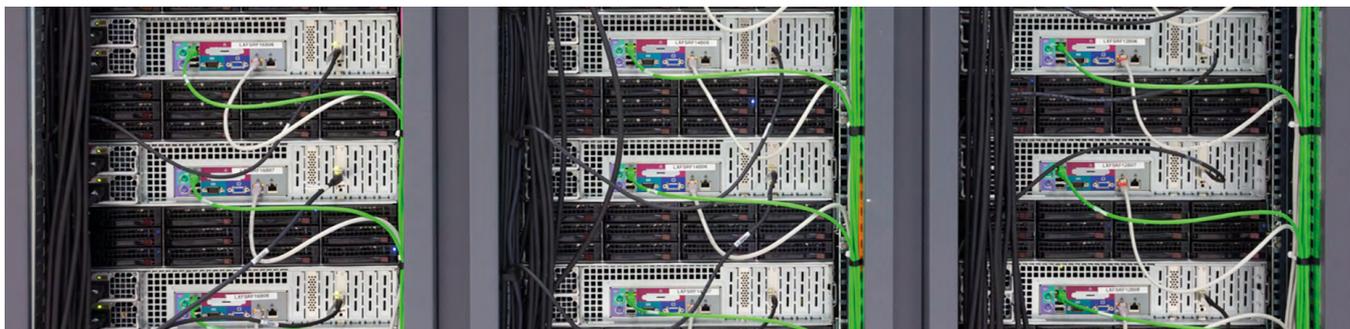
In mid-September, Meyrin's main substation, which has supplied the site with 18 kV since the 1960s, was disconnected for renovation. Major work is also underway at the SPS, where five of the seven 18 kV substations are being renovated. Work on four of them required new buildings to be constructed. In the PSB and the PS, several electrical boards and low-voltage switch boxes dating from the 1970s were replaced, as were the lighting systems, which were replaced with new, specially developed radiation-resistant lights. Many other activities, notably maintenance, were also carried out in preparation for future runs. These included the maintenance of several hundred transformers and circuit breakers, the replacement of the batteries of the LHC's uninterruptible power systems, updating of the network-status control systems, etc.

ONE THOUSAND NEW POWER CONVERTERS

One thousand power converters will be installed during LS2. Production of these converters began in 2016 and will be completed in 2020. The majority were delivered to CERN in 2019, a year that was mainly dedicated to the removal of old converters and to work to adapt the buildings for the new components. However, the first power converters were commissioned in the autumn in the transfer line between Linac4 and the Booster. The East Area's 64 new power converters, which are fitted with an energy-recovery system, have been manufactured; the first units were delivered and successfully tested in 2019.

TWO THOUSAND KILOMETRES OF CABLES

Some 40 000 copper and optical fibre cables need to be removed or installed during LS2. Laid out end to end, they would stretch for 2000 kilometres! The year 2019 saw 20 000 optical fibres installed in the heart of the ALICE experiment and 1200 copper signal cables pulled in the SPS in the context of its fire-safety project. Other big CERN projects also required major cable removal and installation campaigns, notably the LIU project, the East Area renovation work and the commissioning of the ELENA extraction lines. Of the 40 000 cables being dealt with during LS2, 15 000 are obsolete copper cables that need to be removed, some of them as old as CERN itself. The meticulous work of cataloguing and naming each cable began during LS1.



The CERN Data Centre is the heart of CERN's entire scientific, administrative and computing infrastructure. (IT-PHO-CCC-2016-002-61)

COMPUTING PREPARING FOR RUN 3

As the accelerator complex entered its second long shutdown, the CERN Data Centre was kept busy with preparations for the higher flow of data expected when the LHC starts up again. The repatriation of the equipment installed in the CERN Data Centre extension in Budapest, Hungary, and the consolidation of the computing infrastructure are two major milestones of the upgrade plan that were achieved in 2019.

At the end of 2019, CERN ended its excellent seven-year collaboration with the Wigner Data Centre in Hungary, which had been hosting a significant amount of computing equipment providing capacity to the CERN Data Centre for the Worldwide LHC Computing Grid (WLCG). As part of the strategy to tackle the Run 3 challenges and to meet the level of service that is expected to be required, the vast majority of this equipment was repatriated to the CERN Data Centre and recommissioned. In total, this concerned 2628 servers as well as disk storage. A fraction of the equipment brought back was donated to the LHCb experiment, to be installed in its new computing modules (cf. text box p. 31), while the remaining equipment at the Wigner Data Centre was given to the ALICE experiment.

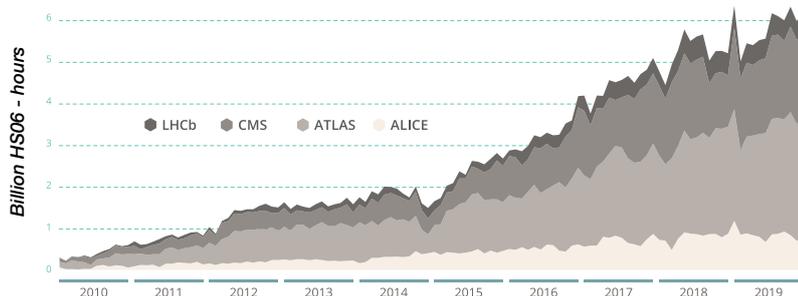
Extensive consolidation of the computing infrastructure was also carried out in 2019. The tape infrastructure, used for long-term data storage, was upgraded. Legacy tape libraries were emptied and decommissioned, with over 80 petabytes of data migrated to the new tape library system. CTA, the new CERN Tape Archive software, which was developed to handle the higher data rate anticipated during Runs 3 and 4 of the LHC, entered production. FTS, the File Transfer Service project, which distributes the majority of LHC data across the WLCG infrastructure, benefitted from

several significant performance improvements in preparation for the Run 3 data challenges. FTS is now also supporting CTA and is used by more than 25 experiments at CERN and in other data-intensive sciences. Campaigns to replace computing equipment that was no longer suited to CERN's research purposes were also carried out in 2019. The retired computing equipment remains suitable for less-demanding applications. The An-Najah National University in Palestine benefitted from a donation of such equipment, which will be instrumental in supporting the creation of a laboratory for high-energy physics (HEP).

THE GRID NEVER SLEEPS

The WLCG performed very well in 2019. It was extremely stable and reliable, supporting the timely delivery of high-quality physics results by the LHC collaborations. Although they did not take data in 2019, the four LHC experiments nevertheless continued to use all of the WLCG services and resources at full capacity in order to analyse the large amounts of data already collected. The levels of core processor time used reached new peaks during the year, equivalent to the continuous use of some one million computer cores. Volunteer computing for CERN, under the LHC@home umbrella, continued to provide significant capacity in 2019 and allowed peaks of 600 000 tasks to be run simultaneously, a new record for the LHC@home initiative.

Data delivery to the global collaborations is a key aspect of the WLCG service, and the sustained level of data transfer rates remained above 50 gigabytes per second in 2019, illustrating the high level of activity within the distributed computing service. FTS transferred more than 800 million files containing 0.95 exabytes of data in total.



Evolution of the global core processor time delivered by the Worldwide LHC Computing Grid (WLCG)

As shown in the graph, the global central processing unit (CPU) time delivered by WLCG (expressed in billions of HS06 hours per month, HS06 being the HEP-wide benchmark for measuring CPU performance) is continually increasing. In 2019, WLCG pooled the computing resources of about one million cores.

PREPARING FOR THE FUTURE

Looking to the future, the High-Luminosity LHC (HL-LHC) presents a major and significant increase in computing requirements compared with Run 2 and the upcoming Run 3. The demand exceeds extrapolations of technology progress within a constant investment budget by several factors, in terms of both storage and computing capacity. In this context, a call for tenders for the creation of a new CERN Data Centre will be prepared in 2020. CERN openlab, the unique public-private partnership through which CERN collaborates with leading ICT companies and other research organisations, launched four projects in 2019 related to quantum-computing technologies, which offer great potential to provide solutions for CERN's future ICT challenges. Several other solutions, such as the DOMA (Data Organisation, Management, Access) project and the use of graphics processing units (GPUs), have also been investigated and are being developed.

The WLCG team is leading the DOMA project, which aims to prototype the concepts of a “data lake”, where data can be streamed on demand to processing centres rather than being pre-placed there. The CERN team is leading a work package, within the EU-funded ESCAPE project, to demonstrate this “data lake” technology for high-energy physics (HEP), as well as for astronomy, astroparticle physics and related fields. It started in early 2019 and is already operating a set of prototypes that will form the basis for future development work in collaboration with these sciences.

As the computational challenges posed to HEP by the HL-LHC and the upgrades of the detectors might not be solved entirely through the use of traditional central processing units (CPUs), the LHC experiments, WLCG and CERN openlab also started investigating novel approaches to accommodate

the large amount of computation that will be required. They invested in R&D efforts to leverage GPUs for traditional HEP data processing and analysis. The ALICE experiment had already pioneered the use of GPUs for its high-level trigger (HLT) during Run 2. After a preliminary study in 2015, ATLAS resumed investigations into the potential use of GPUs for data reconstruction and analysis. The CMS experiment started R&D that has demonstrated that code that accounts for about one third of the time needed to run the HLT event-filtering sequence can be offloaded to GPUs. The LHCb collaboration demonstrated the feasibility of porting on GPUs the first stage of the software dedicated to its newly developed trigger system that is able to decide whether an event contains physics signatures relevant for further processing. GPU resources have also been made available in the CERN Data Centre through a batch system and significantly accelerate certain applications.

SCIENCE IN THE CLOUDS

Over 90% of the resources for computing in the Data Centre are provided using a private cloud based on OpenStack, an open-source project to deliver a massively scalable cloud operating system. In 2019, the use of cloud containers-as-a-service showed a clear move to Kubernetes, an open-source system for managing containerised applications in a clustered environment. Over 500 clusters are now in use and significant enhancements in service functionality via auto-healing and auto-scaling are being contributed to the upstream open-source project. The portability of the Kubernetes workload was demonstrated when the Higgs boson analysis was tested on the CERN cloud and then reproduced in a few minutes using the CERN Open Data portal and external cloud resources. CERN has been actively contributing to the communities of many open-source projects over the years.

THE 30-YEAR ANNIVERSARY OF AN INVENTION THAT CHANGED THE WORLD

In 1989, CERN was a hive of ideas and information stored on multiple incompatible computers. Sir Tim Berners-Lee envisioned a unifying structure for linking information across different computers, and wrote a proposal in March 1989 called “Information Management: A Proposal”. By 1991 this vision of universal connectivity had become the World Wide Web.

To celebrate 30 years since Sir Tim Berners-Lee's proposal and to kick-start a series of celebrations worldwide, CERN hosted several events both on-site and online on 12 March 2019, in partnership with the World Wide Web Consortium (W3C), the World Wide Web Foundation and the FIFDH.



On the stage, from left to right: Lou Montulli, Zeynep Tufekci, Sir Tim Berners-Lee, Robert Cailliau, Jean-François Groff, Frédéric Donck. (CERN-PHOTO-201903-055-85)

In 2019, CERN collected the Procura+ Award for 'outstanding innovation procurement in ICT' for the Helix Nebula Science Cloud Pre-Commercial Procurement (HNSciCloud PCP). In this EU-funded PCP led by CERN, 10 public research entities from seven EU countries kick-started the uptake of new cloud-based systems benefitting from big data storage and analysis tools needed by large scientific projects. CERN is also the coordinator of the CS3MESH project, which will begin in January 2020. CS3MESH allows service providers to deliver state-of-the-art connected infrastructure in order to boost effective scientific collaboration and data sharing according to FAIR principles. The project delivers the core of a scientific and educational infrastructure for cloud storage services in Europe through a lightweight federation of existing sync/share services (CS3) and integration with multidisciplinary application workflows.

All of these projects are contributing to the establishment of the European Open Science Cloud (EOSC). The EOSC initiative was proposed by the European Commission in 2016 with a view to building a competitive data and knowledge economy in Europe. EOSC will provide 1.7 million European researchers and 70 million professionals working in science, technology, the humanities and social sciences with a virtual environment offering open and seamless services for the storage, management, analysis and re-use of research data. These services will be provided across borders and scientific disciplines by federating existing scientific data infrastructures that are currently dispersed across disciplines in the EU Member States.

OPEN SOURCE FOR OPEN SCIENCE

Ever since it released the World Wide Web software under an open-source model in 1994, CERN has been a pioneer in the field of open science, supporting open-source hardware (with the CERN Open Hardware Licence), open access (with the Sponsoring Consortium for Open Access Publishing in Particle Physics – SCOAP³) and open data (with the CERN Open Data portal).

In 2019, the CERN Open Data portal hosted more than two petabytes of LHC data. This portal, which allows the LHC experiments to share their data, expanded its frontiers to host datasets for machine learning in order to address the needs of the wider Data Science community. Several new theoretical research papers using CMS open data were published, validating the importance of open data and open science.

Several CERN technologies are being developed with open access in mind. Zenodo, the free open-data repository co-developed by CERN and available to all sciences, is one example. In 2019, the number of visits to Zenodo doubled again, to 2.3 million, and a collaboration agreement was signed with Dryad, a not-for-profit membership organisation.

Zenodo and Dryad received a joint grant from the Alfred P. Sloan Foundation in order to co-develop new solutions focused on supporting researcher and publisher workflows and promoting best practices in data and software curation.

In 2019, the MALT (Managing Accessibility and Leveraging open Technologies) project was presented to the CERN community. The project, which was launched in 2018, aims to mitigate anticipated increases in software license fees by transitioning to open-source products. Pilot services have already been implemented and tested in 2019 as part of the project, which extends over several years.



The new computing modules at the ALICE and LHCb sites. (CERN-PHOTO-201908-234-5, 201905-123-2)

ALICE AND LHCb UPGRADE THEIR DATA CENTRES

In 2018 and 2019, new data-centre modules using indirect free-air cooling were installed and commissioned at the ALICE and LHCb sites (Points 2 and 8 of the LHC) as part of the upgrades of their data centres for Runs 3 and 4. During LS2 and Run 3, some of the LHCb modules will be shared with CERN's IT department in order to make efficient use of the facility. Servers repatriated from the Wigner Data Centre, as well as new equipment, have already begun operation.

The new computing modules installed at the site of the ALICE experiment will form ALICE's new processing farm for Runs 3 and 4, and will host up to 750 servers with GPUs. Two of the central modules at the LHCb experiment site will be home to the readout system for Run 3; they contain 500 servers comprising special readout cards developed by LHCb. The other four modules will host the servers of the high-level-trigger farm. LHCb will deploy at least 2000 servers at the start of Run 3 and at least 20 petabytes of storage.

SHAPING INNOVATION: FROM CERN TO SOCIETY

CERN's mission to probe the fundamental structure of the universe involves developing breakthrough technologies for accelerators, detectors and computing systems, many of which have applications beyond particle physics. CERN actively cooperates with experts in science, technology, industry and its governing bodies with the goal of maximising the Organization's positive impact and accelerating innovation. This cooperation can take the form of collaboration agreements, measures to encourage entrepreneurship and spin-offs, participation in projects co-funded by the European Commission and more. The resulting transfer of knowledge helps drive innovation, that enhances CERN's economic impact in its Member States and benefits society as a whole.

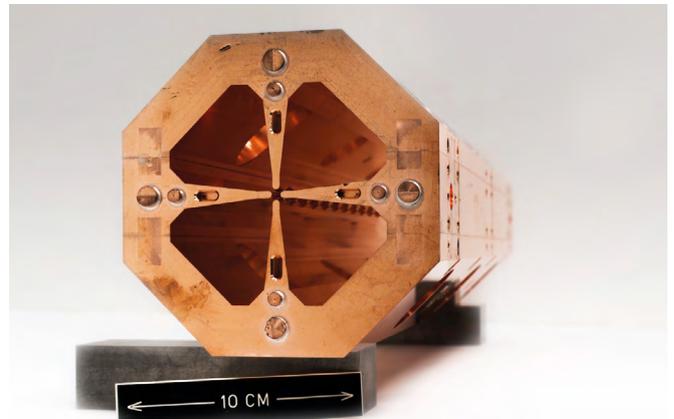


CERN's three pillars of technology are accelerators, detectors and computing. Behind these lie many areas of expertise, from magnets to sensors, microelectronics, radiation monitoring and more. These technologies and the associated expertise have a positive impact beyond CERN across many industries.

Many novel technologies emerge from the tools developed by CERN for particle physics. After identifying technologies and know-how with potential societal impact, CERN seeks out opportunities to work with industry leaders in the fields of medicine, aerospace, cultural heritage and industry 4.0. The following are just some of the knowledge-transfer success stories of 2019.



CERN and Zenuity work together on fast machine learning for autonomous driving.



First brazed HF-RFQ module for medical applications built and assembled at CERN. (CERN-PHOTO-201506-138-2)

SOFTWARE SOLUTIONS FOR AUTONOMOUS DRIVING

With billions of collisions per second taking place in CERN's experiments, scientists need to filter a plethora of data in order to choose which to analyse, and they do so using computing methods such as machine-learning techniques. Similarly, the challenge in developing self-driving cars is the fast interpretation of the multitude of data generated in normal driving conditions. Zenuity, which develops software for automotive safety and autonomous driving, has now teamed up with CERN in the field of fast machine learning. In collaboration, they will explore how these techniques deployed on chips known as field-programmable gate arrays could be applied to autonomous driving so that the fast decision-making used for particle collisions could help prevent collisions on the road.

CREATING TRUST IN THE DIGITAL WORLD

In October, CERN began a two-year collaboration with Bundesdruckerei GmbH, a security company owned by the German government that uses services and technologies to protect sensitive data and infrastructures. The collaboration will explore possible links between quantum physics, identities and trust, focusing on how to transfer findings from quantum physics to IT systems designed for security. The aim is to proactively prepare for the age when quantum computers will protect companies, organisations and citizens and to find a way to develop an easy-to-use secure digital identity.

CERN TECHNOLOGIES FOR NEXT-GENERATION ION-THERAPY CENTRES

The year 2019 saw the official launch of the NIMMS (Next Ion Medical Machine Study) project and the approval of its funding within the scope of the CERN Medical Applications Budget. NIMMS is an umbrella R&D programme for CERN accelerator technologies linked to hadron therapy, which is used in the treatment of cancer. Following input from world experts in the field, CERN's efforts will concentrate on ion-therapy facilities rather than those using protons. In line with CERN's core competences and expertise, superconducting magnets, linacs and gantries were identified as key technologies for this development. NIMMS will provide a toolbox of know-how that end-users can use and adapt to realise a new generation of more compact and cost-effective ion-therapy facilities.

FUNDING OPPORTUNITIES

Since 2011, the Knowledge Transfer Fund has sponsored innovative projects based on CERN technologies that have potential benefits for society. The fund is maintained by revenue from CERN's knowledge transfer commercial agreements. In 2014, additional resources were made available from the Medical Applications Budget to support projects in the medical applications field. In 2019, the selection committee awarded funding to 15 of 23 eligible projects, bringing the total number of projects supported since the fund was established to 89.

FOSTERING A CULTURE OF ENTREPRENEURSHIP

The cultivation of entrepreneurship has continued through CERN's expanding Business Incubation Centre (BIC) network, networking events such as the entrepreneurship meet-ups, where experts inspire and share their knowledge and experience, and programmes such as the CERN Entrepreneurship Student Programme (CESP) and screening weeks where students explore market opportunities for CERN technologies.

During the year, the BIC network welcomed three new start-ups. Arc Power, which develops radiation-resistant electronics for space missions, joined the Swiss BIC, Park Innovaare. Orvium, which aims to change the scientific publication paradigm using Zenodo as a document repository, entered the Spanish BIC Ineustar. PlanetWatch, which is developing a social network for streaming environmental sensor data using C2MON as the monitoring software, joined the French BIC, InnoGEX. There are currently 26 start-ups across the world using CERN technologies.



The market survey for the construction of the Science Gateway was launched in 2019. (CERN-PHOTO-201904-083-28)

DOING BUSINESS WITH CERN

Procurement is a fundamental aspect of CERN's economic impact in its Member States: advancements in accelerators, detectors and computing take shape through successful business collaborations with a variety of industries. In 2019, CERN continued to carry out extensive procurement activities for the HL-LHC project, including three contracts for the supply of detector components.

Two market surveys were launched for the construction of the Science Gateway and a new data centre on the Prevéssin site. Globally, CERN's procurement activities included 30 000 orders of various types, 82 invitations to tender, 101 price enquiries above 50 000 CHF, and the

PROMOTING AN OPEN-SCIENCE POLICY

The Scientific Information Service is involved in a variety of projects to promote the easy and free exchange of scientific knowledge across the scientific community. A new beta version of INSPIRE, a platform that helps researchers to share scholarly information in the field of high-energy physics, was launched in 2019. The platform, which is today run as a collaboration involving CERN, DESY, Fermilab, IHEP, IN2P3 and SLAC, has been available for almost 50 years and was the first database on the Web. SCOAP³, the Sponsoring Consortium for Open Access Publishing in Particle Physics, is another global initiative operated by CERN, involving over 3000 partners from 43 countries. Since its start in 2014, it has made more than 30 000 articles accessible to researchers all over the world. In this framework, CERN has signed contracts with publishers of 11 high-quality journals for another three-year cycle, ensuring that almost 90% of high-energy-physics research published until 2022 is available through open access.

signature of 161 contracts, of which 75 were collaboration agreements.

In 2019, CERN implemented an online tool for the electronic signature of contracts and consolidated the use of its e-Procurement platform, as the number of companies registered continues to increase. So far, more than 18 000 purchase orders have been placed via the platform.

CERN's exceptional activities were recognised at the Procura+ Awards 2019 with the 'Outstanding Innovation in ICT Procurement' award for CERN's role in pre-commercial procurement of innovative open cloud data storage services.

**ATTRACT FUNDED 170 BREAKTHROUGH IDEAS
IN DETECTION AND IMAGING TECHNOLOGIES
IN 2019; CERN PARTICIPATES IN 19 OF THESE
PROJECTS.**

**STRENGTHENING FRUITFUL COLLABORATION
IN EUROPE**

CERN cultivates close collaboration with its Member States through its participation in projects co-funded by the European Commission (EC) under programmes such as Horizon 2020 for scientific and technological cooperation. These activities strengthen CERN's links with European universities, research institutes, laboratories, industrial partners and decision-makers. In 2019, CERN provided input to the Horizon Europe surveys launched by the European Commission and organised the annual CERN-EC meeting, which focused on topics such as Horizon Europe, ATTRACT and the European Open Science Cloud. In addition, CERN began a one-year chairship of the European Intergovernmental Research Organisation forum, EIROforum, which brings together eight of Europe's largest research organisations (CERN, EMBL, ESA, ESO, ESRF, European XFEL, EUROfusion and ILL).

CERN submitted 46 projects to the Horizon 2020 funding programme in 2019, eight of which have already been approved, including two Marie Curie Actions. In addition, five of the six ongoing EC co-funded projects in which CERN is involved (ARIES, AIDA-2020, QUACO, AMICI and ATTRACT) include a strong knowledge-transfer component, corresponding to 33.9 million euros in EC contributions.



A highlight of the ARIES project was the first positive results of using an electron-beam accelerator to reduce pollutants in the exhausts of maritime diesel engines.

**DEVELOPING BREAKTHROUGH DETECTION
AND IMAGING TECHNOLOGIES**

ATTRACT brings together Europe's fundamental-research institutions and industrial communities in order to pursue the next generation of detection and imaging technologies. In 2019, 170 breakthrough ideas, from research data acquisition to front-end and back-end electronics, sensors and software integration received funding. The aim is to develop technologies that could help to improve the clinical diagnosis of cancer, treat heart and neurological conditions, mitigate climate change or boost technological revolutions such as the Internet of Things or Artificial Intelligence.

The projects have one year to show that their disruptive ideas are worth further investment and will present their results at a conference in Brussels in September 2020. During the one-year development phase, business and innovation experts will help the project teams to explore how their technologies can be transformed into innovations with strong market potential.



Funded by the European Commission under the Horizon 2020 programme, ATTRACT is a consortium of nine leading research infrastructures including CERN that promotes growth in detection and imaging technologies.

INSPIRING AND EDUCATING

The science and technology underpinning CERN's research has immense potential to enthuse and engage all sectors of the public in the wonder of science and its impact on our daily lives. In 2019, CERN continued to reach out to young and old, near and far, to empower all generations to make sense of the Laboratory's science and technologies, and to inspire students to pursue careers in science and engineering.

The CERN Open Days on 14 and 15 September gave an estimated 75 000 visitors the opportunity to discover the Laboratory's installations and meet the people behind the science and technology. (CERN-PHOTO-201909-308-12)



ENGAGING LOCALLY AND GLOBALLY

Open Days are an increasingly important part of CERN's outreach and take place during maintenance periods when visitors can access the machines. In 2019, 75 000 visitors to the Open Days experienced just over 150 activities, events and visits across nine sites. A dedicated website drew more than one million visitors, while 26 000 users from more than 100 countries downloaded the Open Days app. Feedback from visitors, in person and on social media, was overwhelmingly positive, particularly concerning the enthusiasm and passion of the 2800 volunteers, who represented all departments and experiments at CERN as well as alumni and contractors.

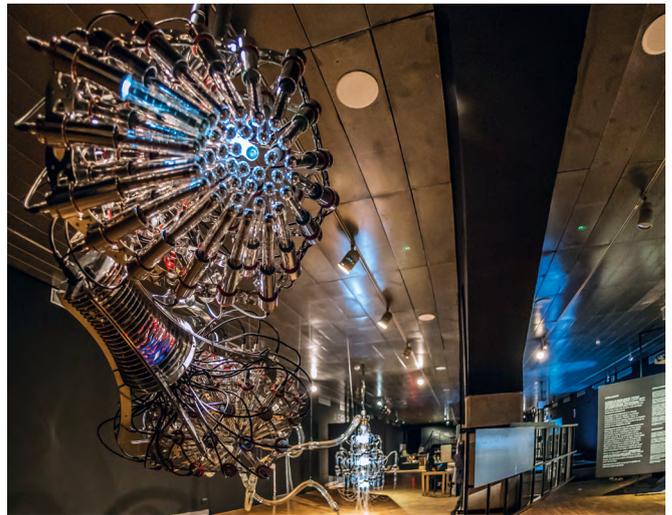
CERN continues to be a much-favoured visitor destination, with more than 150 000 visitors from 95 countries coming for guided tours in 2019, a 12% increase compared to the previous year. Just under half of these visitors were students. Decision-makers from CERN Member States and other countries also regularly visit CERN and, in 2019, 146 protocol visits were organised.

For those who were unable to come to CERN, travelling exhibitions journeyed to many countries. One of the re-developed Accelerating Science exhibitions travelled to India for the first time, touring Bangalore, Mumbai and Calcutta as part of the science exhibition 'Vigyan Samagam'; the other was set up in Tartu, Estonia. The smaller LHC Interactive Tunnel exhibition travelled to 11 different countries.

Engaging with CERN's neighbours continues to be an important part of the Laboratory's outreach. The Globe of Science and Innovation hosted 23 public events for about 7200 attendees from the local area, including several hundred students. CERN researchers and staff also took part in several events off site, visiting local schools for the International Day of Women and Girls in Science. In a new collaboration with EPFL and the University of Geneva, 3000 students from 145 classes had the opportunity to hear from 60 women about their jobs in science and research.



In the Globe of Science and Innovation, some of the 1000 primary-school students who took part in the *Dans la peau de scientifiques* programme in 2019 presented their research through talks, theatre and posters, engaging with CERN scientists who answered their questions.



The international exhibition 'Quantica / Broken Symmetries' showcased artworks by former artists in residence at CERN. Co-produced by FACT, it was shown in Liverpool, UK, to more than 16 000 visitors before travelling to the Centre de Cultura Contemporània de Barcelona, Spain, where it attracted over 80 000 visitors. (OPEN-PHO-MISC-2019-002-30)

The festival programme continues to reach new audiences across Europe. Science Pavilions, co-produced by CERN and collaborating institutes, were present at the Roskilde Festival (Denmark), the Pohoda Festival (Slovakia), the Melting Pot at Ostrava (Czech Republic) and WOMAD (UK), reaching an estimated 20 000 people.

WORLDWIDE MEDIA INTEREST

Media interest in CERN remained high in 2019, with more than 156 000 press articles throughout the year, across the globe. The 30th anniversary of the Web (see p. 30) generated the greatest interest, with 5650 articles on 12 and 13 March. Media visits are a crucial way of sustaining interest in and knowledge about CERN. Throughout the year, 554 media visits were organised, for over 1100 journalists. A highlight was the CERN field trips organised as part of the World Conference for Science Journalists, which welcomed 114 journalists from around the world.

**CERN IS A MUCH-FAVOURED VISITOR
DESTINATION, WITH MORE THAN
150 000 VISITORS FROM 95 COUNTRIES
COMING FOR GUIDED TOURS IN 2019.**



A series of three pavilions and two tubes, connected by a bridge and surrounded by a forest, will house exhibitions, laboratories for informal learning and a 900-seat auditorium. (CERN-PHOTO-201904-083-23)

CERN SCIENCE GATEWAY - A NEW HUB FOR EDUCATION AND PUBLIC ENGAGEMENT

The CERN Science Gateway project was officially unveiled on 8 April, revealing to the world plans for the series of iconic buildings designed by Italian architect Renzo Piano that will house CERN’s new education and outreach centre.

Throughout the year, the architectural plans for the building were further developed, administrative procedures for land and building permits put in place and fundraising efforts sustained. The project will be fully funded through external donations, with the leading contribution coming from the FCA Foundation, a charitable foundation created by Fiat Chrysler Automobiles.

In parallel, development of the content for the Science Gateway’s exhibitions, laboratories and public spaces progressed steadily, guided by input from the international advisory board comprised of science centre directors and education experts. The tender process for the exhibition design and build was launched in December.

EXPANDING CERN’S DIGITAL PRESENCE

With more than nine million visits to the CERN home website in 2019, CERN’s digital presence remained strong. Working with ten social-media influencers to talk about CERN to “hard-to-reach audiences” led to millions of engagements and views on social media.

CERN partnered with Google Arts and Culture for the “Once upon a try” project and developed the Big Bang AR app. Through augmented or mixed reality, the app creates an immersive adventure making it possible to experience the 13.8-billion-year-old story of the universe in just seven minutes.

For the CERN Courier magazine, life began at 60 with its anniversary year seeing a wealth of changes from a magazine redesign with four dedicated anniversary supplements to a move to an online-first publishing model with a new website and social-media presence.

MAXIMISING THE IMPACT OF WHAT WE DO

As CERN reaches ever broader audiences with its communication and education activities, the Laboratory seeks evaluations that go beyond head-counting. Drawing on expertise in social research methodologies, the results inform the planning and prioritisation of future communication activities. Several evaluations were carried out in 2019.

For the Open Days, surveys before and after the event gauged expectations, take-away messages and impressions. About 10% of visitors and 50% of volunteers responded to at least one survey, generating a large and rich data set. The analysis results will be published in 2020.

For the Science Gateway exhibitions, a study involving local primary schools identified potential practical and conceptual barriers to visiting CERN and the Science Gateway, as well as expectations for exhibitions.

For S’Cool LAB, more than 500 high-school students from 15 different countries took part in a quantitative study to assess the educational effectiveness of hands-on sessions. The results confirmed that S’Cool LAB significantly fosters students’ interest in physics, with students appreciating the well-structured learning activities and the support from volunteer CERN scientists.

For CERN’s teacher programmes, a Delphi study involving more than 100 experts from various stakeholder groups assessed goals, objectives and design features. A second study is now being developed to investigate how teachers’ conceptual knowledge changes through participation in these programmes.

EMPOWERING TEACHERS AND STUDENTS

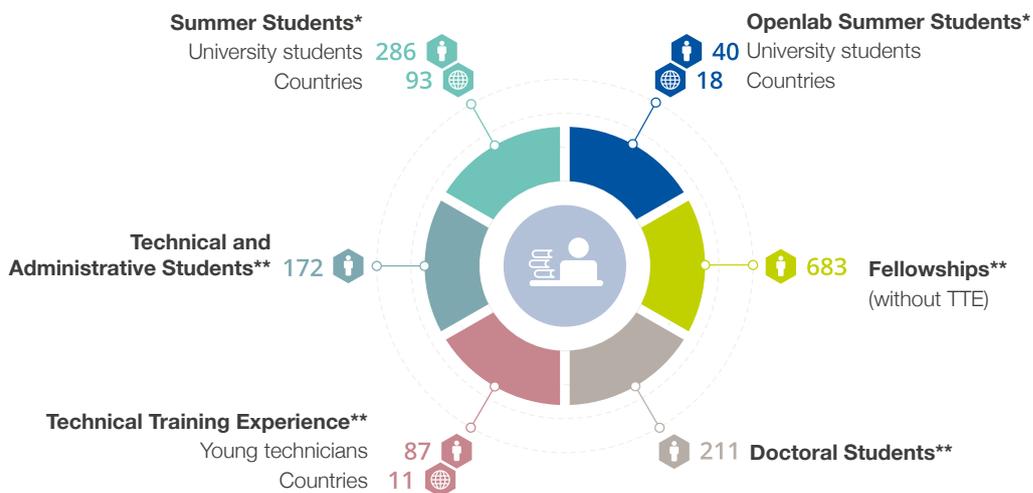
In 2019, 904 teachers from 63 countries participated in 29 national and two international programmes. Each teacher is an ambassador for CERN, taking back inspiring ideas to pass on to students and other teachers. Several thousand students had the opportunity to experience first-hand the cutting-edge research at CERN. Six editions of the High-School Student Internship Programme (HSSIP) welcomed 144 students from Austria, Finland, Germany (twice), Slovakia and Spain. S’Cool LAB, CERN’s hands-on physics-education laboratory, provided workshops for 7860 participants, of which 6480 were students. Of these, 95% came from CERN’s Member States or Associate Member States.

The Beamline for Schools competition continues to motivate students from around the world to propose experiments to be carried out on a beamline. Due to the long shutdown at CERN, in 2019 the competition was held in at DESY, in Hamburg, Germany. The two winning teams, chosen from 178 entries from 49 countries, were from the Netherlands and the US. Seven countries applied for the first time: Albania, Ecuador, Fiji, Sudan, Syria, Ukraine and Uruguay.

TRAINING YOUNG RESEARCHERS

CERN’s educational activities also encompass the essential aspect of the training of young researchers. The working and learning environment that CERN offers students and post-graduates is rich, providing them with excellent technical skills and international experience, which make them highly qualified for business and industry in CERN’s Member States. In 2019, more than 1800 students and graduates came to CERN, including some 770 fellows and over 380 doctoral, technical and administrative students, 117 trainees, some 300 short-term interns; and 286 summer students from 93 countries.

Training programmes at CERN



* during 2019

** as of 31.12.2019

CERN offers a large range of training opportunities providing excellent technical skills and international experience.

A SUSTAINABLE RESEARCH ENVIRONMENT

CERN strives to ensure the wellbeing of everyone using or visiting its facilities, while minimising its impact on the environment.

NEW ENVIRONMENTAL OBJECTIVES

In 2019, CERN's Environmental Protection Steering board, CEPS, working with all CERN departments, prepared a series of new environmental objectives to be presented to the Laboratory's management in 2020. These include minimising primary energy consumption while producing more physics output, significantly reducing the Laboratory's direct emission of greenhouse gases, improving the quality of effluents released by the Laboratory, reducing the potential environmental impact of hazardous substances

and planting trees to replace older ones that have been felled for safety reasons over recent years. One earlier CEPS recommendation that began to be implemented in 2019 is the construction of a retention basin at the main outlet of the Prévessin site to prevent the accidental release of pollutants and regulate surface runoff during heavy precipitation.

For two key areas of environmental management, dedicated activities were carried out in 2019. A workshop in February focused on greenhouse gases used by CERN experiments for cooling and particle-detection purposes. It identified means of reducing emissions and moving towards more

A view of CERN's Meyrin campus, which includes the East Area hall. Restoration of the outer shell and roof of the hall was completed in 2019, greatly improving the building's energy efficiency. (CERN-PHOTO-202004-057-9)



environmentally friendly gases in the future. Also in 2019, an audit was carried out on the prevention of pollution. CERN has a good track record in this respect over recent years. The audit has allowed the Organization to further improve its performance in this area by identifying potential risks and taking appropriate mitigation measures.

CERN is preparing an environment report for publication in 2020, in which the Organization's environmental performance and targets for improvement will be set out in detail.

ENERGY FOR SUSTAINABLE SCIENCE

November 2019 saw the fifth workshop on Energy for Sustainable Science at Research Infrastructures, which was held at the Paul Scherrer Institute in Villigen, Switzerland. Established in 2011 by CERN, the European Spallation Source in Sweden and the Association of European-Level Research Infrastructures Facilities, these workshops bring delegates from research institutes together with policymakers from around the world to discuss energy sustainability. The presentations from CERN included one on a project for energy-efficient refrigeration for a possible Future Circular Collider (FCC). The project found that a mix of helium and neon makes a more energy-efficient cooling system than one using a conventional helium refrigerant. Over ten years, this could save up to 3 TWh of energy. Another project presented by CERN concerned the use of power-transmission lines based on magnesium diboride to power the High-Luminosity LHC's superconducting magnets (see p. 44). Magnesium diboride is superconducting at 39 K, a higher temperature than any other conventional superconductor, making it interesting from an energy-efficiency perspective, both for accelerator applications and for potential electricity-distribution systems in towns and cities. The workshop concluded with the message that research infrastructures are striving for best practice in energy matters and are contributing to solutions for a sustainable future.

MANAGING WASTE

CERN recycles some 57% of its conventional waste, which is above the average for a large organisation in the Geneva region. Nevertheless, there's room for improvement, and a major campaign was launched in summer 2019 to increase awareness of waste management and to inform every member of the CERN community how they can contribute. The campaign covered all aspects of waste management from how to sort what's left on your tray after lunch, to what to do with the old chair in your office when you get a new one.

CERN's approach is based on the principle of reduce, reuse, recycle. Office furniture, for example, can often find a new home. CERN's restaurants are moving away from single-use plastic towards reusable containers, and all food waste is



Sorting waste at CERN prior to disposal and recycling.
(CERN-PHOTO-201911-375-7)

composted. Waste leaving CERN is sent to sorting plants in Switzerland, where it goes through a second, more thorough sorting process. Each different type of waste is then sent to the appropriate recycling facility. Paper and cardboard are recycled into new paper; used wood can be recycled into chipboard, for example; scrap metal goes to steelworks; and certain types of polystyrene are recycled into insulation panels.

RENOVATING FOR IMPROVED EFFICIENCY

Major renovation of the Proton Synchrotron's East Area, which began in 2018, continued throughout 2019. This work will see one of CERN's oldest installations transformed into a modern experimental area at the cutting edge of technology. Restoration of the outer shell and roof of the East Area hall was completed in 2019, greatly improving the building's energy efficiency and winning the project a major grant from the Canton of Geneva's office for energy.

With the building's envelope complete, a metamorphosis is underway inside. Beamlines are being renewed, and power converters dating from the 1950s are being replaced with new ones designed to supply the magnets on a cyclical basis, with an energy recovery stage between each cycle. Electricity consumption is expected to fall from 11 GWh/year to around 0.6 GWh/year.

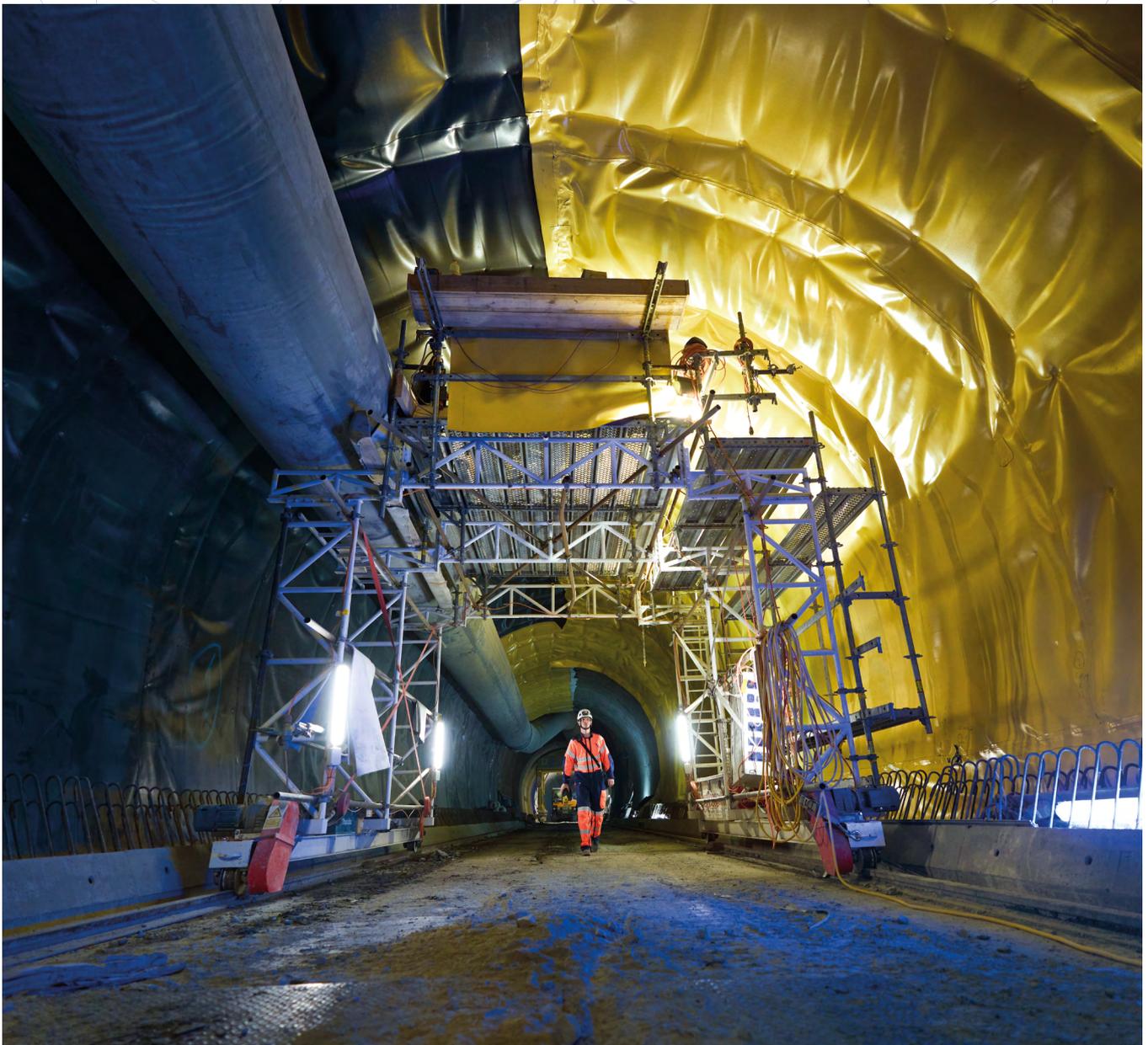
Recommissioning of the East Area is planned for the end of 2020, with physics scheduled to start again in spring 2021. This historic experimental area has served physics for more than six decades and, thanks to modernisation work under way, will continue to do so for many more years to come.

NEW POWER CONVERTERS FOR THE EAST AREA MEAN ELECTRICITY CONSUMPTION IS EXPECTED TO FALL FROM 11 GWh/YEAR TO 0.6 GWh/YEAR.

BUILDING FOR THE FUTURE

Scientists at CERN are devising, designing and building new installations that will enable the particle physics community to further its quest for knowledge. CERN's next flagship project, the High-Luminosity LHC, is now becoming a reality, and long-term projects are also taking shape.

*By the end of 2019, 80–90% of the excavation work for the underground structures of the HL-LHC had been completed.
(CERN-PHOTO-201911-395-1)*





*A prototype superconducting link transported up to 40 000 A.
(CERN-PHOTO-201904-080-7)*

THE HIGH-LUMINOSITY LHC MOVES IN

The High-Luminosity LHC (HL-LHC), which is scheduled to start operation at the end of 2027, is a major upgrade of the LHC. It will be able to reach luminosities five times higher than the LHC, or, in other words, produce a considerably higher number of collisions in the ATLAS and CMS experiments. To achieve this, innovative equipment is being installed along 1.2 km of the current accelerator and new buildings and underground structures are being built to house other new equipment.

The civil-engineering work at Points 1 and 5 of the LHC progressed significantly. 80–90% of the excavation work on the two sites has been completed: after having dug the two new shafts, the service caverns and almost all of the two 300-m service tunnels, the companies started to work on the 50-m tunnels that will connect the new structures to the LHC tunnel. In December, the first connection between the LHC tunnel and the new tunnels of its successor was made. Construction of the surface buildings also began.

Thanks to Long Shutdown 2, the first components of the HL-LHC were installed in the tunnel. By August, the first definitive components, two absorbers located either side of the LHCb experiment to protect the accelerator equipment from the particles coming from the detector, had been installed.

Due to the increase in luminosity, and also because of the increase of the number of particles circulating in the machine, 58 new collimators will be installed to protect the accelerator from particles that stray from the beam trajectory or burst out of the experiments. The first two low-impedance collimators were delivered in November: their jaws contain molybdenum graphite, which reduces electromagnetic interference. The first TCLD (Target Collimator Long Dispersion suppressor) collimator was also manufactured and qualified at CERN. The TCLD collimators will be installed on either side of Points 2 and 7 of the accelerator in bypass cryostats, which were also finalised.

These innovative components allow a collimator operating at room temperature to be inserted into a cold area of the LHC at 1.9 K. One of the two internal beam dumps, intended to stop particles in the event of a fault during injection, was manufactured ready for installation in 2020. The manufacture of the second of these also began.

The increased performance of the HL-LHC will rely to a great extent on about 100 new magnets of 11 different types. Among these, more powerful dipole and quadrupole magnets are being manufactured from the superconducting compound niobium-tin, which will allow them to reach higher magnetic fields than the current niobium-titanium magnets in the LHC. After having developed and tested several short models, teams at CERN and in the United States (at the Fermi, Berkeley and Brookhaven national laboratories) manufactured the first full-size prototypes of the quadrupoles (4.2 and 7.2 m) and dipoles (5.5 m). A 4.2-m quadrupole produced in the US was tested and qualified for installation in the machine.



One of the two beam absorbers installed on either side of the LHCb experiment. They are the first definitive components of the HL-LHC to be installed. (CERN-PHOTO-201908-223-4)



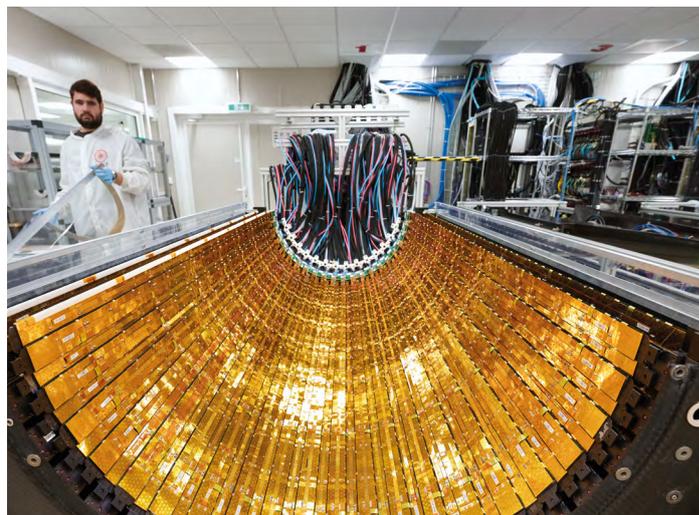
Two of the new dipole magnets using the niobium-tin superconductor, on their test benches at CERN; one of them successfully passed qualification tests in 2019. (CERN-PHOTO-202002-038-6)

At CERN, a 7.2 m quadrupole and three 11 T dipoles were manufactured. One of the dipoles was qualified for installation in the machine.

Other superconducting magnets will be installed on either side of the ATLAS and CMS experiments. The construction of the superconducting separation-and-recombination-magnet prototypes began at KEK in Japan and at INFN in Italy, where a small quadrupole of a new (superferric) design was also developed. A prototype superconducting corrector magnet with a complex nested-coil architecture was successfully manufactured at CIEMAT in Spain and tested at CERN.

Innovative superconducting power lines will connect the power converters to the new magnets. They will be made out of magnesium diboride, a superconductor with a considerably higher temperature than standard superconductors, and cooled to below 25 K in order to transport currents of over 120 000 A. A 60-metre-long partial prototype connection equipped with an innovative flexible cryostat transported up to 40 000 A at the start of 2019. A second full-size prototype, made up of seven cables to carry up to 120 000 A, was completed in December.

After the successful tests of a crab cavity in a test area of the SPS, a prototype using a different architecture (a so-called radiofrequency dipole) was manufactured for insertion into a cryostat and testing during the next run.



Assembly of ALICE's new inner tracker, which comprises 12.5 billion pixels. (CERN-PHOTO-201909-259-2)

THE EXPERIMENTS HEAD FOR HIGH LUMINOSITY

To enable them to select and record the wealth of data that will be collected during the high-luminosity era, the LHC experiments have launched major upgrade programmes during Long Shutdown 2.

ALICE

ALICE is preparing to collect one hundred times more data during Run 3 than it has done to date, with a collision rate of 50 kHz, compared to 8 kHz during Run 2. An ambitious upgrade programme is under way on the detector and the data-taking and data-processing systems. While the inner tracker was being removed from the underground hall, its successor, comprising 12.5 billion pixels, was being assembled on the surface. Its commissioning also began in 2019.

The time-projection chamber has been brought to the surface, where its wire chambers and electronics cards have been replaced with gas electron multipliers (GEMs) and completely new electronics that are much faster and more precise. The infrastructure for these new detectors (cable, optical fibre and cooling networks) has been installed in the cavern. Several other detectors have also been upgraded or renovated, namely the transition radiation detector (TRD), time-of-flight (ToF) detectors, muon detectors and photon spectrometer.

A new data centre has been built on the surface to host the integrated Online-Offline (O2) system. This system, which combines all the computing functions required by the experiment – data read-out, event reconstruction, data collection, detector calibration, data reconstruction and physics simulation and analysis – will host up to 750 servers.

ATLAS

Major upgrade work is being carried out on the read-out electronics of the liquid-argon calorimeter in order to increase the level of segmentation for the level-1 trigger system. Major maintenance projects have also begun on the hadron calorimeter, the transition radiation tracker (TRT) and the resistive plate chambers (RPCs), including leak repairs.

To improve muon identification, new “small” muon wheels, made up of sixteen sectors with two types of chamber, are being developed. The first sector was installed in 2019 and the installation of the second was started.

The trigger and data acquisition (TDAQ) system is being considerably improved: the installation of a new optical-fibre network, new switches and new routers has begun. Production is underway on the FELIX (Front-End Link eXchange) system, which will provide the interface between the front-end electronics of the detectors, the trigger system, the acquisition system and the LHC’s “clock”. It is designed to simplify the read-out architecture and will be used by some of the subdetectors during Run 3, before being fully deployed in Run 4.

Many of the subdetectors will be replaced or upgraded during Long Shutdown 3. The R&D on the 3D pixels of the future inner tracker was completed in 2019. Following the approval of the technical design reports, the prototyping and module-0 construction phase began for several subdetectors.

CMS

The pixel detector at the heart of the CMS experiment and the beam pipe were removed at the start of the year as the innermost layer of this tracker will be replaced during the long shutdown. The new components, which are being manufactured and assembled, are composed of material that can better withstand the radiation that will result from operation at high luminosity. The beam pipe will also be replaced with a smaller-diameter pipe compatible with the shape of CMS’s future pixel detector, which will be installed during LS3.

The first phase of the upgrade of the hadronic calorimeter was completed. A key aspect of this upgrade was the replacement of the hybrid photodetectors in the barrel with new more powerful silicon photomultipliers. Between July and October, 72 of the 144 new muon detection modules, known as gas electron multipliers (GEM), were installed on one of the endcaps on the outside of the detector. The upgrade of CMS’s data-acquisition system to make it ready for Run 3 is in progress; the system is due to be commissioned in 2020. R&D work and prototype manufacturing for the second phase of the upgrades have advanced significantly, with excellent progress achieved on the MIP (Minimum Ionising Particles) timing detector, the high-granularity calorimeter (HGCal) and the new tracker.

Part of the work on the infrastructure of the experimental cavern in preparation for second phase has been completed and further work will follow in 2020.

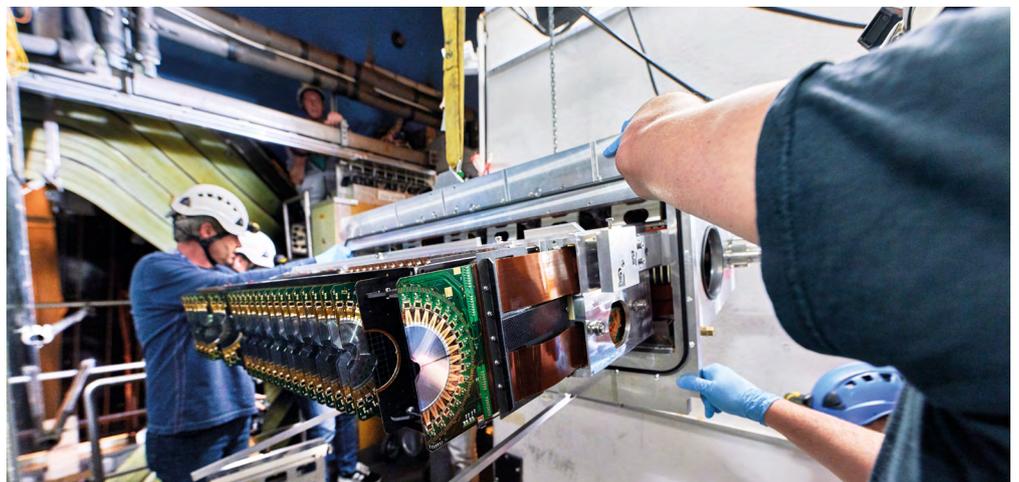
LHCb

During the long shutdown, the LHCb detector is being almost completely rebuilt to enable it to record events at a rate ten times higher than previously. The work includes the installation of new subdetectors, which are currently being constructed.

As well as replacing almost all the electronic and data-acquisition systems to cope with the increased data production, LHCb is replacing its trackers with new devices. The tracker closest to the collision point, the VELO (vertex locator) detector, was removed at the start of the year and its successor is being assembled, along with the SciFi (scintillating fibre) tracker.

The construction of LHCb’s new data centre was completed in the spring. Six new computing modules, with a total power of 2 MW, have been installed on the experiment’s site (see p. 31).

The VELO detector, the tracker closest to the collision point, at the heart of LHCb, was removed at the start of 2019. (CERN-PHOTO-201902-043-22)



A ROADMAP FOR PARTICLE PHYSICS IN EUROPE

Several important stages of the update of the European Strategy for Particle Physics were completed in 2019. The aim of the update is to determine the long-term direction of the discipline in Europe.

In May 2019, a symposium held in Granada in Spain brought together almost 600 members of the community to discuss 160 submissions on possible future projects and experiments. These submissions had been received by the

European Strategy Group in December 2018 from universities, laboratories, national institutes, collaborations and individual scientists. CERN and its partner institutes contributed several major submissions, notably on projects for new colliders (FCC and CLIC) and experiments using CERN's existing facilities in the framework of the Physics Beyond Colliders programme.

Following the symposium, the submissions, discussions and analyses were summarised in a 250-page briefing book. This book, which was published in October,

contains a summary of the 160 submissions, a full overview of the discipline from theoretical and experimental perspectives, and details of the prospects for the future. It emphasises the role of R&D on detectors, accelerators, computing and instrumentation, and the importance of energy efficiency.

This full analysis will be used by the representatives of the community who will be invited to draft recommendations for the future of particle physics in January 2020.

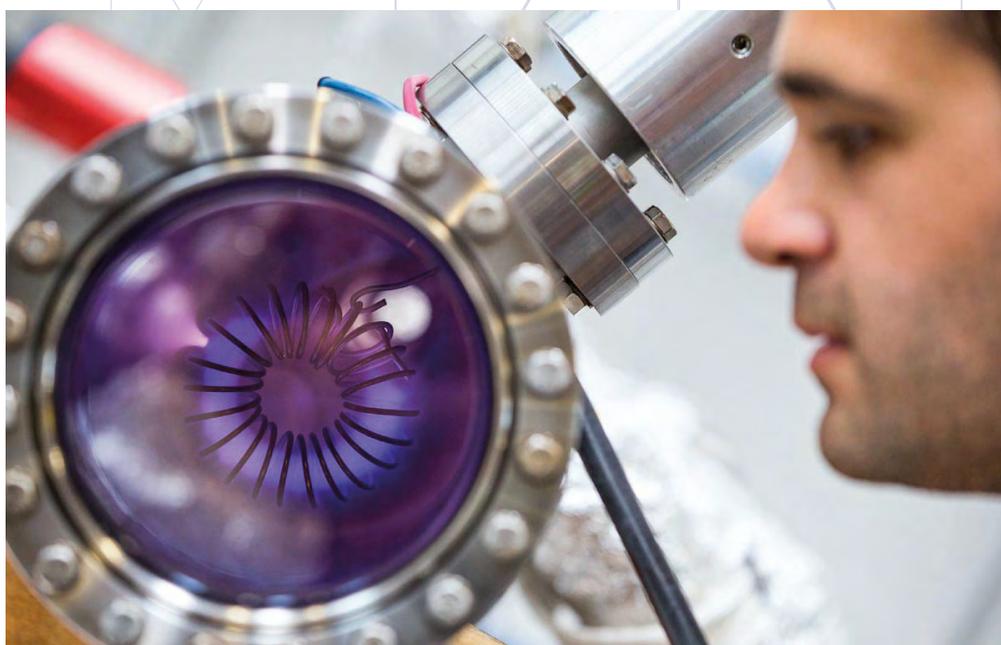
THE FUTURE CIRCULAR COLLIDER (FCC) STUDY

The Future Circular Collider (FCC) study concerns a major new piece of infrastructure, a tunnel with a circumference of around 100 km that could house a lepton collider (FCC-ee), a 100 TeV hadron collider (FCC-hh) or both, the latter succeeding the former. A lepton-hadron option is also being considered, as well as a high-energy version of the LHC in the existing tunnel. By the end of 2019, 139 institutes in 34 countries had joined the FCC collaboration.

Following the publication of the Conceptual Design Report, which was submitted as input for the update of the European Strategy, work on the location, integration and architecture of the different machines and the components required for their operation continued in 2019. In particular, a study carried out in collaboration with the French and Swiss authorities focused on the optimum locations for the surface sites. Studies of the socio-economic impact of the electron-positron machine were launched. A more detailed

financial study was carried out in order to develop a strategy for financing the project. Physics studies, involving input from many theoretical and experimental physicists, focused on the full exploration of an integrated FCC programme, maximising the synergies between the FCC-ee and FCC-hh colliders.

The construction of such colliders requires major innovations in the fields of superconducting radiofrequency cavities, cryogenics, superconducting magnets and vacuum systems for the beams. Research on the RF cavities focused on new manufacturing techniques, new materials and new RF sources. Tests were carried out at CERN and at INFN in Italy for the design of high-performance seamless copper cavities. CERN tested the use of electroforming: the electrolytic deposition of pure copper on an aluminium mandrel, in the manufacturing process. Studies of techniques for coating such cavities with pure niobium,



The FCC study is developing techniques for the manufacture of better-performing radiofrequency cavities, notably innovative techniques for coating with pure niobium.



*A scientist from the CLIC project studies silicon sensors for the new CMS calorimeter project.
(CERN-PHOTO-201910-361-54)*

using HiPIMS (High Power Impulse Magnetron Sputtering) technology, are also in progress. An industrial prototype of a more efficient 400 MHz klystron has been designed and could be tested in the HL-LHC.

Research is continuing on magnets generating 16 T magnetic fields, which are twice as intense as those of the current magnets in the LHC. This programme is based on niobium-tin superconductors, building on the progress made for the HL-LHC. Highly promising results on niobium-tin wires were obtained in the United States by teams at the Applied Superconductivity Center of the University of Florida and at Fermilab and the University of Ohio. The two teams focused on niobium-tin wires that would allow magnetic fields greater than 16 T to be achieved, as required for the FCC-hh.

In parallel, the high-field-magnet programme produced some encouraging results. The H2020 DS EuroCirCol project was completed, resulting in four proposals for magnet architecture and the assembly of a cos-theta-type magnet. Manufactured as part of the Magnet Development Program (MDP) in the United States, this magnet was successfully tested at 14.1 T at Fermilab. Development work also continued at the other collaborating institutes, with design work carried out at CEA (France), INFN (Italy) and CIEMAT (Spain) and manufacturing done at CERN and PSI (Switzerland).

As part of the EuroCirCol programme, prototype vacuum chambers with beam screens have been manufactured for the superconducting magnets of the FCC-hh. They were tested under real-life conditions, under synchrotron rays, using the synchrotron source at the Karlsruhe Institute of Technology (Germany).

The work on the FCC is supported by EuroCirCol and Marie-Curie EASITrain, which are both Horizon 2020 programmes of the European Union.

THE COMPACT LINEAR COLLIDER (CLIC) STUDY

The CLIC project concerns the construction of a linear electron-positron collider in three stages, from 380 GeV to 3 TeV. This future collider project is based on an innovative two-beam acceleration concept, which could produce acceleration fields of up to 100 MV/m, allowing the size and cost of the project to be kept under control.

The collaboration, comprising 75 institutes worldwide, finalised its implementation plan and the documents required for the update of the European Strategy for Particle Physics. Studies on performance and luminosity continued, with additional work carried out on an operating mode that focuses on the production of Z bosons at high luminosity and on the possible production of gamma-gamma collisions.

Work common to both the CLIC and the ILC (International Linear Collider) projects continued, and further tests took place at the ATF2 facility at KEK (Japan).

X-band radiofrequency accelerating structures are a key component of CLIC's two-beam acceleration system. These accelerating structures were tested in 2019 at CERN's cutting-edge Xbox facility, which can also be used by groups of users from other laboratories under the transnational access plan of the European project ARIES.

Work on the high-efficiency klystrons and RF energy sources advanced further in 2019 with the development of the design and the simulation code, specific implementation studies and knowledge transfer to leading companies in the field. CLIC is a project that encourages knowledge transfer: a growing number of the collaboration's partners have been able to acquire expertise in the development, testing and use of X-band accelerating structures, thanks in particular to the European CompactLight study, which aims to develop a new generation of free-electron lasers (FEL) that are smaller

and more energy efficient. The study, which comprises 24 institutes and industrial partners, has established baseline parameters for X-band linac modules for particle physics projects and beyond.

The CLEAR facility, which is used to test equipment with electron beams, had a very fruitful year, supplying 38 weeks of electron beams to the users.

On the detector side, work continued on the monolithic and hybrid silicon sensors for the vertex and tracking detectors. The teams developed an ultra-fast monolithic silicon sensor. The calorimeter technologies intended for a future experiment at CLIC are similar to those adopted for the new CMS high-granularity calorimeter, which is under development for the High-Luminosity LHC. As a result, members of the CLIC project are contributing know-how to the CMS calorimeter project on the characterisation of silicon sensors and the approach to testing them with beam. In 2019, CLIC also actively participated in comparative physics studies involving all the future collider options as part of the update of the European Strategy for Particle Physics.

PHYSICS BEYOND COLLIDERS

The Physics Beyond Colliders programme is studying new opportunities at CERN's accelerator complex and its other facilities for experiments complementary to those carried out using high-energy colliders. These facilities could be used for many searches for physics beyond the Standard Model, for searches for dark-matter particles or for precision quantum chromodynamic measurements. The

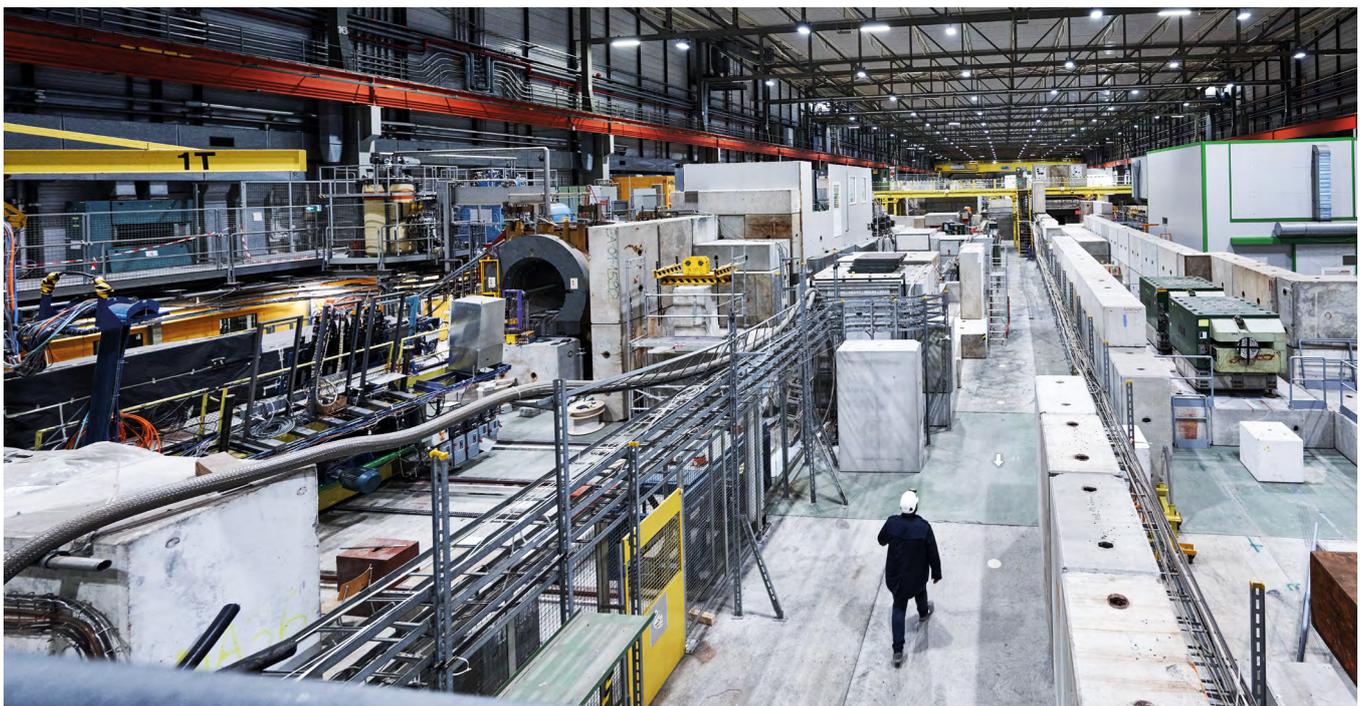
advantage of this programme is its inclusion of theoretical studies and its identification of key CERN technologies that could benefit the projects, allowing possible synergies between the proposals to be explored. On the theory side, the BSM (Beyond the Standard Model) and QCD (Quantum Chromodynamics) groups have produced reference analyses that compare the physics potential of CERN's infrastructure with that of other facilities around the world.

The programme comprises around 20 proposals that were submitted as input for the update of the European Strategy for Particle Physics. Some of these are focused on the North Area, which receives beams from the Super Proton Synchrotron (SPS). Studies of experiments in the North Area that could carry out precision searches on dark matter and on quantum chromodynamics were pursued. In particular, work on providing the NA64, COMPASS and MuonE experiments with a muon beam during Run 3 progressed well.

A flagship project in the North Area is the BDF (Beam Dump Facility), a high-intensity fixed target that would primarily produce charm hadrons for research into dark matter and the hidden sector. The BDF would supply experiments tracking hypothetical very-weakly-interacting particles, the first of these being SHiP (Search for Hidden Particles), which was the impetus for the project. After three years of studies and tests, the BDF collaboration published a comprehensive design study.

Two other projects are studying the use of the SPS. The design study for the eSPS facility, which would supply a dark-matter experiment with an electron beam, continued. The feasibility study for nuSTORM, a muon storage ring producing a neutrino beam, was being finalised in 2019.

The Physics Beyond Colliders programme includes many potential experiments located in the North Area, using the beam lines of the Super Proton Synchrotron (SPS). (CERN-PHOTO-202001-006-9)



Several collaborations are studying fixed-target experiments at the LHC. LHCb developed a gas-storage cell that will be installed at the heart of the detector to produce collisions between protons from the LHC and gas molecules. Experiments on this technique were carried out during previous runs and it will be deployed fully in Run 3. Gas targets pave the way for studies on quantum chromodynamics and the structure of hadrons. The study on the use of crystals to bend proton beams also progressed. This opens up the possibility of measuring the electrical and magnetic moments of short-lived baryons.

The gamma factory project aims to use beams from the LHC to produce high-intensity gamma rays coming from the excitation of partially ionised atoms. After a successful test of the acceleration of partially ionised lead atoms in 2018, the project collaboration submitted a letter of intent

for a proof of principle test at the SPS. The Physics Beyond Colliders programme also supported the FASER experiment, which was approved by the CERN Research Board in December. Located 480 m downstream of the ATLAS interaction point, FASER aims to identify long-lived exotic particles and dark-matter particles. Work began to install the experiment during Long Shutdown 2.

Finally, the EDM collaboration, which aims to precisely study the electric dipole moment of the proton and the deuteron to find flaws in the Standard Model, published a feasibility study.



*The AWAKE collaboration is carrying out tests on a helicon plasma cell with a view to generating wakefields over greater distances.
(CERN-PHOTO-201910-349-1)*

AWAKE, THE WAKEFIELD ACCELERATION PROJECT

The AWAKE (Advanced Wakefield Experiment) project is studying the use of protons to create wakefields in order to accelerate electrons. A proton beam is sent through a plasma cell, generating waves (wakefields), and an electron beam is then injected. Just like surfers on ocean waves, the electrons are accelerated by the wakefield. This technology makes it possible to reach acceleration gradients hundreds of times higher than those that can be achieved with traditional radiofrequency cavities.

In 2018, using a proton beam from the SPS, AWAKE managed to accelerate electrons with an average gradient of 200 MeV/metre. In 2019, the

collaboration analysed this first run and began preparing for a second, which is due to take place after the long shutdown. Work was carried out to improve the electron beam through studies and simulations of the beam diagnostics and the electron source. Machine-learning techniques were also used.

AWAKE's ten-metre-long plasma cell contains gaseous rubidium, which transforms into plasma when laser pulses are passed through it. Measurements of the propagation of the laser in the gaseous rubidium were carried out.

The collaboration, made up of 23 institutions from around the world, also defined the programme for its second run, the aim of which will

be to accelerate electrons to higher energies while preserving the quality of the beam. AWAKE also intends to demonstrate that it is possible to use the technique on a larger scale. Tests were therefore carried out on a prototype helicon plasma cell, which, in the longer term, will allow acceleration over longer distances.

Proposals for applications of wakefield acceleration, for example for fixed-target experiments, were submitted as input for the update of the European Strategy for Particle Physics.

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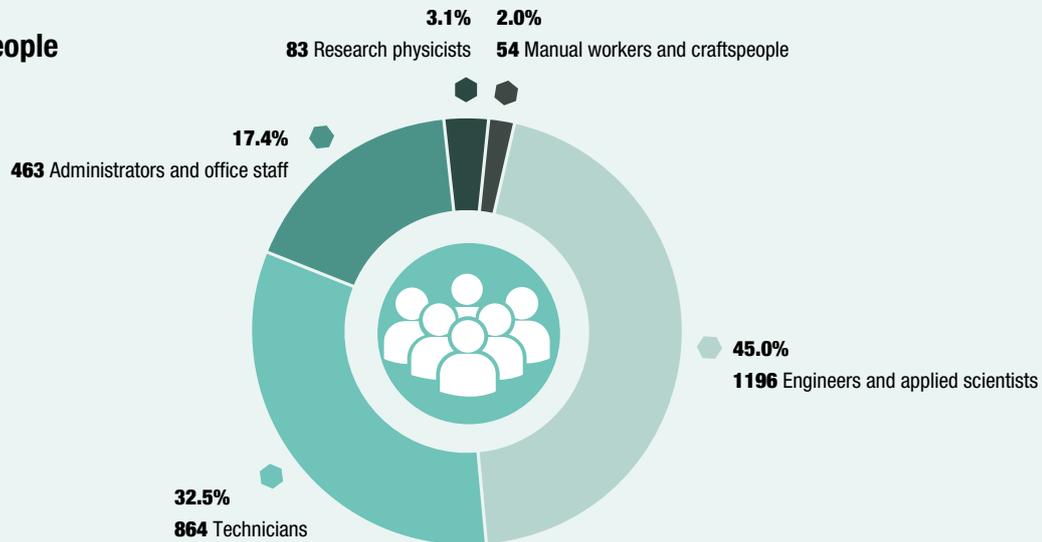
Advanced Wakefield Experiment (AWAKE)
CERN Neutrino Platform
Extra Low Energy Antiproton (ELENA)
Future Circular Collider study (FCC)
High-Luminosity LHC (HL-LHC)
LHC Injectors Upgrade (LIU)
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CERN STAFF

Total: 2660 people



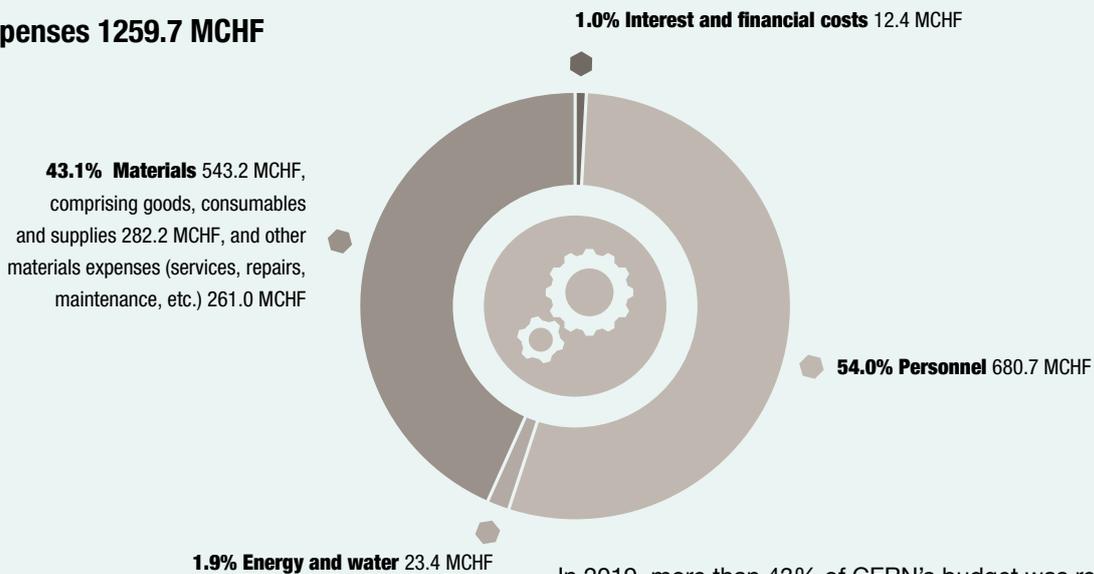
EVOLUTION OF STAFF NUMBERS

2015	2531
2016	2560
2017	2633
2018	2667
2019	2660

In addition to staff members, CERN employed 770 fellows (including TTE technicians), trained 520 students and apprentices, and hosted 1285 associates in 2019. CERN's infrastructure and services are used by a large scientific community of 12 427 users (see p. 12).

CERN EXPENSES

Total expenses 1259.7 MCHF



In 2019, more than 43% of CERN's budget was returned to industry through the procurement of supplies and services. CERN strives to ensure a balanced industrial return for its Member States (see p. 34).

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Sixty-fifth Annual Report of the European Organization for Nuclear Research
CERN's Annual Report aims to present the highlights and the main activities of the Laboratory.
For the electronic version, see: <https://library.cern/annual-reports>

In addition to this report, an annual progress report details the achievements and expenses by activity with respect to the objectives agreed by the CERN Council. This report is available at: <http://cern.ch/go/annual-progress-report-2019>

The biennial Environment Report 2017–2018 is available at:
https://e-publishing.cern.ch/index.php/CERN_Environment_Report

The 2019 Knowledge Transfer annual report is available at:
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The 2019 CERN openlab annual report is available at:
<https://openlab.cern/resources/annual-reports>

The 2019 CERN & Society annual report is available at:
<https://cern.ch/go/cernandsociety2019>

CERN's list of publications, a catalogue of all known publications on research carried out at CERN during the year, is available at: <https://library.cern/annual/list-cern-publications-2019>
A glossary of useful terms is available at: <https://cern.ch/go/glossary>

Images:

Antonino Panté: p. 6
ATTRACT: p. 8 (left) and p. 35 (right)
ProtoDUNE: p. 10 (top right)
ESA: p. 11 (bottom left)
Zenuity: p. 33
ARIES: p. 35 (left)
Lois Lammerhuber: p. 46
CERN: all other images

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