Annual Report
2021

CERN

CONTENTS

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.

MESSAGE FROM THE PRESIDENT OF THE COUNCIL

Despite all our hopes, COVID-19 remained with us throughout 2021. The Council's meetings were again held online, or in hybrid format at best, and we all missed the inspiration and lively exchanges that in-person meetings bring. Yet, compared to the pain and sorrow this pandemic has brought to many, as well as the consequences for economies around the world, our experience is just a minor inconvenience. Now, everywhere, the hope that the Omicron variant might herald the final wave is tangible.

At CERN, we can be collectively proud of everything that was achieved despite the difficult circumstances. The long shutdown allowed major work towards the High-Luminosity phase of the LHC (HL-LHC), as well as further improvements to the detectors, to be accomplished. Excitement about the resumption of data taking is in the air and we all look forward to new measurements to come.

The community's main focus over the coming years will be the successful completion of the HL-LHC upgrades. The stakes are high and the challenges numerous: new technologies have to be tested and implemented, procurement of high-tech components has become far from simple, and ambitious detector upgrades are being pursued by the collaborations in parallel with data taking and analysis. Yet, success is crucial if we are to dream of more ambitious projects for the post-LHC era.

Preparing for future projects beyond the LHC is essential for a field whose large research infrastructures can take decades to prepare. The Council therefore approved the organisational structure for the Future Circular Collider Feasibility Study in June, and expressed strong support for the accelerator and detector R&D roadmaps presented in December. These roadmaps, coordinated and prepared by the European Laboratory Directors Group and the European Committee for Future Accelerators, represent the fruit of a major effort across the field, and give a comprehensive overview of ongoing developments in European laboratories. As a next step, they must be prioritised and implemented.

This last year brought the most recent five-yearly review of the financial and social conditions of CERN personnel to a conclusion, and I would like to thank all those involved. Continuous and respectful dialogue will be required going forward to ensure that CERN remains an attractive place to work. Meanwhile, the Council will be preparing the terms for the next five-yearly review over the months to come.

In 2021, we welcomed Estonia as an Associate Member State in the pre-stage to Membership and Latvia as an Associate Member State, laying the foundation for a new research dynamic in high-energy physics and related technology developments in the Baltic states.

Finally, 2021 was my last year as President of the Council. I am profoundly grateful for the opportunity to lead such an important body and to learn so much about the unique Organization it governs. My best wishes go to Professor Eliezer Rabinovici for his upcoming mandate. I would like to thank the Council for the trust it placed in me over the last three years and the Director-General, Fabiola Gianotti, for her confidence. The President's Group provided me with extremely valuable support and I owe my thanks to all those involved. My gratitude also goes to the holders of Council offices, whose engagement is essential for the successful governance of the Organization. Particular thanks are due to the Council Secretariat, the Translation and Minutes service and the Legal Service for their unfailing and friendly support over the years. A piece of my heart will stay with CERN!

Ursula Bassler

MESSAGE FROM THE DIRECTOR-GENERAL

One of the highlights of 2021 at CERN was the restart of the injectors after Long Shutdown 2 (LS2). Following two years of major upgrades in preparation for the High-Luminosity LHC (HL-LHC) era, the injectors progressively burst back into life, providing physics beams to ISOLDE, n_TOF, the new ELENA ring at the Antiproton Decelerator (AD), the fixed-target experiments in the North Area and other experimental areas. In October, a pilot run was held at the LHC, with beams colliding at the injection energy of 450 GeV. This run was an invaluable test for the LHC and the experiments. The latter carried out major upgrades during LS2 in preparation for Run 3, which will get under way in 2022. Following the training of the LHC magnets during 2021, the operating energy for Run 3 has been set at 13.6 TeV, up from the 13.0 TeV of Run 2. Good progress was also made by the HL-LHC project and the upgrades of ATLAS and CMS for the HL-LHC era.

The year also saw the publication of many beautiful physics results from the LHC experiments and beyond. A highlight came from the NA62 experiment, which published a measurement of the very rare decay of a positive kaon to a positive pion and two neutrinos. With more data, this theoretically very clean channel may become highly sensitive to new physics. This is a good example of the complementarity between the LHC and the fixed-target programme, where searches and precision measurements offer strong potential to unlock new physics.

Much progress was also made on priorities identified in the 2020 update of the European Strategy for Particle Physics. The organisational structure of the Future Circular Collider (FCC) Feasibility Study was approved by the Council, the preferred baseline placement of the FCC ring was identified, and deliverables and milestones were mapped out to the end of the Study in 2025. In parallel, the European particle physics community, under the guidance of the European Committee for Future Accelerators and the European Laboratory Directors Group, developed detector and accelerator R&D roadmaps. These were completed in December, paving the way for the new technologies necessary for the future of the field, whatever form tomorrow's facilities and experiments may take.

In other developments, the Council unanimously approved the CERN Medium-Term Plan for 2022–2026, as well as CERN's objectives for the period 2021–2025 and the five-yearly review of the financial and social conditions of members of the personnel. The Organization's second Environment Report, covering the years 2019 and 2020, was published, and a campaign to raise awareness of environmental issues was launched among the CERN community. Our second Environment Report discusses Scope 3 greenhouse gas emissions for the first time, along with progress on actions identified in the first report. The construction of the Science Gateway building began in earnest, as did work towards the exciting and innovative education and outreach programmes it will host from 2023 onwards.

2021 was another year affected by COVID-19, and I'd like to thank the entire CERN community for its patience and for having adapted to the health measures introduced, which was crucial to achieving our goals for the year. I would also like to thank our Member and Associate Member States for their continued unwavering support.

I would also like to thank Ursula Bassler, as she steps down as President of the Council, for her excellent, dedicated work over the last three years, and for many fruitful and pleasant exchanges.

Fabiola Gianotti

2021 IN PICTURES

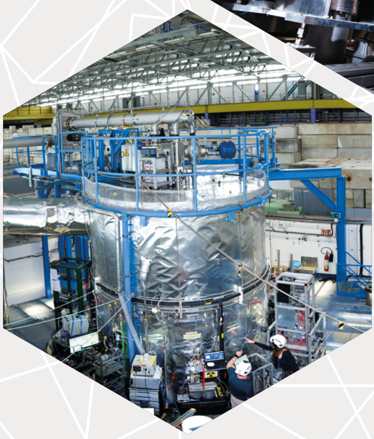
With Run 3 of the LHC around the corner, it has been a year of milestones at CERN! The accelerators saw their first beams circulating, and the experiments underwent significant transformations to boost their detection potential. Enjoy a visual journey through some key moments of 2021.

26 JANUARY

The BASE experiment sets new limits on how easily axion-like particles can turn into photons, opening up new possibilities in the search for cold dark matter.
(CERN-PHOTO-202101-011-5)

31 JANUARY

Following major renovation work, the East Area – one of the Laboratory's oldest experimental areas – unveils its more environmentally friendly beamlines.
(CERN-PHOTO-202101-009-1)



5 FEBRUARY

The CLOUD experiment reveals the role of iodic acid in the formation of atmospheric aerosols, which suggests the existence of a new mechanism that could accelerate the loss of Arctic sea ice.
(CERN-HOMEWEB-PHO-2021-021)

16 FEBRUARY

Arts at CERN awards the 2021 Collide artistic residency – split between CERN in Geneva and the city of Barcelona – to the Black Quantum Futurism collective.

4 MARCH

The Proton Synchrotron accelerates its first beam following a comprehensive two-year overhaul.

(CERN-PHOTO-202007-095)

5 MARCH

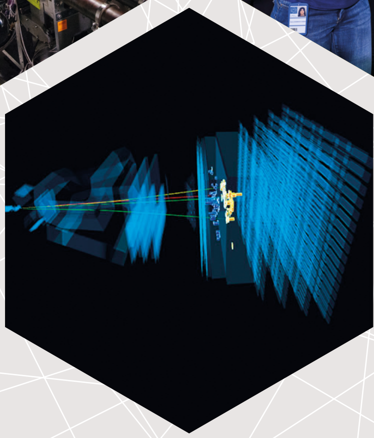
The TOTEM (CERN) and DØ (Fermilab) collaborations announce the discovery of the odderon – a three-gluon state.

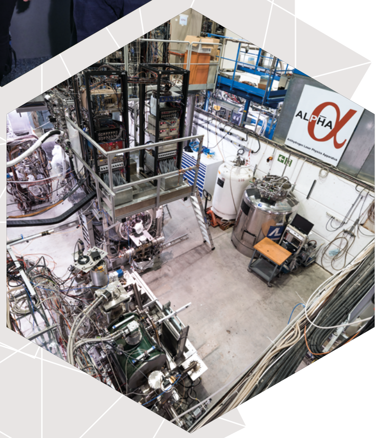
(CERN-PHOTO-201609-210-4)

15 MARCH

After more than two years in the hands of the LS2 teams, the key to the LHC is given back to the Operations group.

(CERN-PHOTO-202103-034-4)





18 MARCH

CERN launches a new Technology Impact Fund designed to bridge the gap between CERN technologies and their potential applications in addressing global challenges.

(CERN-GRAPHICS-2021-004-4)

23 MARCH

A new result from the LHCb experiment strengthens hints of a violation of lepton flavour universality.

(OPEN-PHO-EXP-2018-004)

31 MARCH

The ALPHA collaboration succeeds in cooling antimatter using laser light, opening the door to considerably more precise studies of the internal structure of antihydrogen and of how it behaves under the influence of gravity.

(CERN-PHOTO-201601-005-5)

30 APRIL

The CMS collaboration installs the new heart of its detector, the beam pipe. This constitutes the biggest upgrade of the experiment's beam vacuum system since commissioning in 2008.

(CERN-PHOTO-202103-040-36)

4 MAY

The SPS accelerates its first LHC-type beam and sends beams to the North Area, where the physics season gets under way.

(CERN-PHOTO-201902-037-3)

19 MAY

The AMS experiment celebrates the tenth anniversary of its installation on the International Space Station and the first transmission of data back to Earth.

1 JUNE

CERN welcomes visitors back on site, first at the Microcosm exhibition and later for guided tours.

2 JUNE

FASER detects the first candidate events for neutrinos produced in a collider.

(CERN-PHOTO-202103-038-10)

21 JUNE

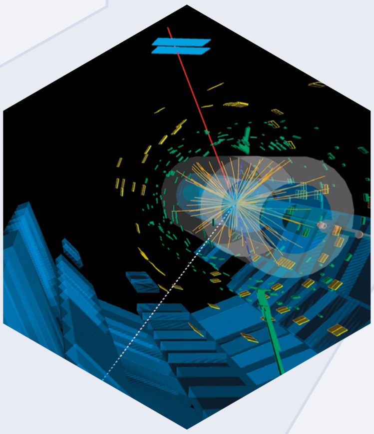
The laying of the first stone of Science Gateway marks the ongoing construction of the Laboratory's new flagship project for education and outreach.
(CERN-PHOTO-202106-082-4)

21 JUNE

ALICE receives the last of its new subdetectors, the Fast Interaction Trigger (FIT), as part of the LS2 upgrades.
(ALICE-PHO-INSTALL-2021-001-3)

23 JUNE

Teams from Italy and Mexico win the Beamline for Schools competition.



26 JULY

The ATLAS collaboration announces the first observation of WWW production: the simultaneous creation of three massive W bosons in high-energy LHC collisions.
(ATLAS-PHOTO-2021-066-01)

27 JULY

As part of a renewed partnership, CERN and Pro Helvetia announce the winners of the *Connect* and *Connect South Africa* artistic residency awards.

2 AUGUST

Latvia becomes a CERN Associate Member State.
(CERN-PHOTO-202108-100-2)

1 SEPTEMBER

CERN acquires four new buildings for the High-Luminosity LHC.
(OPEN-PHO-CIVIL-2021-002-2)

17–18 SEPTEMBER

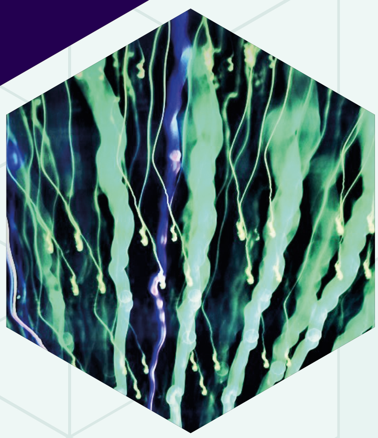
CERN launches the first edition of the new Sparks! forum, focusing on the theme of future intelligence.
(CERN-HOMEWEB-PHO-2021-148)

24 SEPTEMBER

Eliezer Rabinovici is elected as the 24th President of the CERN Council for a one-year term of office.
(CERN-PHOTO-202109-135-2)

5 OCTOBER

CERN and WHO join forces to define a standard for airborne transmission of respiratory pathogens, based on the CARA (COVID Airborne Risk Assessment) model.



14 OCTOBER

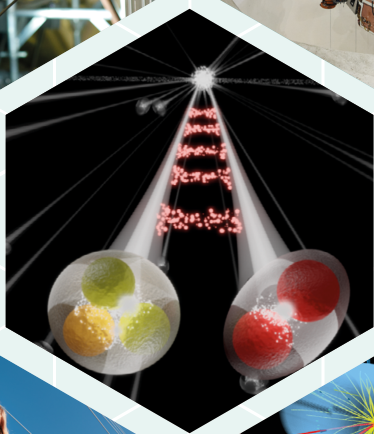
The Quantum Technology Initiative (QTI) reaches a new milestone with the unveiling of its roadmap for quantum research at CERN.
(CERN-HOMEWEB-PHO-2021-179-1)

18 OCTOBER

The LHCb detector's beam pipe is reinstalled – a landmark development in the experiment's upgrade.
(CERN-PHOTO-202108-101-12)

4 NOVEMBER

The ATLAS experiment installs its New Small Wheels after nearly a decade of design and construction.
(CERN-PHOTO-202111-166-5)

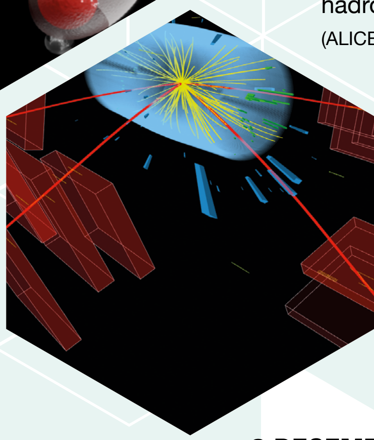


17 NOVEMBER

The ALICE collaboration observes the residual strong interaction between protons and phi mesons for the first time – a next step in understanding the interaction between hadrons.
(ALICE-PHO-PHYS-2021-001)

24 NOVEMBER

CERN's second Environment Report sets out concrete actions to reduce the Laboratory's environmental footprint.
(CERN-PHOTO-202106-080-5)



2 DECEMBER

The CMS collaboration reports a value for the Higgs boson's lifetime with a small enough uncertainty to confirm that the particle has a tiny lifetime.
(CMS-PHO-EVENTS-2019-008-1)

A LABORATORY FOR THE WORLD

In another year marked by the health restrictions associated with the COVID-19 pandemic, CERN continued to be a focal point for a closely connected international community of scientists. The 16 200 members of this CERN community were thus able to take part in the work involved in the year's major projects. The almost 2700 staff played their part, each in their own way, in bringing CERN's accelerators through their second long shutdown and back into service. At CERN and around the world, more than 11 000 users of 115 different nationalities from institutes in 77 countries contributed to CERN's scientific mission by carrying out a varied research programme based on the data extracted during the recent periods of accelerator operation.

(CERN-PHOTO-202001-011-4)

BREAKDOWN OF CERN USERS ACCORDING TO THE COUNTRY OF THEIR HOME INSTITUTE, AS OF 31 DECEMBER 2021

NUMBER OF USERS: 11 175

MEMBER STATES (6642)

Austria 74 – **Belgium** 122 – **Bulgaria** 39 – **Czech Republic** 227 – **Denmark** 42 – **Finland** 71 – **France** 811 – **Germany** 1129 – **Greece** 133 **Hungary** 69 – **Israel** 67 – **Italy** 1423 – **Netherlands** 157 – **Norway** 69 – **Poland** 278 – **Portugal** 89 – **Romania** 105 – **Serbia** 36 – **Slovakia** 66 **Spain** 328 – **Sweden** 88 – **Switzerland** 372 – **United Kingdom** 847

ASSOCIATE MEMBER STATES IN THE PRE-STAGE TO MEMBERSHIP (55)

Cyprus 10 – **Estonia** 24 – **Slovenia** 21

ASSOCIATE MEMBER STATES (367)

Croatia 36 – **India** 130 – **Latvia** 11 – **Lithuania** 12 – **Pakistan** 30 – **Turkey** 122 – **Ukraine** 26

OBSERVERS (2917)

Japan 189 – **Russian Federation** 971 – **United States of America** 1757

OTHER COUNTRIES (1194)

Algeria 3 – **Argentina** 16 – **Armenia** 10 – **Australia** 20 – **Azerbaijan** 3 – **Bahrain** 2 – **Belarus** 24 – **Brazil** 106 – **Canada** 189 – **Chile** 23 **Colombia** 18 – **Cuba** 3 – **Ecuador** 6 – **Egypt** 16 – **Georgia** 36 – **Hong Kong** 17 – **Iceland** 3 – **Indonesia** 6 – **Iran** 11 – **Ireland** 6 – **Jordan** 5 **Kuwait** 5 – **Lebanon** 15 – **Madagascar** 1 – **Malaysia** 4 – **Malta** 2 – **Mexico** 48 – **Montenegro** 5 – **Morocco** 18 – **New Zealand** 8 – **Oman** 1 **People's Republic of China** 314 – **Peru** 2 – **Philippines** 1 – **Republic of Korea** 113 – **Singapore** 3 – **South Africa** 52 – **Sri Lanka** 10 – **Taiwan** 45 **Thailand** 18 – **United Arab Emirates** 6

In 2021, CERN continued to reap the benefits of a policy of openness to the world, both within Europe, where the Organization has its foundations, and beyond. Estonia became an Associate Member in the pre-stage to Membership in February and is now preparing for accession to full Membership. Following the signature of an accession agreement in April 2021, Latvia became an Associate Member State in August. Cooperation with partners across the Atlantic continued in parallel. In September, the Council adopted a resolution on the admission of Brazil as an Associate Member State. In addition, Fermilab, the major US particle physics laboratory, signed a Memorandum of Understanding with CERN in March, which laid down its contributions to the Organization's flagship project, the High-Luminosity LHC. The Organization also signed international cooperation agreements with Bosnia and Herzegovina and with Honduras, heralding the start of formal relations with these two countries, and continued to implement its cooperation programmes with states that have limited scientific resources. Thanks to CERN's donation of computer equipment (p. 31), countries such as Lebanon were able to develop their particle physics research capacities.

Fabiola Gianotti and Katrin Saarsalu-Layachi, Ambassador of the Republic of Estonia to the United Nations Office in Geneva on the occasion of the notification of Estonia's Associate Membership of CERN. (CERN-PHOTO-202102-021-4)

A virtual CERN was created for the "Alumni Second Collisions" event, in which over 450 alumni took part. (CERN-HOMEWEB-PHO-2021-157-1)

After 67 years of existence, CERN has thousands of alumni around the world. The members of this dynamic network serve as ambassadors for the Organization and can count on each other's support to advance their careers in various fields. For over four years now, alumni have had access to the CERN Alumni programme, which aims to organise and connect the community. In 2021, the programme counted 7408 members, some of whom have organised themselves into regional groups (Athens, Boston, Eindhoven, French-speaking Switzerland, London, Milan and Turin, New York, Paris, Texas and Vienna). From 1 to 3 October, over 450 alumni took part in a virtual-reality event called "Alumni Second Collisions", which highlighted the impact of CERN alumni on society. The presentations by participants from sectors including space, medical and quantum technologies, the environment and scientific communication reflected the diverse range of jobs that await alumni after their time at CERN. In addition, the year was punctuated with events designed to support the network's goals, especially those concerning early-career alumni. The latter were able to meet companies interested in recruiting highly sought-after CERN alumni through the two-monthly Virtual Company Showrooms. In parallel, events hosted by colleagues from across the Laboratory gave alumni first-hand insight into the work being carried out and the technologies being developed at CERN, enabling them to share the latest developments at CERN with their personal networks.

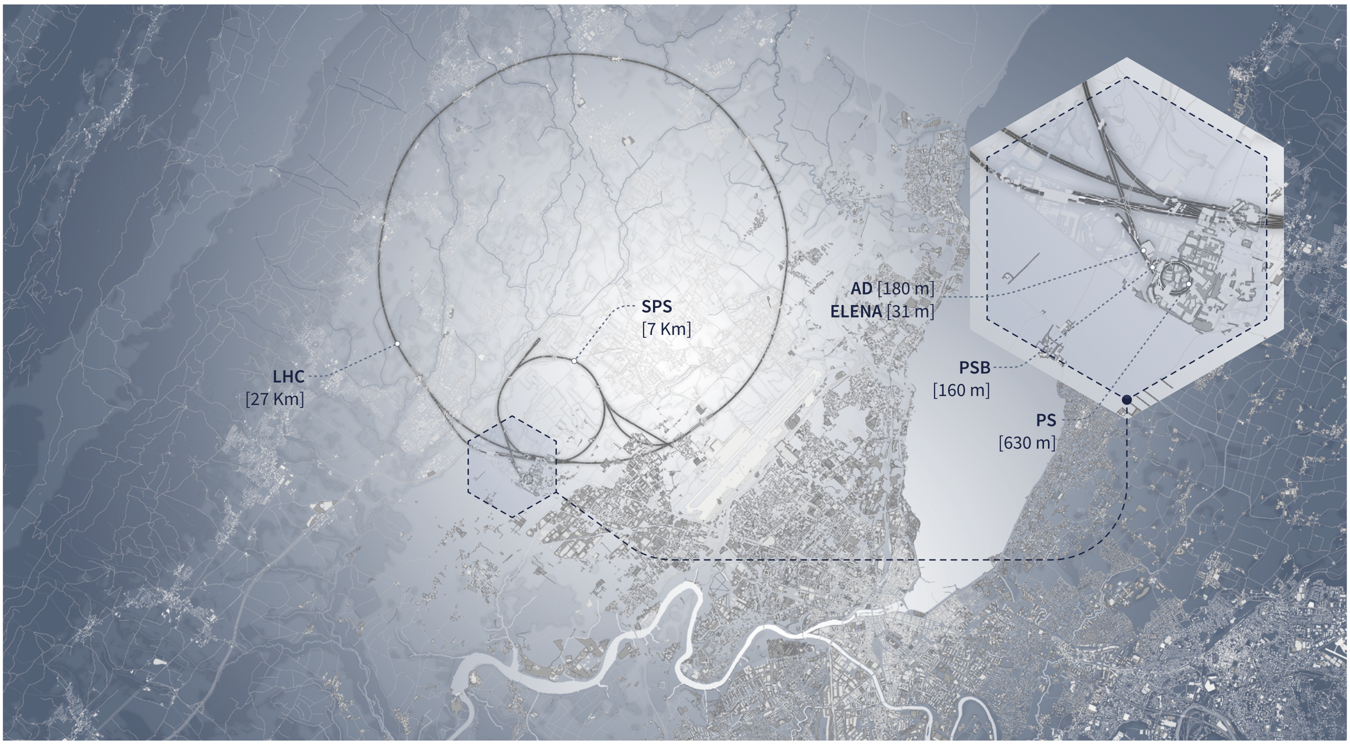
EXPLORING THE NATURE OF THE UNIVERSE

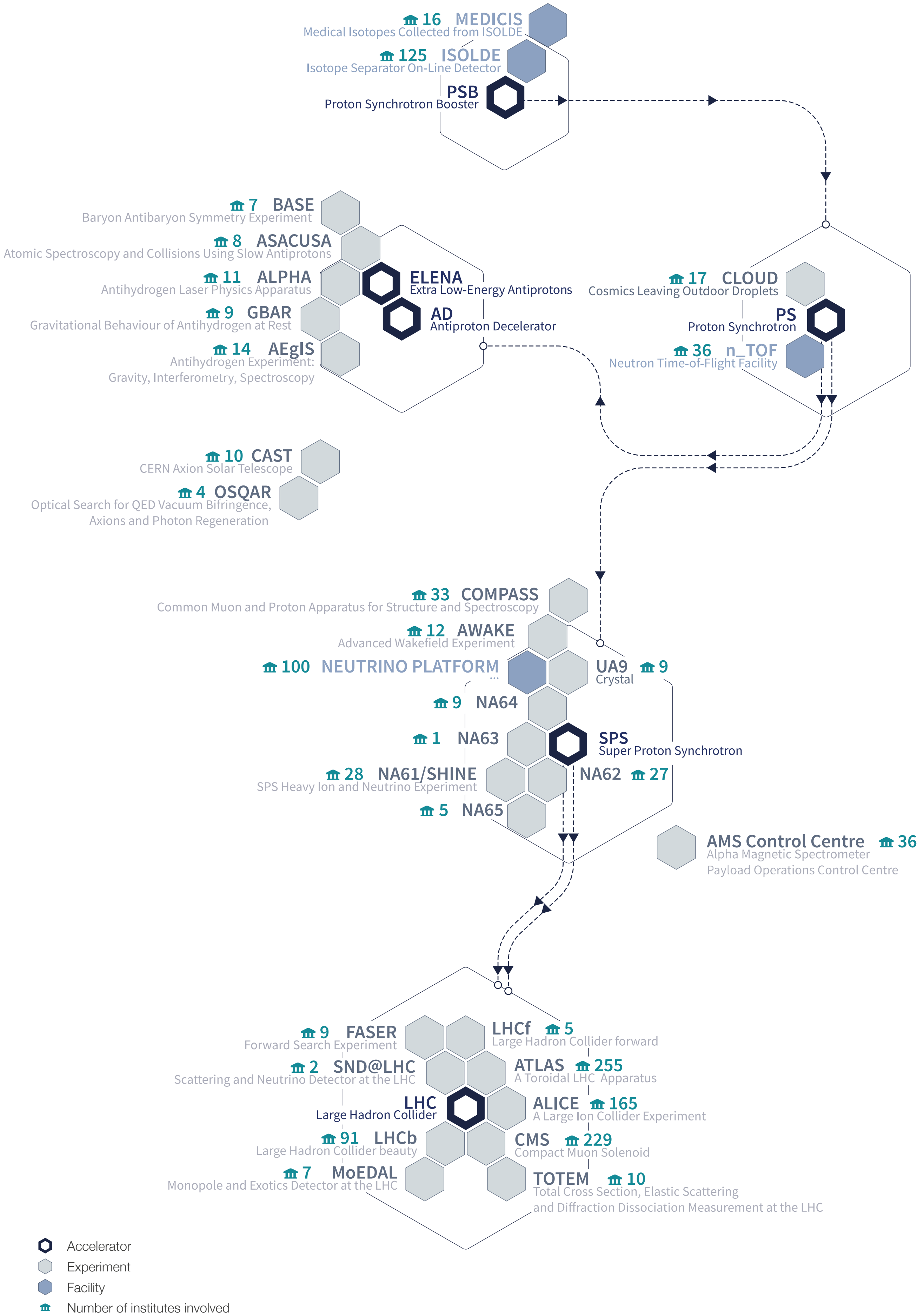
To study the universe at the most fundamental level, CERN operates a unique network of accelerators that collide particle beams head on or direct them onto fixed targets. The products of these collisions are recorded by state-of-the-art detectors and investigated by thousands of scientists at CERN and beyond.

CERN'S ACCELERATOR COMPLEX AND THE EXPERIMENTS THAT IT FEEDS

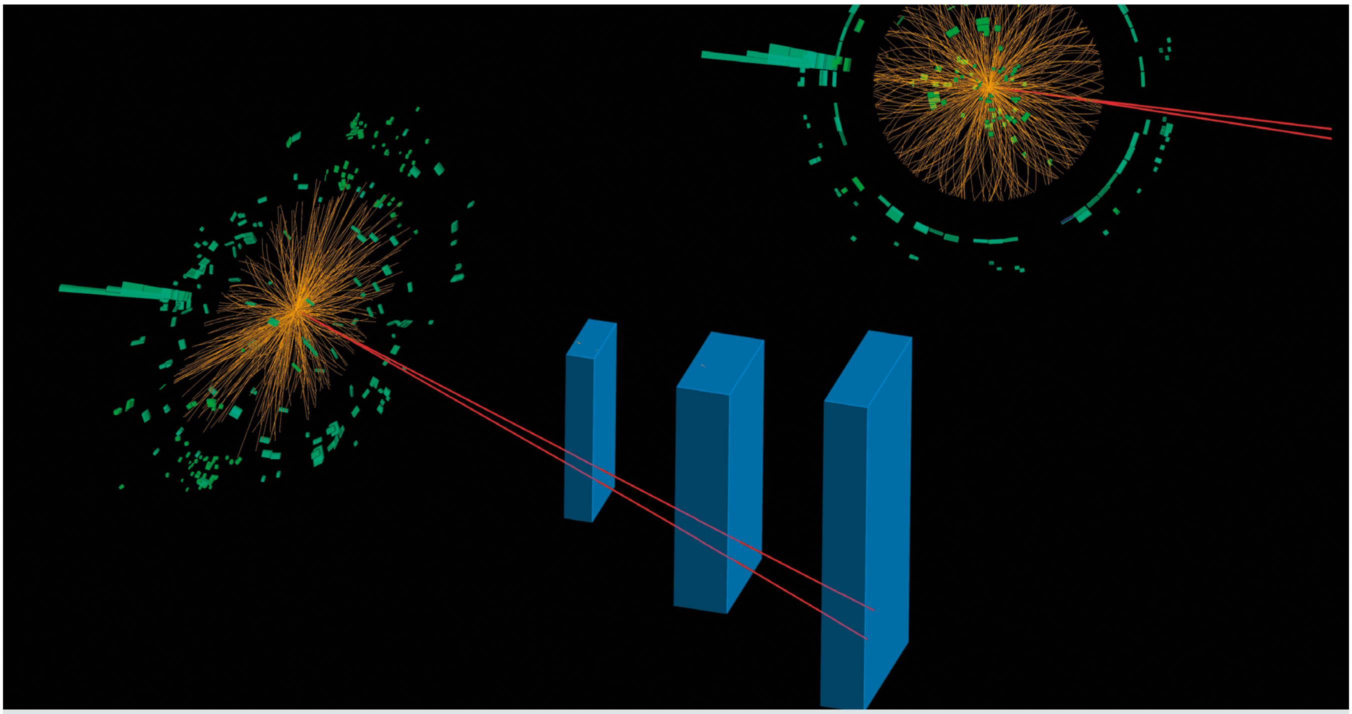
The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator. It collides beams of protons and other particles at the highest energies ever achieved, and the outcomes of these collisions are recorded by seven experiments – ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL and TOTEM – and will soon also be recorded by FASER and SND@LHC, the most recent members of the LHC family. The year 2021 represented the beginning of the end of the Laboratory's second long shutdown, with the progressive restart of the accelerator complex and its experiments after a period of intensive maintenance and upgrade work.

This milestone was complemented by remarkable physics results from the LHC experiments, as well from the diverse experiments that are fed by particle beams from the accelerators at CERN. These included intriguing results that strengthen hints of a violation of a key Standard Model feature known as lepton flavour universality, refined knowledge of the Higgs boson and its interactions with other particles, unexpected findings on how quarks form composite particles called hadrons, and advances in techniques to cool antimatter.





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



An ATLAS candidate event for a Higgs boson decaying into two muons (red lines) and a photon (pale green bars). (ATLAS-PHOTO-2021-003-2)

THE HIGGS BOSON UNDER THE LENS

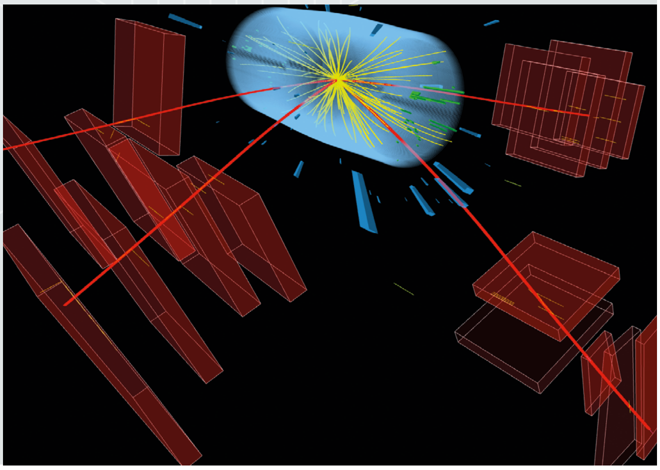
Since the discovery of the Higgs boson in 2012, the ATLAS and CMS collaborations have been refining their knowledge of the properties of this special particle and how it interacts with other particles. In the Standard Model, the strength of the Higgs boson's interaction with elementary particles is proportional to their mass. Any deviation from this behaviour could point to new phenomena. ATLAS and CMS investigate the Higgs boson's interactions by looking at how it transforms, or "decays", into lighter particles and how it is produced in association with other particles. The two collaborations have previously observed the interaction of the Higgs boson with other bosons, with the heaviest, third generation of fermions (the tau lepton and the top and bottom quarks) and, more recently, in 2020, they obtained the first indications that the boson interacts with a muon and thus with a second-generation fermion.

Highlights from further investigations carried out in 2021 include the placing of new bounds by both collaborations on the strength of the Higgs boson's interaction with itself, obtained from searches for the production of pairs of Higgs bosons, a process in the Standard Model that is much rarer than the production of a single Higgs boson. The results will guide future studies of the Higgs boson's self-interaction, the observation of which is one of the *raisons d'être* of the High-Luminosity LHC (p. 43).

Other highlights among the rich array of Higgs results obtained include ATLAS's evidence of the Higgs boson decaying into two leptons (either an electron or a muon pair with opposite charge) and a photon. This is one of the rarest Higgs boson decays yet seen at the LHC, and observing it with high statistical significance in the future will make it possible for physicists to study a fundamental symmetry of nature called charge-parity symmetry.

Another highlight was CMS's evidence of the production of "off-shell" Higgs bosons, i.e. Higgs bosons with a much larger mass than the particle's nominal mass of 125 GeV. From this result, obtained with data on Higgs bosons transforming into two Z bosons, which themselves transform into four charged leptons or two charged leptons plus two neutrinos, CMS determined the lifetime of the Higgs boson to be 2.1 x 10^{-22} seconds, with an upper/lower uncertainty of (+2.3/-0.9) x 10^{-22} seconds. This value, the most precise yet, aligns well with the Standard Model prediction.

A CMS candidate event for a Higgs boson transforming into four muons (red lines). (CMS-PHO-EVENTS-2019-008-1)



TESTING THE STANDARD MODEL AND ITS EXTENSIONS

The LHC collaborations continue to subject the Standard Model and its extensions to stringent tests. In March 2021, LHCb announced a new result that strengthens hints of a violation of a key feature of the Standard Model known as lepton flavour universality. Measuring the ratio of the rates at which certain B mesons decay into electrons or muons, the team found that it deviates from one with a statistical significance of 3.1 standard deviations, whereas it should be very close to one if lepton flavour universality is respected. A few months later, in October 2021, the collaboration presented the results of similar tests of lepton flavour universality using different types of B mesons, finding indications of a deviation from one but with a much lower statistical significance. As with previous related studies from LHCb and other experiments worldwide, none of these new results is individually significant enough to constitute evidence of new physics beyond the Standard Model, but together they represent an intriguing pattern.

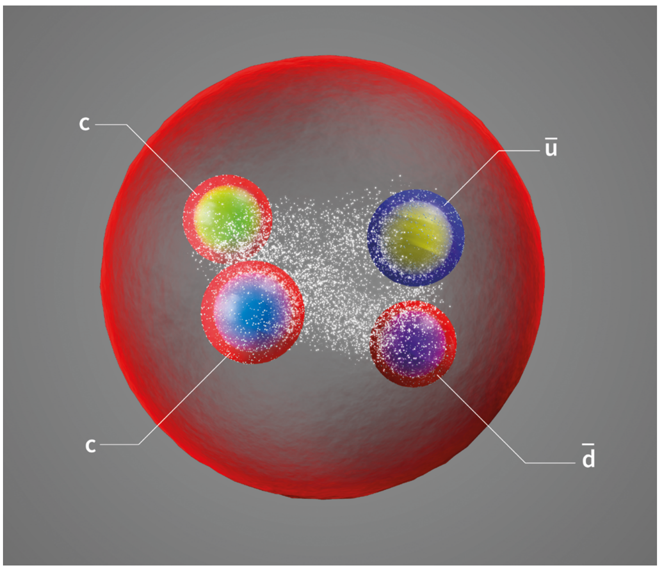
LHCb ANNOUNCED A NEW RESULT THAT STRENGTHENS HINTS OF A VIOLATION OF A KEY FEATURE OF THE STANDARD MODEL KNOWN AS LEPTON FLAVOUR UNIVERSALITY.

In the first half of the year, LHCb also achieved a milestone in the study of how a particle known as a D^0 meson changes from matter into antimatter and back by measuring the key quantity that controls the speed of this oscillation – the difference in mass between a heavier and a lighter D particle that both result from the quantum superposition of the D^0 particle and its antiparticle. With a value of 10^{-38} g, this mass difference is one of the smallest mass differences ever measured. The result came a couple of months after the announcement of a high-precision LHCb measurement of the matter–antimatter oscillation frequency of the B_s^0 meson, which places strong limits on physics beyond the Standard Model.

LHCb also discovered several new hadrons, specifically exotic four-quark particles, or tetraquarks, one of which is the longest-lived exotic matter particle ever discovered and the first to contain two heavy quarks and two light antiquarks. These new particles, as well as a new one detected by CMS (described below), add to the more than 50 new hadrons found at the LHC since the first hadron was discovered there by ATLAS about a decade ago.

Further testing the Standard Model, ATLAS observed the simultaneous production of three W bosons, carriers of the electroweak force, which allows hints of new interactions to be searched for; obtained strong evidence for the simultaneous production of four top quarks, which provides a unique window to search for new physics; studied the subtle differences in the energies of top and anti-top quarks, which were found to be in agreement with the Standard Model prediction; combined several high-precision measurements of particle-production processes to determine the proton's parton distribution functions, which describe what fraction of a proton's momentum is taken by its constituent quarks and gluons; extended the mass reach of searches for new physics; and searched for lepton-flavour violation using a large sample of Z bosons, outperforming searches carried out at the LHC's predecessor, LEP.

Tests of the Standard Model by CMS included the most precise yet direct single measurement of the so-called width of the decay of the Z boson into "invisible" particles; the observation of the production of three J/ψ particles emerging from a single proton–proton collision, which opens a new window into how quarks and gluons are distributed inside the proton; searches for long-lived particles in decays involving leptons; precision measurements of the W-boson branching fractions (the rate at which the W boson undergoes a particular decay), which improve on long-standing LEP results; a record-breaking measurement of the integrated luminosity, which quantifies the total number of collisions produced over a period of time, with an uncertainty of only 1.2%; and the discovery of a new excited beauty–strange baryon, which adds to the growing list of hadrons found at the LHC.



An artist's impression of the longest-lived exotic matter particle ever found, a tetraquark discovered by LHCb that is composed of two charm quarks and an up and a down antiquark.
(CERN-HOMEWEB-PHO-2021-128-2)

The smaller LHC experiments – LHCf, MoEDAL and TOTEM and the newly installed FASER – also chalked up many achievements in 2021. These include MoEDAL's results on the first search at a particle collider for magnetic monopoles produced through the Schwinger mechanism, by exposing the experiment's magnetic monopole trappers to lead–lead collisions produced at the LHC in 2018; the announcement by TOTEM and the DØ collaboration at Fermilab's Tevatron collider of the discovery of the odderon – an elusive state of three or a higher odd number of gluons that was predicted almost 50 years ago; and FASER's detection, using 2018 data from a pilot version of the FASERν detector, of the first candidate neutrinos produced at a collider. The year 2021 also saw the approval by the CERN Research Board of the fifth smaller LHC experiment, SND@LHC. Like FASERν, SND@LHC is designed to detect and study neutrinos, complementing and extending the physics reach of the other LHC experiments.

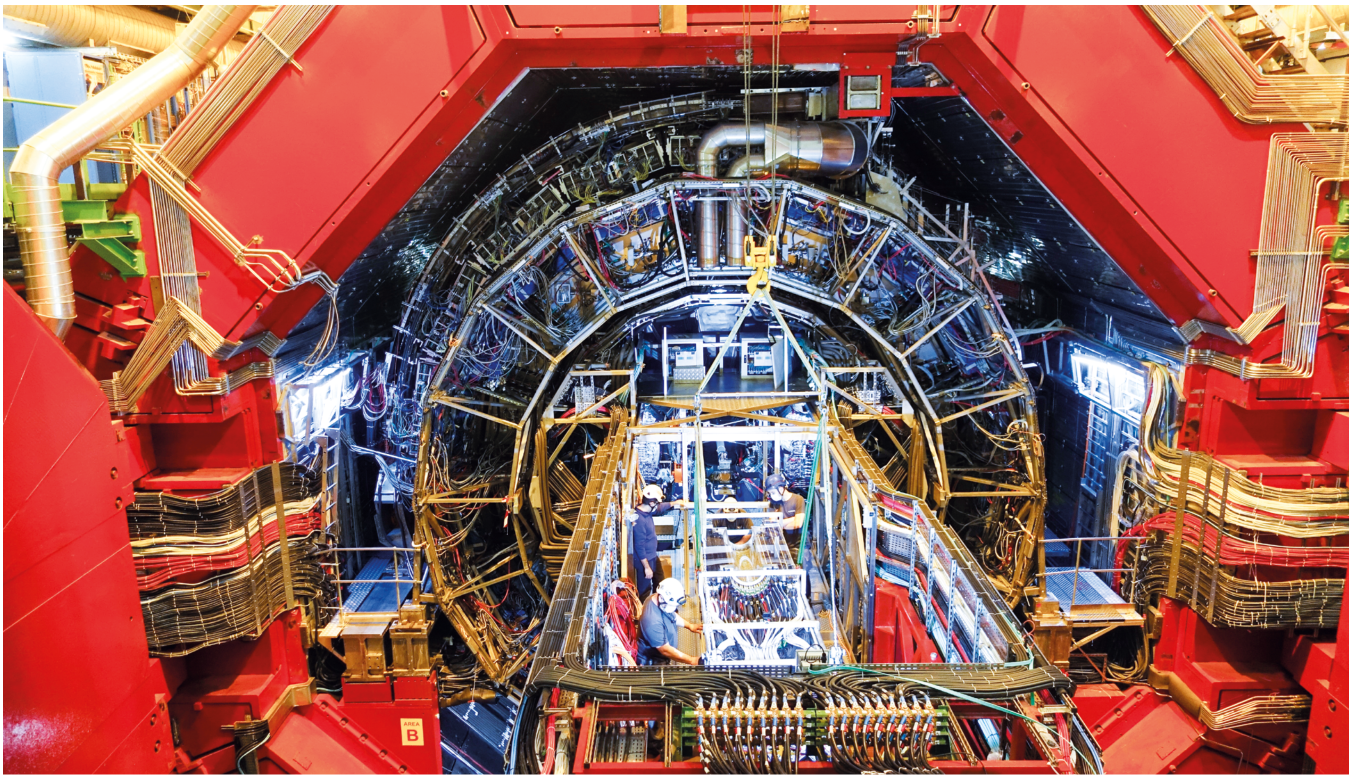
ALICE IN HEAVY-ION LAND

The LHC also collides lead nuclei to recreate a dense state of deconfined quarks and gluons, called the quark–gluon plasma, which is thought to have existed in the very early universe. The properties and effects of this state can be determined from the marks it leaves on the particles produced in heavy-ion collisions. In 2021, ALICE, the LHC's heavy-ion specialist, made several comparisons of data from heavy-ion collisions with data from proton–proton and proton–lead collisions. Such comparisons allow researchers to examine the quark–gluon-plasma properties of the heavier collision systems. Examples of such analyses include a novel study of the formation of two-quark and three-quark hadrons (mesons and baryons), which showed that hadron formation outside particle "jets" differs from that within jets, and new measurements of jets demonstrating that they become narrower after "quenching" in the quark–gluon plasma.

ALICE also showed that the formation of baryons from charm quarks in proton–proton collisions takes place four times more often than what was expected based on measurements made at colliders using electron beams. This process was previously considered to be independent of the type of colliding particles. This result therefore demonstrates that hadron formation is still a poorly understood aspect of the strong interaction that binds quarks and gluons together into hadrons. A further measurement showed that the relative abundance of charm baryons and mesons is modified in lead–lead collisions compared to proton–proton collisions in a specific particle-momentum interval, as predicted by theoretical models in which charm-hadron formation occurs both by recombination of quarks in the quark–gluon plasma and by charm-quark fragmentation in the vacuum.

Applying a method known as femtoscopy to proton–proton collision data, ALICE also observed the strong interaction between a ϕ (phi) meson and a proton. The moderate strength of the interaction between these two particles measured by ALICE provides a quantitative reference for studies of the ϕ meson's properties within dense nuclear matter, and it also sheds light on the interaction between hadrons inside neutron stars.

A view of the ALICE experiment during the installation of new components. *(ALICE-PHO-ITS-2021-001-3)*



THEORY THRIVES

In 2021, CERN's Theoretical Physics department conducted cutting-edge research supporting the Laboratory's activities and serving the international theoretical physics community. This research, which led to the submission of over 330 papers to the arXiv preprint server, spanned many areas, from string theory and quantum field theory to collider physics, cosmology and astroparticle physics.

Examples of the many important results obtained include state-of-the-art calculations of Standard Model particle processes in proton–proton and heavy-ion collisions; a new phenomenon in quantum cosmology to explain, among other features, the lightness of the Higgs boson; a detailed calculation of the formation of primordial black holes during a first-order phase transition in the early universe; a new machine-learning approach to explore the sources of the observed excess of gamma-ray radiation from the galactic centre; and the study of the structure of abstract mathematical entities called superconformal manifolds.

The department made fundamental contributions to all working groups on the physics of the LHC, the High-Luminosity LHC (p. 43), and the proposed projects CLIC (Compact Linear Collider), FCC (Future Circular Collider) and a muon collider. The department also participated in the CERN Quantum Technology Initiative (p. 31) and played a leading role in research concerning the Neutrino Platform (p. 48) and the Physics Beyond Colliders programme (p. 49).

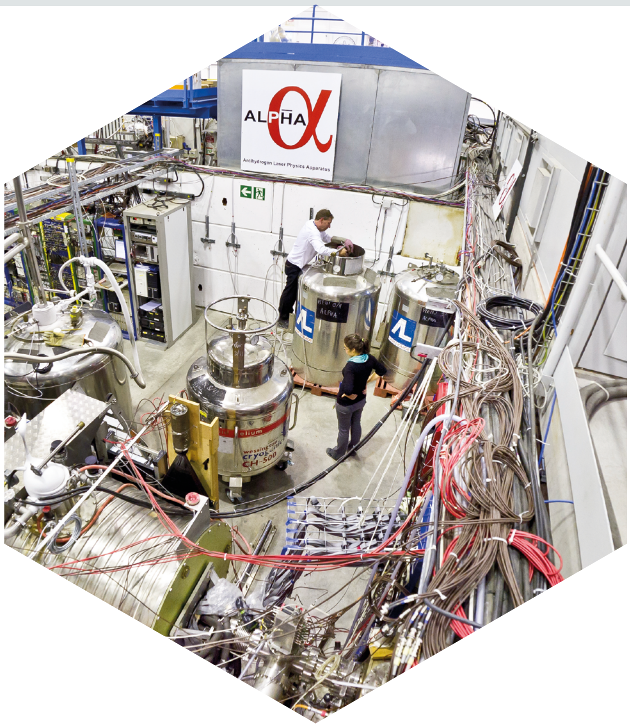
Despite the COVID-19 pandemic, the department hosted 124 external scientists and held two theory institutes, fully online. It also organised a rich programme of virtual scientific activities, from seminars to small workshops and open discussion sessions.

ANTIMATTER TERRITORY

CERN's Antimatter Factory supplies low-energy antiprotons to experiments that allow ever more precise comparisons to be made between the properties and behaviour of matter and antimatter. These comparisons test a fundamental symmetry of the Standard Model called charge-parity-time invariance and a fundamental principle of general relativity known as the weak equivalence principle. In 2021, low-energy (100 keV) antiprotons from the new ELENA ring, which slows down antiprotons even further than the facility's Antiproton Decelerator, were routinely delivered to the ALPHA, AEgIS, ASACUSA, BASE and GBAR experiments. The year also saw the approval by the CERN Research Board of two new experiments, BASE-STEP and PUMA, which will transport antimatter to other facilities.

Physics highlights in 2021 included ALPHA's successful cooling of antihydrogen atoms – the simplest form of atomic antimatter – using lasers. Laser cooling was first demonstrated 40 years ago on normal matter and is a mainstay of many research fields. Its first application to antihydrogen by ALPHA opens the door to considerably more precise measurements of the internal spectral structure of antihydrogen atoms and of how they behave under the influence of gravity.

ALPHA and BASE also made advances in "sympathetic" cooling, whereby one particle species is used to cool another. ALPHA demonstrated a way to enhance antihydrogen production by using laser-cooled beryllium ions to sympathetically cool a plasma of positrons, and BASE reported sympathetic cooling of a single proton using laser-cooled beryllium ions and an electrical circuit. The latter achievement promises substantial improvements to studies of antiprotons and could have applications in the field of quantum information.



The ALPHA experiment at the Antimatter Factory.
(CERN-EX-1011301-01)

BASE also set new limits on the interaction between photons and candidate dark-matter particles called axions, opening up new possibilities in the search for dark matter.

Another 2021 highlight was AEgIS's use of techniques developed in 2018 for the pulsed production of antihydrogen atoms. This form of antihydrogen synthesis allows the time at which the antiatoms are formed to be pinned down with high accuracy, and its demonstration by AEgIS represents a milestone for measuring the influence of gravity on antimatter.

The AMS detector on the International Space Station.

AMS, 10 YEARS IN SPACE

19 May 2021 marked a decade since the Alpha Magnetic Spectrometer (AMS-02) detector, which was assembled at CERN, was installed on the International Space Station and started sending data back to Earth – to NASA and then to CERN. Ten years and more than 175 billion cosmic rays on, AMS has delivered scientific results that have changed and confounded our understanding of the origin of these particles and how they journey through space. Highlights from the many AMS results obtained during the past decade include a 2020 result showing that, contrary to expectations, primary cosmic rays – which are mostly produced in supernovae explosions and can travel for millions of years before reaching AMS – have at least two distinct classes, one consisting of light nuclei and the other of heavy nuclei. Intriguingly, however, a 2021 study revealed that iron nuclei – the most abundant primary cosmic rays after silicon nuclei and the heaviest cosmic rays measured by AMS until now – belong not to the same class as the other heavy nuclei but instead to the class of light nuclei.

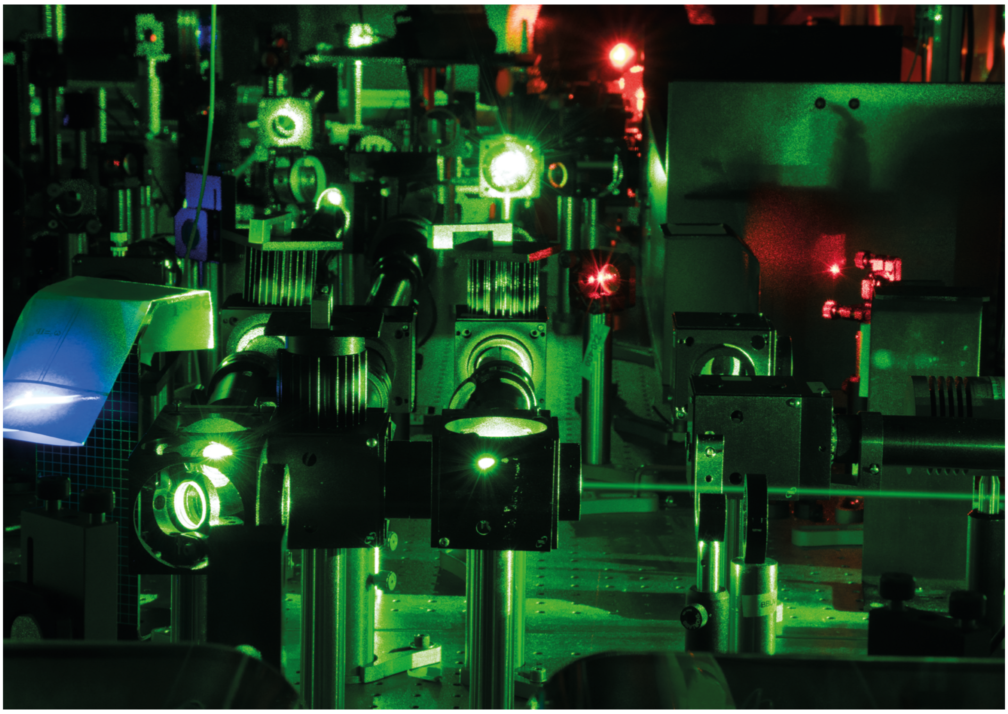
AMS HAS DELIVERED SCIENTIFIC RESULTS THAT HAVE CHANGED AND CONFOUNDED OUR UNDERSTANDING OF THE ORIGIN OF COSMIC RAYS.

THE ATOMIC NUCLEUS AND ISOLDE

The ISOLDE nuclear-physics facility directs a 1.4-GeV proton beam from the PS Booster to a target station to produce exotic radioactive-ion beams for a wide range of investigations in several fields, including nuclear and atomic physics, condensed-matter physics and life sciences. These exotic beams can be re-accelerated, using the HIE-ISOLDE linear accelerator, to energies close to 10 MeV per nucleon (proton or neutron). Following the partial restart of the CERN accelerator complex in 2021, ISOLDE saw radioactive beams delivered to many experiments between June and November (p. 26), followed by a successful winter physics campaign into December involving previously irradiated targets.

Results obtained from analyses of ISOLDE data taken prior to the second long shutdown advanced the understanding of atomic nuclei that have “magic numbers” of protons or neutrons, or both, arranged into filled shells within the nucleus. Early in the year, a study of the sizes of potassium nuclei rich in neutrons showed no signature of a magic number of neutrons in potassium-51, which has 19 protons and 32 neutrons. This finding challenges nuclear-physics theories and the proposed magic nature of nuclei with 32 neutrons.

ISOLDE also shed new light on one of the most iconic “doubly magic” nuclei: tin-100. With 50 protons and 50 neutrons, tin-100 is of particular interest for studies of nuclear properties because it is the heaviest known nucleus comprising protons and neutrons in equal number – a feature that gives it one of the strongest beta decays, in which a positron is emitted to produce a daughter nucleus. Studying the neighbouring indium nuclei of tin-100, an ISOLDE study obtained a mass for indium-100 that is 90 times more



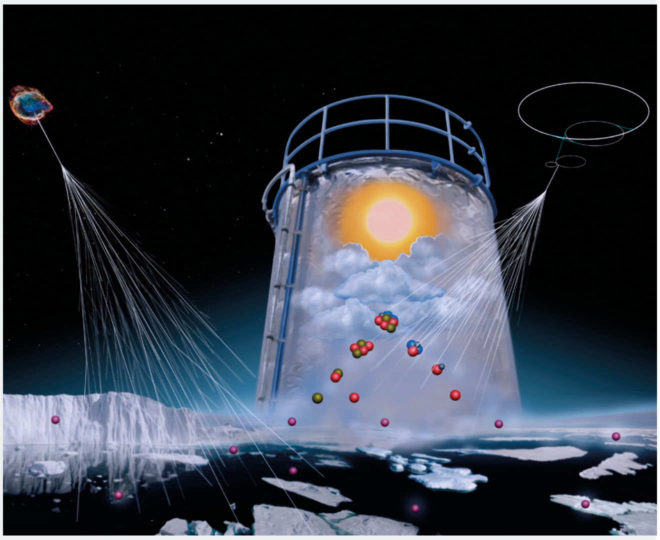
The ultrasensitive ISOLDE experimental set-up used to study bismuth nuclei. *(CERN-PHOTO-201602-031-8)*

precise than the previous one, magnifying a discrepancy in the values of the tin-100 mass deduced from the most recent beta-decay studies.

Another physics highlight was the observation that bismuth nuclei alternate dramatically in shape between spheres and rugby balls as single neutrons are removed from, or added to, the nucleus. This unusual nuclear physics phenomenon, first discovered at the ISOLDE facility 50 years ago, had previously been seen only in mercury nuclei. This work answers a long-standing question as to whether elements other than mercury also display this unusual phenomenon, and challenges theoretical understanding of nuclear shapes.

FIXED-TARGET EXPERIMENTS AND MORE

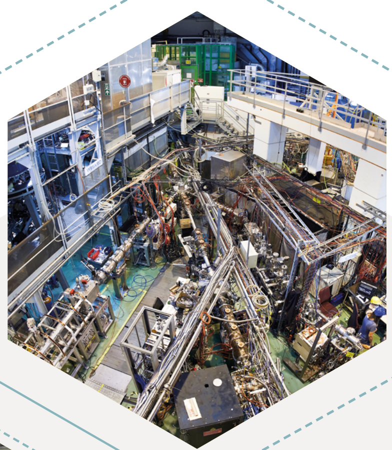
Other CERN-based experiments, many of which are fed by particle beams from the PS Booster and the PS and SPS accelerators (p. 25), also made great advances in 2021. Highlights include a new study from the one-of-a-kind experiment, CLOUD, showing that iodic acid may be the main driver of atmospheric particle formation in pristine marine regions. The results suggest a new mechanism that could accelerate the loss of Arctic sea ice. Another highlight was the publication by the NA62 collaboration of the first evidence of the ultra-rare decay of a positively charged kaon into a pion and a neutrino–antineutrino pair, a decay that is very sensitive to new physics phenomena. NA64 also obtained noteworthy results, including the placing of bounds on the extent to which new lightweight “X bosons” could contribute to the electron’s magnetism, while COMPASS reported that a signal observed by the experiment in 2015 is likely not to be a new exotic hadron after all but instead the first sighting of a “cascade” of hadron decays known as a triangle singularity. Last but not least, one of the newest detectors of the CAST experiment, RADES, joined the worldwide hunt for axions, searching for these hypothetical particles in the Milky Way’s “halo” of dark matter and setting a limit on the strength of their interaction with photons.



Simulation of the marine atmosphere in the CLOUD chamber. Iodine emitted from the sea and ice is converted by ozone and sunlight into iodic acid and other compounds. These form new particles and increase clouds, warming the polar climate. Cosmic rays strongly enhance the particle formation rates.

DISCOVERY MACHINES

2021 saw the end of the second long shutdown (LS2) for the CERN accelerator complex, after more than two years spent carrying out maintenance and renovation work and replacing equipment. On 30 June, the LHC Injectors Upgrade (LIU) project, which had been launched in 2015, was officially brought to a close. Major upgrades were successfully carried out in all the machines in preparation for the third run of the LHC and, later, the High-Luminosity LHC (HL-LHC). These upgrades will benefit the users of all the accelerators and make it possible to push back the frontiers of our knowledge of the constituents and laws of the universe.



LINEAR ACCELERATOR 4 (LINAC4)

August 2020: the first beams at the nominal energy of 160 MeV pass through all the accelerating structures of Linac4 to a dedicated absorber at the other end of the accelerator. (CERN-PHOTO-202202-028-4)

ISOLDE

June 2021: physics resumes in the ISOLDE target area, with 1.4 GeV proton beams. (CERN-PHOTO-201911-394-11)

PS BOOSTER (PSB)

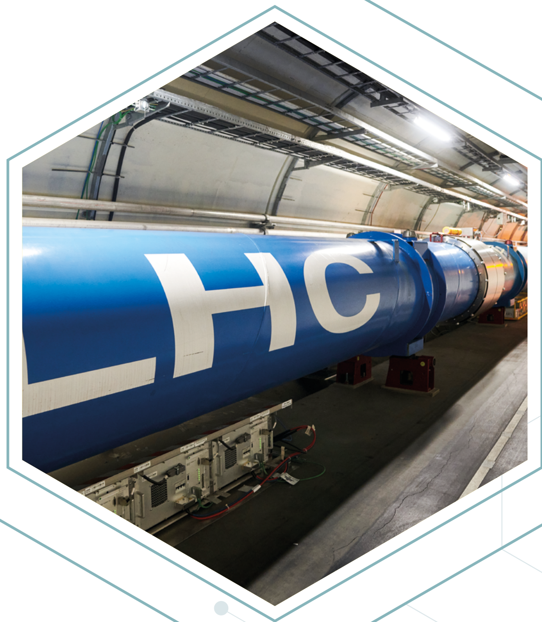
December 2020: the Booster receives its first beam from Linac4, marking the first ever connection between the two accelerators. (CERN-PHOTO-202202-028-1)

SUPER PROTON SYNCHROTRON (SPS)

April 2021: the first beam is injected from the PS into the SPS. The first acceleration using the brand-new SPS acceleration system, based on radiofrequency transistor power amplifiers, takes place three weeks later.
(CERN-PHOTO-201802-048-16)

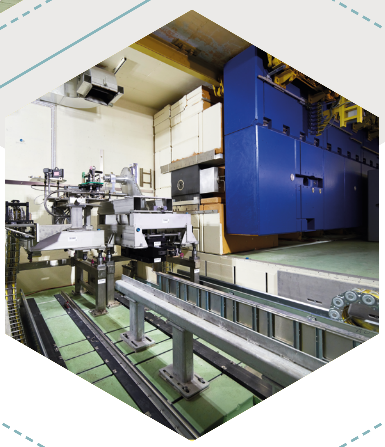
LARGE HADRON COLLIDER (LHC)

October 2021: the first pilot beams circulate in the LHC. A few days later, low-intensity test collisions are carried out in the four large LHC experiments at an injection energy of 450 GeV.
(CERN-PHOTO-202109-138-6)



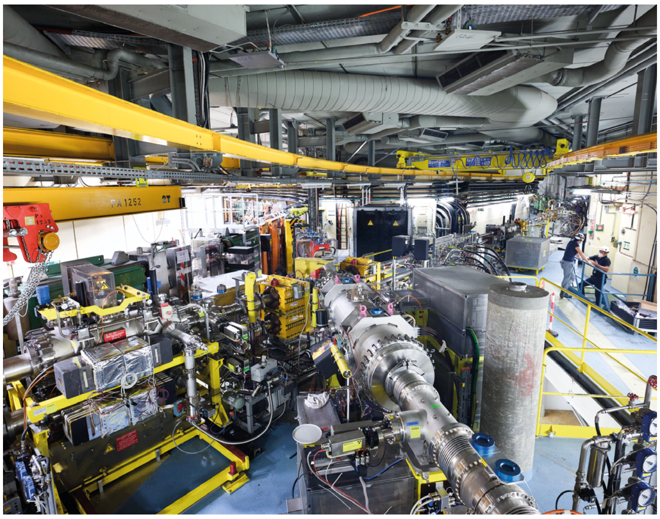
PROTON SYNCHROTRON (PS)

March 2021: the PS accelerates its first beam after a total overhall. In 2021, the PS operated smoothly in its energy range of 2 GeV at injection up to 26 GeV at extraction.
(CERN-PHOTO-202004-081-1)

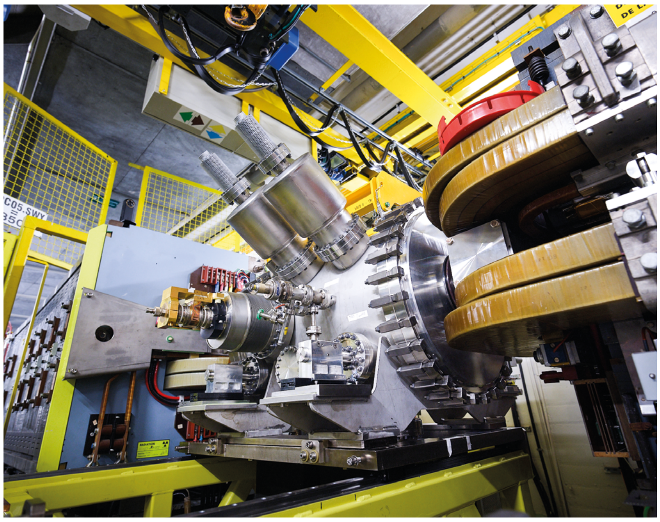


ANTIPROTON DECELERATOR (AD) AND ELENA

August 2021: physics resumes in the AD/ELENA complex. The AD is now equipped with a new iridium target.
(CERN-PHOTO-202104-081-11)



The PSB after its transformation, with some 40% of equipment replaced or upgraded during LS2. (CERN-PHOTO-202006-091-4)



The new PS septum magnet is based on the principle of Foucault currents; this is the first time that this kind of septum magnet has been used at CERN. (CERN-PHOTO-202006-090-16)

ALL THE INJECTORS ARE BACK UP AND RUNNING

Following the very first connection between **Linear accelerator 4** (Linac4) and the **Proton Synchrotron Booster** (PSB) in December 2020, the whole accelerator chain at CERN was progressively recommissioned over the course of 2021.

Linac4, the first link in the proton-accelerator chain and the most recent of CERN's accelerators, proved impressively reliable during its first year of operation, supplying the required beam with an availability of 96.8%.

In the "new" **PSB**, where some 40% of the equipment was replaced or upgraded during LS2, the brand-new injection and acceleration systems and main power supply were successfully commissioned and operated. They made it possible, for the first time, to circulate beams in the machine at an energy of 2 GeV (compared with 1.4 GeV prior to LS2), with lower beam losses and lower induced radioactivity than previously. The luminosity of the LHC beam was even slightly higher than expected.

On 4 March, it was the turn of the **Proton Synchrotron** (PS) to accelerate its first beam. The injection of the first beam was followed by several months of commissioning to fine-tune the machine.

To ensure that the 60-year-old PS could withstand receiving higher-energy, 2 GeV beams from the PSB, the accelerator ring had been fitted out with cutting-edge equipment in recent years, including refurbished magnets, new beam instrumentation devices, upgraded radiofrequency (RF) and cooling systems and new beam-dump systems.

Thanks to these upgrades, the PS operated smoothly in its new energy range of 2 GeV at injection up to 26 GeV at extraction. Overall, 2021 – despite being a difficult year due to the pandemic-related restrictions in particular – was a very successful year for the PS complex. All the systems and machines were commissioned and operated, delivering beams as planned to a wide range of users. The LIU intensity target for the PS, namely 2.6 x 10^{11} protons per bunch for the LHC beams, was surpassed in 2021. This was made possible by the improved feedback of the 40/80 MHz RF cavities and the reduced impedance of the power amplifiers of the 10 MHz RF cavities. The targeted increase in LHC beam luminosity for 2021 was also achieved.

The **East Area**, which is supplied by the PS, is one of CERN's oldest facilities. Outer shell, floors, configuration, cooling and ventilation systems, power converters, magnets, beam-dump systems, instrumentation – the renovations of the East Area during LS2, which were completed in 2021, left nothing untouched.

The IRRAD, CHARM and CLOUD experiments will now make the most of particle beams whose energy range has been broadened to span 0.3 to 15 GeV/c. These performances perfectly complement the energy range available in the SPS North Area, which ranges from 15 to 400 GeV/c.

These upgrades, coupled with better instrumentation relying on scintillating fibre technology, have already attracted a number of potential new users, including neutrino research collaborations.

The East Area, which was inaugurated more than 50 years ago, is now packed with cutting-edge equipment after a four-year-long makeover. *(CERN-PHOTO-202101-009-5)*

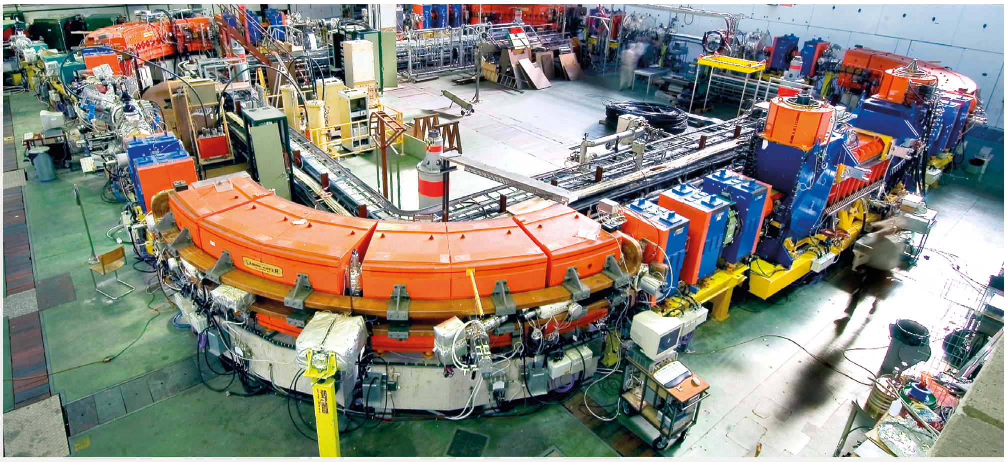
On 12 April, as per the revised LS2 activity schedule drawn up in June 2020, the first beam was injected into the **Super Proton Synchrotron** (SPS) from the PS. Three weeks later, on 4 May, the first acceleration using the SPS's brand-new acceleration system, based on RF transistor power amplifiers, took place. This new system has been in operation since November 2020 and reached a power of 750 kW in continuous mode at 200 MHz – a world record – in early 2021. All the SPS equipment was then tested and commissioned with different beam types and demonstrated excellent performance.

The new SPS beam-dump system also worked as expected, although a defect in a new kicker magnet, which guides the beams towards the beam dump, limited the beam intensity for certain operating modes. This problem was resolved by replacing the magnet during the 2021–2022 year-end technical stop (YETS).

Over the summer, despite some challenges that slightly delayed the start of physics for some experiments, the SPS began sending accelerated beams to the **North Area**, where a new physics campaign is now under way. The SPS is not only a key link in the LHC accelerator chain, but also provides beams to the fixed-target experiments located in the North Area, as well as to the AWAKE experiment and the HiRadMat facility, all of which successfully received beams. The SPS also delivered the first high-intensity beams to the LHC during a two-week test run in October.

THE LAST TWO YEARS HAVE HAD THEIR SHARE OF CHALLENGES AND, IN THESE CIRCUMSTANCES, THE PROGRESS MADE ON ALL FRONTS IS PARTICULARLY REMARKABLE.

The new SPS radiofrequency acceleration system. *(CERN-PHOTO-201902-037-3)*



View of LEIR.
(CERN-EX-0509046-01)

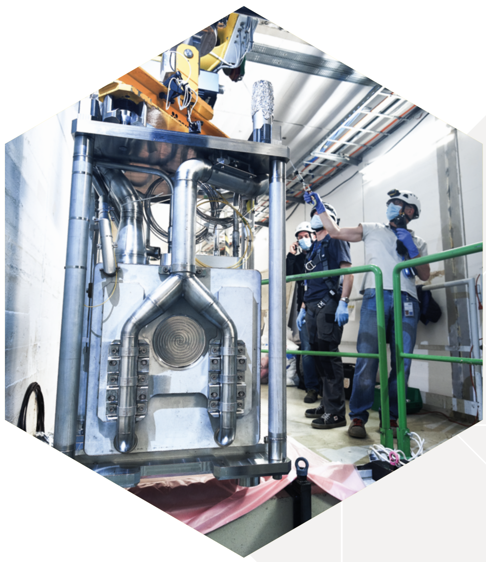
LINAC3 COMPLEX – LEIR RESUMES OPERATION

Linear accelerator 3 (Linac3) is the departure point for ions, usually lead nuclei, which are used either for collisions in the LHC or for fixed-target experiments. Linac3 sends long pulses of lead ions to the **Low-Energy Ion Ring** (LEIR), which transforms them into short, dense bunches. These bunches are then sent to the PS, where they are stored, before being injected into the SPS and then the LHC.

The main modernisation and consolidation work required throughout the Linac3–LEIR complex as part of the LIU project was completed in 2021. The new systems and configurations were tested, commissioned and put into operation. The pre-LS2 ion-beam conditions were successfully re-established in Linac3 and LEIR up to the PS.

RESTART OF OPERATIONS AT THE NUCLEAR PHYSICS FACILITIES

In the **ISOLDE** (Isotope Mass Separator On-Line Detector) target area, physics resumed on 21 June, with 1.4 GeV proton beams. When the beams collide with the ISOLDE targets, rare radioactive isotopes of various periodic-table elements are produced, some of which are then selected using a combination of lasers and electric and magnetic fields. The beams, which are either used at low energies or reaccelerated by the HIE-ISOLDE (High Intensity and Energy Isotope Mass Separator On-Line) linear accelerator, are steered towards several experiment facilities that cover a wide range of disciplines, from the study of nuclear structure and decay to astrophysics, condensed matter physics and life sciences.



The new n_TOF target was installed in April.
(CERN-PHOTO-202103-043-7)

The construction of the "nano-lab" – a unique facility designed for the development of innovative materials for the ISOLDE targets and located in the new extension of the ISOLDE nuclear materials handling laboratory – was completed. It will be commissioned in 2022, once the final pieces of laboratory equipment have been delivered.

The new target for the **Neutron Time-of-Flight (n_TOF) facility**, which studies nucleus–neutron interactions, was commissioned. This third-generation target, which comprises six U-shaped lead blocks weighing a total of 1.5 tonnes, presents significant advantages for both physics and logistics: first of all, the new configuration allows the lead to be cooled with nitrogen gas at ambient pressure, instead of with water as was the case with the former target; this significantly reduces the pollution of the circuit by removing the erosion and corrosion mechanisms induced by the water coming into direct contact with lead. Secondly, the new target sits on top of a demineralised water tank, which is located in the path of the neutron beam produced by the collisions that occur between the

The new AD target is ready to receive beams from the PS and start generating antiprotons for the AD/ELENA complex.
(CERN-PHOTO-202104-081-13)

DECELERATING ANTIPROTONS

The **Antiproton Decelerator** (AD) produces low-energy antiprotons for the study of antimatter and to "create" atoms of antimatter. It was recommissioned with its new target area following the programme of magnet and radiofrequency system renovation carried out during LS2. The current target comprises a rod of air-cooled iridium inside a graphite matrix, protected by a titanium-alloy double shell. The renovation of the target area will allow new types of target to be tested, with a view to enhancing the production of antiprotons.

The AD sends antiprotons to **ELENA** (Extra Low-Energy Antiprotons), CERN's new deceleration ring, at an energy of 5.3 MeV. ELENA then decelerates the antiprotons to 0.1 MeV, enabling the experiments to trap almost 100 times more antiprotons than previously. This year, for the first time, ELENA successfully delivered antiprotons to all the antimatter factory experiments: ALPHA, AEgIS, ASACUSA, BASE and GBAR. This first run at 0.1 MeV marks the start of a new era of precision antimatter physics. ELENA will soon also supply the new PUMA and BASE-STEP experiments, which were approved by the CERN Research Board in March.

high-energy protons from the PS and the lead nuclei of the target. This tank improves the quality of the neutron beam in the vertical experiment area, which is a key aspect of the research being carried out at n_TOF.

In addition, the target shielding was modified in order to provide access to the target area for inspection purposes, and also to allow activation measurements to be taken in the new NEAR station and tests to be carried out on electronic components and materials in the framework of the R2E (Radiation to Electronics) project.

FIRST PILOT BEAMS IN THE LHC

On 15 March, the keys to the **Large Hadron Collider** (LHC) were handed over to the Operations group in the Beams (BE) department, after more than two years in the hands of the teams responsible for the second long shutdown activities.

The rest of the year was spent commissioning equipment, carrying out electrical power supply tests and training the superconducting dipole magnets (see box on p. 28). During the commissioning period, several magnet-related issues that required additional machine warming and cooling cycles were resolved. In the wake of these challenges, a risk analysis showed that training the full machine to the nominal energy of 7 TeV per beam would have a 63% probability of causing an incident that would require another sector to be warmed up; limiting the energy to 6.8 TeV per beam would greatly reduce this probability to around 17%. Taking into account these elements, as well as the data provided by the four large LHC experiments (ALICE, ATLAS, CMS and LHCb) on the impact that operating at a slightly lower energy would have on physics, it was decided to begin LHC Run 3 at the target energy of 6.8 TeV, i.e. 0.3 TeV above the Run 2 beam energy of 6.5 TeV.

On 19 October, the first pilot beams were circulated in the LHC to allow the initial commissioning of all the key beam-related systems. On 26 October, low-intensity test collisions were carried out at an injection energy of 450 GeV per beam in the four large LHC experiments so that they could test their data acquisition systems after more than two years of upgrade and maintenance work.

This pilot-beam test revealed an aperture restriction in LHC sector 2–3 caused by one magnet interconnection module with twisted RF fingers. The sector was brought back up to ambient temperature before Christmas and was replaced during the 2021/2022 year-end technical stop (YETS).

On 15 March, Maria Barberan (Accelerator Coordination and Engineering group, left, holding key) handed over the keys to the LHC to Matteo Solfaroli (Operations group, right), in the CERN Control Centre (CCC).
(CERN-PHOTO-202103-034-2)

By the end of the year, seven of the eight LHC sectors had been trained to 6.8 TeV. Sector 2–3 will be trained in 2022.

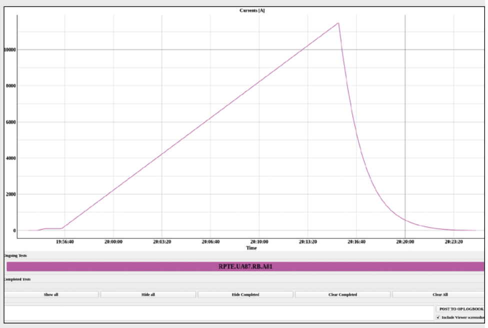
In December, the CERN Council approved a revised long-term schedule for the LHC, based on the recommendations of the LHC Experiments Committee (LHCC) and the CERN Machine Advisory Committee (CMAC). Run 3 has been extended until the end of 2025, and Long Shutdown 3 will last for three years instead of the originally planned two and a half. Postponing Long Shutdown 3 will allow the delays caused by the pandemic to be absorbed and the construction work for the HL-LHC project and the Phase 2 upgrades of the ATLAS and CMS experiments to be completed.

The last two years have had their share of challenges and, in these circumstances, the progress made on all fronts is particularly remarkable, paving the way for another successful year for the injectors and a good start to LHC Run 3.

TRAINING THE LHC MAGNETS

The LHC magnets must be trained in order to limit the risk of quenches occurring randomly during the run. Quenches occur when a small number of coils within the magnets overheat under the effect of high-intensity currents and lose their superconductivity. The current must therefore be extracted very quickly and safely to avoid damaging the magnets.

Training involves deliberately triggering quenches, which "teach" the magnets to "outperform themselves". Following a quench that causes the circuit to warm up, the magnets are cooled back down to 1.9 K (-271.3 °C) and the current is circulated again until the next quench occurs, and so on and so forth, increasing the intensity, until the magnets can cope with their nominal current without quenching. Training represents a major phase of the LHC restart, as around 12 000 tests are needed to train some 1600 superconducting circuits with nominal intensities ranging from 60 A to 13 kA.



Intensity of the current in a main dipole-circuit during training. The constant slope represents the gradual increase of the current, and the exponential decrease shows the safe extraction of the current when the protection system detects a quench.
(CERN-HOMEWEB-PHO-2021-164-2)

The CERN Data Centre in Meyrin is at the heart of WLCG, a global network consisting of 170 data centres in 42 countries.
(CERN-PHOTO-201601-014-3)

COMPUTING: ENABLING RESEARCH AND SUPPORTING OUR COMMUNITY

The experiments at CERN produce vast quantities of highly complex data. Computing plays a vital role in unlocking the secrets hidden therein. In 2021, the majority of work carried out in the CERN Information Technology (IT) department focused on preparing for Run 3 of the LHC. The upgraded networking, computing and storage systems required have all been put in place.

In parallel, the IT department provided key tools and services to support the increased level of remote working required by the COVID-19 pandemic. For example, remote access to files was facilitated by upgrades to the cloud storage and synchronisation hub “CERNBox”. Important work was also undertaken to help people remain cybersecure when working remotely. On top of this, a new desktop softphone client released in 2021 played an important role in reducing the costs borne by the Organization for phone calls made during periods of remote work.

In addition, the IT department continued to develop and refine the services it provides in support of the particle physics research community and beyond. Significant upgrades were made to the CERN Open Data Portal; to the REANA platform for reproducible data analysis; and to the Invenio open source software framework for managing digital repositories, which supports both the CERN Document Server and CERN’s library catalogue. Furthermore, the open access repository Zenodo was upgraded to take account of its growing popularity across research fields: the platform is now visited around 15 million times per year.

READY FOR RUN 3

In addition to the many key services that the IT department provides to the Organization, the clear focus was preparation for Run 3. This involved teams across the whole of CERN – and from research institutions around the world.

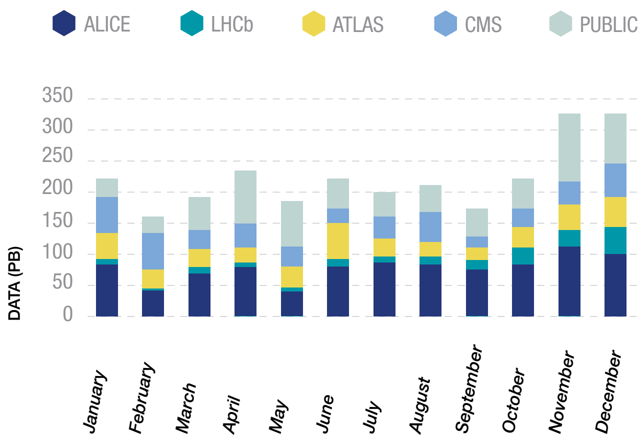
Work was carried out to prepare key databases used for controlling and monitoring CERN’s accelerator complex, including a new logging system called NXCALS. Important databases used by the experiments were upgraded for Run 3 too.

The experiments’ “trigger” systems – used to filter the torrent of particle-collision data – were upgraded, with increased use of graphical processing units. The IT department has played an important role in helping the experiments to port and optimise code for running on heterogeneous computing architectures.

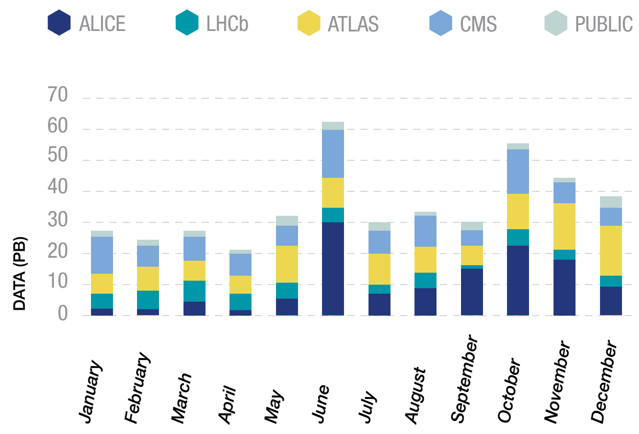
A set of data-taking tests was organised with the LHC experiments to prepare for Run 3. Following these, both the experiments and the IT department’s teams used the lessons learned to make key upgrades to the relevant systems.

An important example of work carried out in this area in 2021 comes from the “ALICE O2” upgraded computing model. This has been developed to address the increased data rates that will be seen in Runs 3 and 4 by significantly reducing the data volume read out from the detector as early as possible during the data-flow process to ensure that data rates remain manageable. Tests with EOS, CERN’s disk-based low-latency storage system, showed the ALICE O2 system reaching up to 200 GB/s data ingestion, which will be required during the LHC’s next run.

*Amount of data **read** in 2021*



*Amount of data **written** in 2021*



The volume of data read from and written to the EOS disk-based storage system in 2021.

THE GRID THAT NEVER SLEEPS

2021 was an important year for the Worldwide LHC Computing Grid (WLCG). This global computing network, involving 170 data centres in 42 countries, continues to store and analyse a flood of data from the experiments, even when the LHC is not running. The levels of central processing unit (CPU) time used reached new peaks during the year, with up to 1.4 million CPU cores concurrently in use by the four main LHC experiments. The usual resources provided by the WLCG sites were boosted by the opportunistic use of other facilities, such as the experiments' high-level trigger farms and several high-performance computing (HPC) centres. Volunteer computing also continued to play an important role in boosting the computing capacity available to the experiments. Today, the total amount of storage available to the experiments through WLCG is roughly 1.5 exabytes: 40% is provided by disks and 60% is provided by tapes.

In 2021, important work was carried out – involving teams at CERN and beyond – to optimise the code used for simulating particle-collision events. This activity requires significant computing resources; updating the underlying code helps to ensure that the hardware available through WLCG is used as efficiently as possible.

The WLCG and CERN data centre teams continued to work hard to overcome the procurement and deployment delays caused by the COVID-19 pandemic. While the global semiconductor shortage still poses challenges for computing, the teams are confident that WLCG is ready to meet the demands of Run 3. In preparation, several data challenges were organised in the second half of the year. These served to validate the Tier 0 workflows, the global data-distribution capabilities and the archive storage infrastructure. A network challenge organised in October showed that the upgrades made to the external networks during LS2 will successfully meet the demands of Run 3.

CERN DATA CENTRE: UPGRADES AND CONSTRUCTION PLANS

The CERN Data Centre in Meyrin is at the heart of WLCG. Around 27 tonnes of new equipment were delivered to the centre in 2021. By the end of 2021, there were around 470 000 processor cores and 11 000 servers installed in the data centre. Over 90% of the centre's compute resources are provided through a private cloud based on OpenStack.

In terms of storage, there are now over 32 000 tape cartridges in the data centre, with around 380 petabytes (PB) used. The EOS disk-based storage system now manages over 550 PB of raw storage, with yet more capacity being added before the start of Run 3.

In 2021, planning work for the new CERN Data Centre in Prévessin also continued. A contract was signed for the design, construction and ten-year operation of this new energy-efficient data centre. Planning permission was obtained at the end of the year. Construction starts in April 2022, with the first phase – providing an initial IT capacity of 4 MW – set for completion in the third quarter of 2023.

LOOKING BEYOND RUN 3 TO THE HL-LHC ERA

Enrica Porcari joined CERN as the new head of the IT department in mid-2021. She kick-started a process to devise a new strategy, focusing on ensuring the department is an enabling partner for stakeholders across the full CERN community. This strategy helps pave the way for a successful Run 3 and provides a framework for meeting the IT challenges that will be thrown up by Run 4, when the HL-LHC is launched.

CERN openlab is one entity that will work to address these challenges. This unique public–private partnership between CERN and leading IT companies supports over 30 R&D

projects tackling cutting-edge IT challenges faced across the Organization. CERN openlab began a new three-year phase in 2021, with its work split into three main technology areas: exascale technologies, artificial intelligence (AI) technologies and quantum computing.

CERN openlab's projects on quantum computing contribute to the broader CERN Quantum Technology Initiative (QTI). In 2021, CERN QTI published its first roadmap, which sets out a research programme divided into four main areas: quantum computing and algorithms; quantum theory and simulation; quantum sensing, metrology and materials; and quantum communication and networks. In 2021, CERN QTI established 20 research projects to explore how quantum technologies can best benefit the particle physics research community and beyond.

MAKING A POSITIVE IMPACT

Collaboration plays a central role in preparing for the IT challenges raised by the LHC's ambitious upgrade programme. Collaboration is also vital in ensuring that CERN's work in the field of IT has the greatest positive impact on wider society. The IT department works closely with the Knowledge Transfer group, including through several joint CERN openlab projects that focus on impact in research fields beyond particle physics (particularly for medical applications).

The IT department also continues to host and support UNOSAT, the United Nations Satellite Centre. UNOSAT provides satellite imagery and geospatial information to support the UN's humanitarian efforts, protecting refugees following natural disasters, disease outbreaks and other crises. Indeed, a CERN openlab project is even studying the use of AI technologies to improve object recognition in satellite imagery, thus making it easier to support displaced people by identifying shelters.

CERN's positive impact on wider society is also boosted by the IT-related European Union projects in which it participates. In 2021, the IT department worked together with other leading research institutes on projects driving the development of the next generation of supercomputers, supporting the European Open Science Cloud and advancing open scholarship. These efforts – coupled with the open source tools outlined above, such as Indico, Invenio, Zenodo and CERNBox – have a strong positive impact in a range of fields. Indico, for example, is now used by several UN organisations for event management.

Further positive societal impact is achieved by CERN's Computer Security team. In 2021, CERN cofounded a global trust group called SAFER, aimed at protecting research-and-education facilities from cyberthreats. And the CERN Computer Security team continued to help the medical sectors of Switzerland and France to protect their digital infrastructures.

Finally, CERN supports research in developing countries by donating computing equipment that no longer meets the Laboratory's highly specific efficiency requirements but is still more than adequate for less exacting environments. In 2021, CERN donated 104 servers and five network switches to the Takoradi Technical University in Ghana. This donation included more than 2300 processor cores for computing, and more than 1100 terabytes for storage. Work was also carried out in 2021 to prepare a similar donation to Lebanon in early 2022.

TRAINING THE NEXT GENERATION OF COMPUTING SPECIALISTS

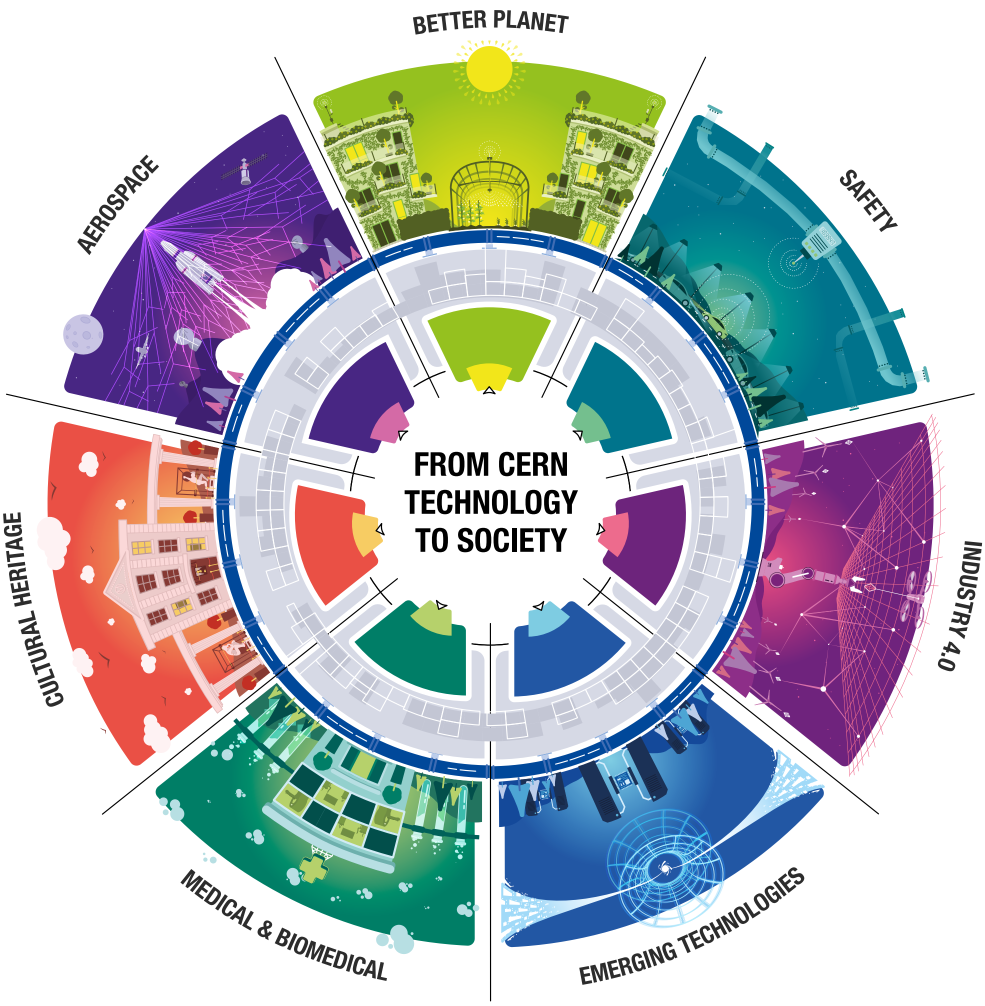
The IT department organised a wide range of education and training activities in 2021.

The CERN School of Computing ran two thematic schools, each focusing on scientific software for heterogeneous computing architectures. The first was held online in June and the second took place in person in Split, Croatia, in October.

CERN openlab ran its summer student programme online in full for the first time ever in 2021. The lecture programme was made available to the public via livestream and recordings, proving popular. On top of this, the CERN openlab team played a central role in organising the CERN Webfest. 300 people, from 63 countries, signed up for this global, online hackathon, which focused on addressing several key UN Sustainable Development Goals.

PUSHING THE FRONTIERS OF TECHNOLOGY

In pursuing its mission to perform world-class research in fundamental physics, CERN pushes the frontiers of technology. It is particularly through successful collaborations with businesses across a variety of industries that advancements in accelerators, detectors, computing and many other areas become realities. These developments not only serve to unveil the mysteries of the universe, but also find applications in fields beyond high-energy physics. The resulting transfer of knowledge helps drive innovation, which enhances CERN's economic impact in its Member and Associate Member States and benefits society as a whole. To do so, CERN actively cooperates with a variety of partners through procurement contracts, business opportunities, collaboration agreements, measures to encourage entrepreneurship and spin-offs, participation in projects co-funded by the European Commission and more.



The applications of CERN technologies extend beyond high-energy physics to a vast range of areas such as aerospace, medical and biomedical, industry 4.0, cultural heritage, safety, and efforts to build a better planet. (CERN-GRAPHICS-2021-004)

Many novel technologies emerge from the knowledge developed at CERN for particle physics. By identifying key technologies with potential societal impact, CERN seeks out opportunities to work with industry on a wide range of applications. In harmony with various CERN initiatives to address the Organization's environmental impact and in order to maximise the global positive impact in this area, CERN has now launched an Innovation Programme on Environmental Applications (CIPEA). This chapter features several other knowledge-transfer success stories from 2021. Additional examples are featured in chapter 2, "2021 in pictures" (pp. 6–11).

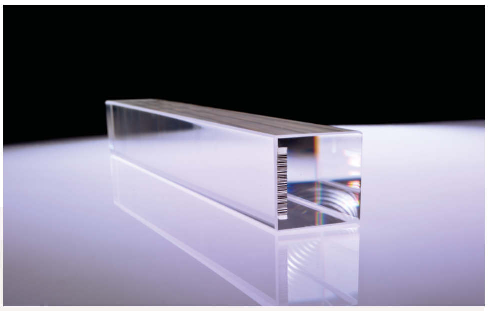
The Lumina experiment is part of the CERN–CNES bilateral collaboration framework and is supported by CERN's Radiation to Electronics (R2E) project.

CERN-TESTED OPTICAL FIBRES NOW ON THE INTERNATIONAL SPACE STATION

Just like the LHC at CERN, space is a complex radiation environment that requires bespoke dosimetry devices to protect the spacecraft, its crew and hardware from radiation. In August, European Space Agency astronaut Thomas Pesquet activated the Lumina experiment – whose development was coordinated by the French Space Agency (CNES) – inside the International Space Station. Lumina uses two several-kilometre-long optical fibres as active dosimeters to measure ionising radiation with very high sensitivity. Building on its experience of studying radiation effects on electronics and developing optical sensing solutions, CERN contributed to the theoretical model of the dosimeter and carried out the low- and high-dose irradiation tests needed to calibrate it.

MAKING AN IMPACT WITH CERN'S COVID AIRBORNE RISK ASSESSMENT TOOL

CERN developed the COVID Airborne Risk Assessment (CARA) software as an additional tool to help CERN office managers to evaluate the risk of COVID-19 infection in enclosed spaces and adopt appropriate measures. In 2021, following numerous requests from global health players and research institutes, CARA was released as open source. The software was used, for example, by specialists in infectious diseases to evaluate the effectiveness of different measures to limit SARS-CoV-2 aerosol transmission in schools. CERN was also invited by the World Health Organization (WHO) to bring the CARA expertise into ARIA, an international expert working group focused on developing standards for airborne transmission of respiratory pathogens. CARA has been repeatedly validated by experts in health science and is now used by researchers, advisory bodies and facility managers worldwide.



2021 marked 30 years of CERN's Crystal Clear Collaboration – exploring scintillating crystals for exciting new avenues not only in high-energy physics, but also in innovative medical applications like positron emission tomography. (CERN-EX-0803027-02)

DEEP-TECH STARTUPS: FROM LAB TO MARKET

Scattered around the Member States, the Business Incubation Centres of CERN technologies assist entrepreneurs in taking the Organization's technologies and expertise to the market. In 2021, the network was joined by three new startups: condenZero, pursuing resilient instrumentation in ultra-high vacuum and cryogenic conditions; Lumiphase, built around optical communication chips for harsh and radioactive environments; and Delta Bioscience, aimed at using microscale detection systems to build a next-generation drug-candidate screening platform.

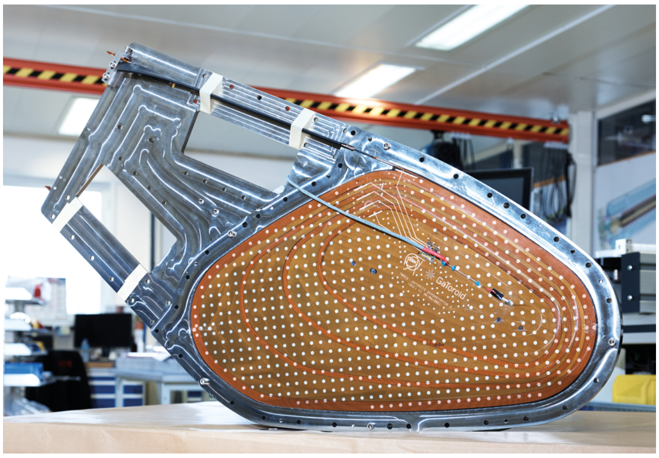
Also in 2021, CERN spin-offs TERAPET and PlanetWatch laid the foundations for future positive impacts on health and the environment. TERAPET benefited from CERN's expertise in scintillating crystals to develop its first full-scale prototype for non-invasive dose monitoring for cancer treatment. PlanetWatch's global environmental monitoring network rapidly expanded to encompass 32k+ connected sensors worldwide, including impact commitment from the city of Miami, United States.

A NEW FUND FOR TECHNOLOGY IMPACT

In March, the CERN Technology Impact Fund was launched – a new tool to bridge the gap between the technology developed for research at CERN and its potential applications in addressing societal challenges. The CERN & Society Foundation is actively supporting the fund and seeking external donors. Financial backing provided by the fund will enable selected CERN technologies to contribute to the 17 Sustainable Development Goals (SDGs) adopted by all United Nations Member States. The first technology selected was the Compact Precision Laser Inclinometer (CPLI). Originally intended for measuring ground movements around CERN's ATLAS detector, CPLI can be adapted as an extremely sophisticated early-warning system for seismic events, helping emergency response operations in regions prone to such natural disasters.

ONCOLOGY TREATMENTS OF TOMORROW

In 2021, CERN carried on its decades-long tradition of active technology transfer to several types of radiotherapy. CERN and Switzerland's Lausanne University Hospital (CHUV) continued work on an innovative facility for FLASH radiotherapy (p. 48). CHUV secured a large donation for the construction of a prototype. The NIMMS (Next Ion Medical Machine Study) activities continued to make headway on developing technologies for cancer therapy with ion beams. The collaboration between CERN and Spain's CIEMAT on a future carbon-ion therapy linear accelerator reached a milestone with the completion of the first of the four modules of the radiofrequency quadrupole. CERN also completed the assembly of the first high-temperature superconductor prototype coil for GaToroid, a novel non-rotating gantry for ion therapy.



In 2021, CERN finished assembling the first high-temperature superconductor prototype coil for GaToroid, a novel non-rotating gantry for hadron therapy invented by the Laboratory.
(CERN-PHOTO-202202-018-6)

DOING BUSINESS WITH CERN

Procurement is a fundamental aspect of CERN's economic impact in its Member and Associate Member States: advancements in accelerators, detectors and computing take shape through successful business collaborations, helping drive innovation in a variety of industries. In the light of the findings of CERN's second Environment Report, the Procurement Service launched the CERN Environmentally Responsible Procurement Policy Project (CERP3) with the aim of reducing greenhouse gas emissions from the supplies and services procured by CERN.

In 2021, CERN continued procurement for the HL-LHC, for the ATLAS and CMS Phase 2 upgrades, and for the operation and maintenance of the CERN accelerator complex. In line with CERP3, special attention was given to sustainable projects, such as the supply of refrigeration systems for the ATLAS and CMS experiments using CO_2 coolant instead of hydrofluorocarbons. Overall, CERN's procurement activities included 26 000 orders of various types, 77 invitations to tender, 90 price enquiries above 50 000 CHF, and the signature of 223 contracts, 105 of which were collaboration agreements. Expenditure on various orders and contracts totalled 472 MCHF (approximately 39% of the budget).

The Procurement Service organised virtual industry events in 2021 with Denmark, Germany, India, Italy, the Netherlands and the United Kingdom, with 29% of the industry days focused on very poorly balanced Member States. A total of 143 firms participated in these events, and their representatives held more than 550 business-to-business meetings with CERN personnel. These events are important not only for matching industry capabilities with CERN projects and needs, but also for addressing the challenge of achieving balanced industrial return across the Member and Associate Member States. A Baltic conference was also held to establish close contacts with industry in the new Associate Member States.

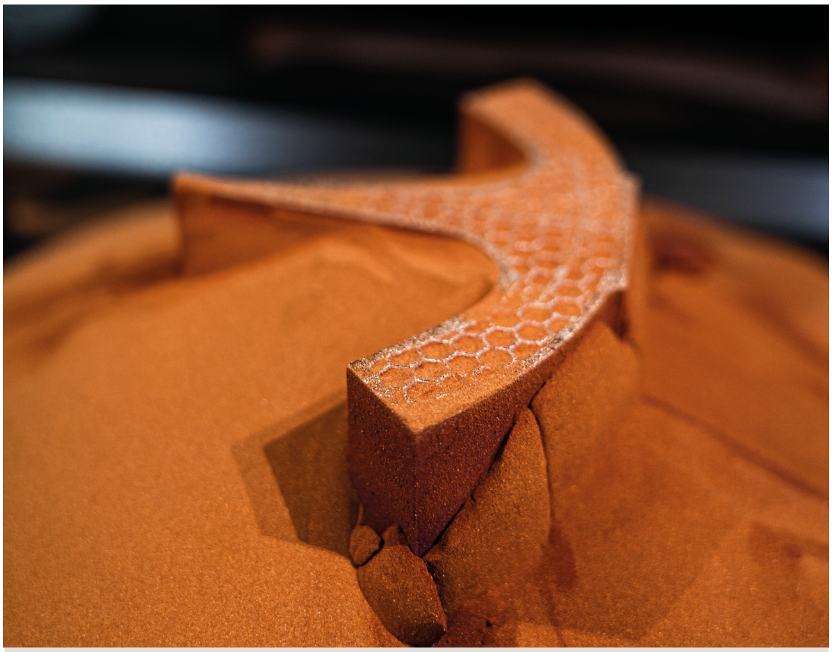
COVID-19 measures continued to impact the operations of CERN and its industrial partners in 2021. Similarly, disruptions to international supply chains and increases in the price of raw materials have become a growing concern. Nevertheless, in the spirit of collaboration with its contractors, the Procurement Service managed to find pragmatic solutions to ensure the continued performance of ongoing supply contracts and to limit delays or cost increases.

During 2021, the Procurement Service negotiated reductions of over 20 MCHF on submitted bid prices – a strong result for mostly lowest-compliant-offer tendering processes.

ATTRACT ENTERS PHASE 2

Phase 1 of the ATTRACT project supported 170 breakthrough technology concepts in the field of detection and imaging technologies across Europe. Implementing Phase 2 in 2021, it launched three open funding calls for total funding of EUR 28 million:

1. The most promising opportunities arising from ATTRACT Phase 1, for a smooth transition from the lab to the market;
2. Young innovators from universities developing ideas and prototypes for social innovation in collaboration with professional researchers within the ATTRACT ecosystem;
3. Professional scholars undertaking a socioeconomic study of the ATTRACT initiative.



Additively manufactured copper components for linear accelerators.

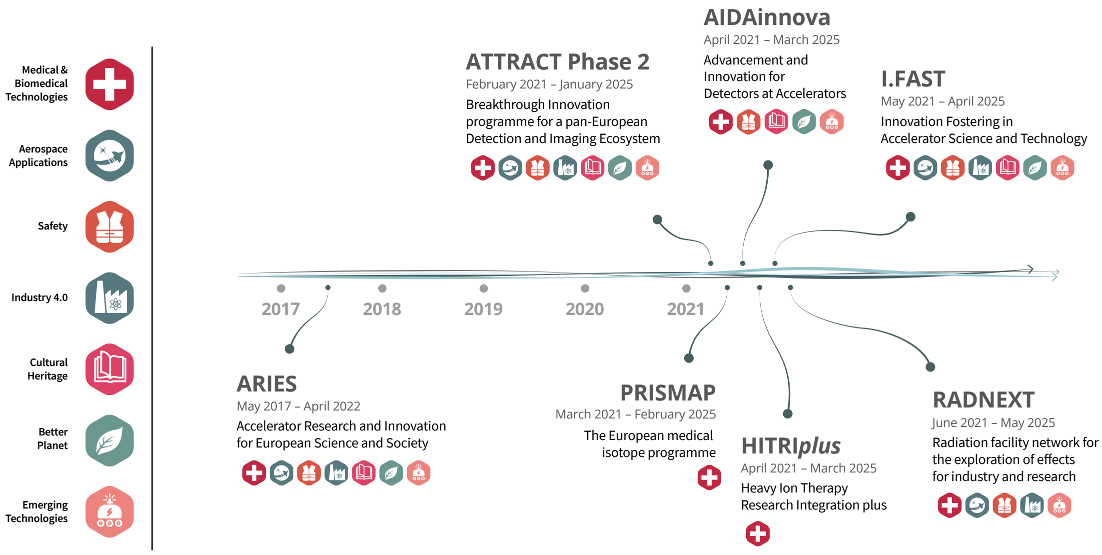
ADDITIVELY MANUFACTURED COPPER COMPONENTS FOR LINEAR ACCELERATORS

Over 30 000 accelerators are currently in use worldwide, most of which are used for healthcare, environmental and industrial purposes. 3D printing, also known as additive manufacturing, is one way to make such accelerators more accessible to users.

In 2021, through the CERN-coordinated I.FAST project, researchers succeeded for the very first time in additively manufacturing an accelerator quadrupole component, which is essential for linear particle accelerators. Made of pure copper powder, this component has a hollow structure that helps save both material consumption and manufacturing time. This achievement was made possible by the Fraunhofer Institute for Material and Beam Technology, together with CERN, Riga Technical University and the Polytechnic University of Milan, all partners of I.FAST.

INNOVATING WITH EU PROJECTS

As the leading European particle physics organisation, CERN actively participates as a partner in and/or coordinates projects co-financed by the European Union (EU) under its framework programmes for research and innovation. In 2021, CERN was involved in 57 EU projects and coordinated 20, with the corresponding European Commission contribution to CERN amounting to some 44.8 million EUR. Additionally, six new projects with a strong knowledge-transfer component got under way (AIDAinnova, ATTRACT, HITRI*plus*, I.FAST, PRISMAP and RADNEXT). Total EU funding for those six projects amounts to some 70 million EUR, distributed among the participating institutes and companies.



EU-funded projects with a strong knowledge-transfer component.

INSPIRING AND EDUCATING

The science and technology underpinning CERN's research have immense potential to inspire students to pursue careers in science and engineering, as well as to enthuse and engage citizens of all ages in the wonder of science and its impact on our daily lives.

Despite the changes imposed by the COVID-19 pandemic, in 2021 CERN continued to reach audiences across the Member States, Associate Member States and beyond, with a rich mix of online and in-person activities.

Construction of Science Gateway, CERN's new education and outreach centre, is proceeding apace. (CERN-PHOTO-202201-003-11)

REOPENING DOORS TO THE PUBLIC

With some easing of COVID-19 measures, CERN was again able to welcome visitors on site: 22 000 people visited the Microcosm exhibition, with 18 000 of them taking part in guided tours. The Globe of Science and Innovation again bustled with activity: a total of 46 events took place, including 40 science shows. Several were live-streamed online, thus reaching a much wider audience than just those in attendance in the Globe.

A concerted move to online formats, begun in 2020, ensured strong and sustained engagement. A total of 249 virtual talks and tours for schools and the general public, in eight languages, reached around 7700 participants. The majority (74%) of the participants were students.

Despite the constraints imposed by COVID-19, a total of 79 visits by decision makers from CERN Member States, Associate Member States and other countries took place, 80% of them on site.

In preparation for the complete re-opening of the Laboratory to the public, work progressed at several visit points. The first part of LHCb’s new exhibition, with a fully immersive experience, was completed. A new exhibition focusing on CERN Science Gateway was developed and installed on the Esplanade des Particules, to be enjoyed by visitors and the CERN community alike.

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

Construction of CERN Science Gateway progressed visibly in 2021, notably with the placement of the two iconic tubular structures and the bridge over the Route de Meyrin.

The three main visitor experience areas – exhibitions, education labs and events venues – made great strides. The final designs of the three exhibitions (Discover CERN, Our Universe and Quantum World) were completed and prepared for sign-off. The artworks that will accompany the main artwork of the Exploring the Unknown exhibition were selected.

In the education labs, enquiry-based activities began to be prototyped and the necessary infrastructure for the laboratories defined. An international workshop for science shows was held in April, bringing together experts from across the globe. The outcomes are being fed into the development of the science shows for CERN Science Gateway.

The auditorium will be a prime venue for scientific, public and private events, so equipping it effectively is key. In 2021, the market survey for the audiovisual infrastructure of the auditorium was developed.

Fundraising efforts continued: 78 MCHF out of a total requirement of 87 MCHF has been raised, exclusively through external donations. The opening of CERN Science Gateway is scheduled for summer 2023.

ENGAGING LOCALLY AND GLOBALLY

Engaging with CERN’s neighbours has always been an important part of the Laboratory’s outreach activities. The International Day of Women and Girls in Science has become a regular and very successful fixture. In 2021, 40 volunteers from CERN, EPFL and the University of Geneva were able, despite very stringent COVID-19 measures, to talk about working in science to more than 1350 schoolchildren in the local area, either in person or online.

For the tenth edition of Be a Scientist, around 780 students from local schools were introduced to the scientific process through investigations into the contents of mystery boxes.

CERN’s travelling exhibitions (both the flagship Accelerating Science exhibition and the LHC Interactive Tunnel) travelled to Ukraine, Germany and Portugal, attracting an estimated 10 000 visitors.

2021 marked the 10th anniversary of the Arts at CERN programme, and the CERN Cultural Board was relaunched. Eleven artists took up on-site residencies and several of the programme commissions were again shown in leading art museums worldwide, including the Grand-Hornu (Belgium), Centre Pompidou-Metz (France), Sprengel Museum (Germany), MIT List Visual Arts Center (United States) and LUMA Arles (France).

Volunteers from CERN, EPFL and the University of Geneva visited schools in the local area to mark the International Day of Women and Girls in Science. (OPEN-PHO-LIFE-2022-002-9)

Fifty participants from CERN, academia, industry and policy discussed Future Intelligence at the Sparks! forum. (CERN-PHOTO-202109-131-11)

CURATING SERENDIPITY

The first edition of Sparks!, the serendipity forum at CERN, took place in September, on the theme of Future Intelligence. CERN is ideally placed to host this new annual, two-day multidisciplinary science innovation forum and public event, where discussions are guided to conclusions that will benefit society as a whole. Sparks! brings together scientists from diverse fields with decision makers, representatives of industry, philanthropists, ethicists and the public.

Carried out in a hybrid format, Sparks! 2021 encompassed a closed discussion forum with 50 participants from CERN, academia, industry and policy, and a public event, which included thought-provoking presentations and a Q&A with leading scientists in the field of artificial intelligence. A CERN Yellow Report on the outcomes of the closed forum is in preparation.

Videos of the individual talks and discussions held during the public event have been published on CERN's YouTube channel.

WORLDWIDE MEDIA INTEREST

Media interest in CERN remained high in 2021, with 190 journalists visiting CERN on 75 organised media visits, and just over 143 000 press clippings from media outlets across CERN's Member States, Associate Member States and beyond. The LHCb collaboration's findings on the decay of beauty quarks (p. 17) generated the highest media coverage and journalist engagement.

Media visits are a crucial way of sustaining interest in and knowledge about CERN. To complement the on-site media visits, a programme of online national media visits was launched: 12 journalists from eight Swedish media outlets took part in a tailor-made programme.

GROWING CERN'S DIGITAL PRESENCE

In May, the CERN home website introduced a new cookie policy in order to be fully compliant with GDPR, allowing visitors to opt out easily from tracking tools. Extrapolated data obtained using analytics tools shows that CERN's strong digital presence continued in 2021, with approximately 5 million visitors to the home website. A total of 172 news stories about the Laboratory's activities were published on CERN's home website. News of physics results accounted for 20% of these publications.

CERN's presence on social media generated 127 million views and high levels of engagement, reaching up to 347 200 people with a single post. Seven multichannel live broadcasts covering LS2 milestones and other key events were produced, reaching over 300 000 people.

The *CERN Courier* magazine is estimated to have reached 100 000 readers in 2021, with 335 000 unique visitors to cerncourier.com. The new *CERN Courier* webinar series was launched, with six events supporting CERN's strategic objectives attracting approximately 3000 participants.

EMPOWERING TEACHERS AND STUDENTS

Despite the cancellation of on-site teacher programmes due to the COVID-19 pandemic, 15 online programmes were held in 2021, thus sustaining the crucial relationship with teacher communities across the globe. A total of 1900 teachers from 79 countries took part in the online programmes.

Each year, several thousand students have the opportunity to experience first-hand the cutting-edge research being carried out at CERN. S'Cool LAB activities resumed in November, in compliance with the COVID-19 measures in force, with 118 participants. In addition, the S'Cool LAB team delivered live and interactive online science shows, with a total of 2679 participants from 16 countries.

Five High-School Students Internship Programmes (Belgium, Denmark, Greece, Romania and Switzerland) took place. The Beamline for Schools competition allowed two winning teams from Italy and, for the first time, Mexico to carry out their winning proposals at DESY, in Hamburg, Germany, due to CERN being in the Long Shutdown period. Once again, participation in this competition broke records, with 289 teams from 57 countries submitting proposals.

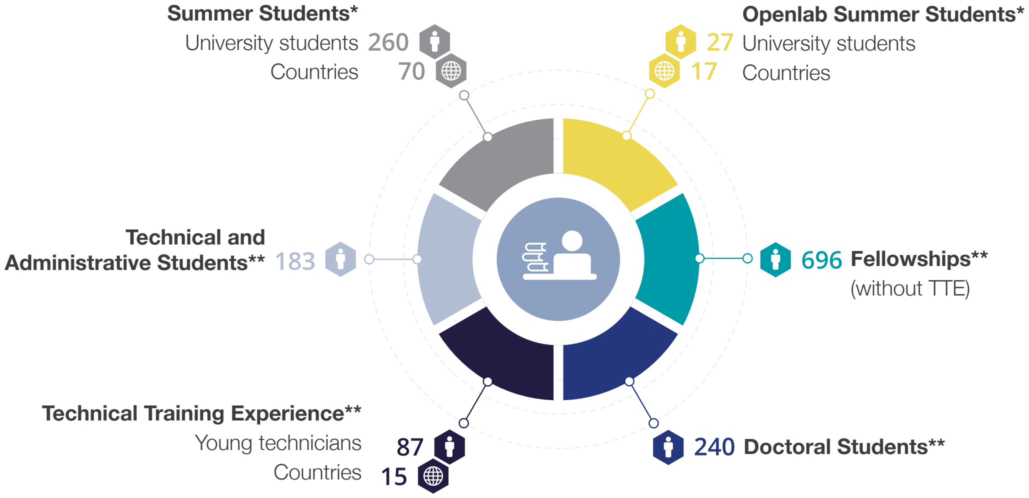
TRAINING YOUNG RESEARCHERS

CERN offers a unique learning environment for students and young professionals, providing them with excellent technical skills and international experience, which makes them highly qualified for business and industry in CERN's Member and Associate Member States. In 2021, some 783 fellows and over 420 doctoral, technical and administrative students, 118 trainees and some 215 short-term interns all took part in these unique opportunities to work and learn. In addition, more than 280 summer students were selected from over 70 countries for a comprehensive online experience of this key programme, once again impacted by the COVID-19 pandemic.

Due to the COVID-19 pandemic, the 2021 CERN Openlab Summer Student Programme was held in a fully online format for the first time ever, with 27 students from 15 countries participating. Virtual visits were organised for the students and the lectures were made available online to a broader audience, garnering much interest.

The CERN Entrepreneurship Student Programme (CESP), a launch pad for the next generation of technical entrepreneurs, provided a great opportunity for technical master's-level students from five different countries (Canada, India, Mexico, North Macedonia and the United Kingdom) to develop their entrepreneurial skills, working with experts from within and outside CERN.

Training programmes at CERN



* Number of selected summer students. However, given that the programme had to be adapted to an online format in the context of the pandemic, only a subset could finally participate in the virtual projects proposed.

** as of 31.12.2021

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

A SUSTAINABLE RESEARCH ENVIRONMENT

CERN is fully committed to ensuring the health and safety of everyone participating in its activities, present on the site or living in the vicinity of its installations, and strives to limit its impact on the environment.

COVID-19

As an international organisation straddling the Franco–Swiss border, with researchers coming from all over the world, CERN has been particularly challenged by the COVID-19 pandemic. From the early stages of the pandemic, CERN put in place specific COVID-19 health and safety measures, which it updates regularly to reflect both the evolving regulations in its Host States and scientific findings and recommendations.

Testing is an important part of CERN's toolbox in protecting its community from COVID-19 transmission. Two types of testing were used in 2021: stratified testing of people who are critical for CERN's business continuity and, to accompany the return of personnel on site, testing using a pooling technique that is open to anyone who is asymptomatic. In total, the Laboratory carried out over 11 000 tests during the year.

In the autumn, the Organization opened a COVID-19 vaccination centre on the Meyrin site in collaboration with the French and Swiss authorities. The centre was open to members of the personnel and their families, as well as retirees and contractors' personnel, and is part of both the French and Swiss vaccination campaigns. It has administered both first and second doses as well as booster shots.

Furthermore, CERN developed the COVID Airborne Risk Assessment (CARA) tool to assess the risk of COVID-19 infection in enclosed spaces like offices and meeting rooms. In June 2021, CERN presented CARA to the World Health Organization's COVID Expert Panel (p. 33).

The opening of CERN's COVID-19 vaccination centre in September. By the end of 2021, CERN had administered over 1500 vaccine doses. (CERN-PHOTO-202109-140-11)

An emergency response exercise was held at Point 5 of the LHC in November 2021, involving the CERN Fire and Rescue Service and French and Swiss safety and rescue teams. The 260 participants worked for almost four hours both on the surface and down in the CMS and HL-LHC caverns. The exercise was conducted as part of the tripartite agreement between CERN, France and Switzerland on mutual aid in emergencies.
(CERN-PHOTO-202111-17-176-27)

ENVIRONMENTALLY RESPONSIBLE RESEARCH

A dedicated communication campaign, running from June 2021 to June 2022, highlights CERN's commitment to environmental protection and raises awareness of environmental issues related to CERN's activities. The campaign was officially launched by the Director-General in June 2021 and has since featured a series of articles and dedicated events. Another highlight of 2021 was the publication of CERN's second public Environment Report, covering the years 2019 and 2020.

On the occasion of the UN Climate Change Conference (COP26), the European Intergovernmental Research Organisation forum (EIROforum) and the US Department of Energy's national laboratories held a workshop on uniting science to tackle climate and clean energy challenges. Key leaders and researchers from 25 scientific laboratories affirmed their common commitment to work together to contribute to a sustainable and resilient global society and economy.

RADIATION PROTECTION SUPPORTING CERN'S PRESENT AND FUTURE ACTIVITIES

CERN's Radiation Protection (RP) group provided much-appreciated support during LS2. RP personnel approved more than 3000 works in areas where ionising radiation is present and measured more than 1800 items taken out of the accelerator facilities. Compared with LS1, LS2 saw more ALARA ("as low as reasonably achievable") level 3 works, which can potentially deliver a significant dose to workers. Nevertheless, operational doses were lower than in LS1 thanks to an efficient process aimed at systematic dose optimisation and taking into account the lessons learned from past interventions for future work and dose planning. All doses stayed well below legal limits.

The RP group also supported the facilities' restart, in particular through studies and simulations, with some prominent examples being the new nitrogen-cooled n_TOF target and new radiation shielding of the East Area.

A hydrogeological study of a deep aquifer under the Prévessin site was conducted for environmental monitoring purposes. The study involved geophysical surveys, drilling, pumping, tests, core analyses and water-level follow-up. The deep aquifer is now fully characterised and can be monitored.

Furthermore, a new RP signage scheme was implemented in 2021, reflecting best practice in European countries, with the corresponding CERN rules and training updated accordingly.

NEW FRAMEWORK FOR SAFETY INCIDENT MANAGEMENT

In 2021, a new framework for safety incident management was implemented. A new safety rule defining roles and responsibilities in matters of safety incident management was published and a new declaration form and process released. The aim of the new rule and process is to encourage and facilitate safety incident declaration and follow-up, which are key for the continuous improvement of safety at CERN.

IMPROVING CABLE SAFETY

Following the findings of a dedicated working group whose work spanned three years, CERN launched a Cable Ageing Research (CARE) project in 2019. The project focuses on cables exposed to radiation and considers different parameters, such as thermal cycles, various loads, personnel safety and the cost of cable procurement and replacement.

In 2021, the CARE project developed methods for selecting the right cables for the HL-LHC. An irradiation campaign was conducted at an external facility, and thermal ageing testing and simulations were carried out at CERN. A dedicated project database was also set up.

BUILDING TOMORROW AND BEYOND

In the underground caverns and tunnels, the laboratories, workshops and meeting rooms of the Organization's vast site, the CERN community continued to build its future in 2021. The year's busy menu included preparations for the imminent restart of the accelerator complex, work to complete the comprehensive upgrade – the High-Luminosity LHC – by 2027 and initial consideration of the LHC's successor.

The main gallery of the newly built underground structure for the HL-LHC at Point 1. (CERN-PHOTO-202105-067-6)

On 23 September, CERN Council delegates visited the new underground cavern at Point 1.
(CERN-PHOTO-202109-139-11)

CONSTRUCTION OF THE HL-LHC'S CONCRETE AND STEEL ENVELOPE WAS COMPLETED IN 2021.

FOLLOWING THE PATH MARKED OUT BY THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

The many programmes, projects and activities that CERN continued to work on in 2021 follow the guidelines of the European Strategy for Particle Physics, whose 2020 update set out the Organization's medium- and long-term future. Approved in 2006 and updated in 2013 and 2020, the European Strategy for Particle Physics is the result of a process of scientific deliberation that lays the foundations for the future of particle physics in Europe, with CERN at the forefront of the players and beneficiaries. The latest update of the Strategy, which was published following a participatory process that involved the particle physics community as widely as possible, places the full exploitation of the Large Hadron Collider (LHC) and the High-Luminosity LHC (HL-LHC) at the centre of European particle physics in the years to come. The updated Strategy identifies an electron–positron collider operating as a "Higgs factory" as the priority facility after the LHC. The realisation of this future accelerator will depend on the results of a study of its technical and financial feasibility, as recommended by the Strategy. The Strategy states that CERN should, in parallel, continue to support particle physics experiments and facilities worldwide and step up its research and development activities on state-of-the-art accelerator, detector and computing technologies. In 2021, CERN pursued its efforts to meet the many expectations of the European Strategy in order to ensure a bright future for particle physics.

THE HIGH-LUMINOSITY LHC

Tangible, concrete, physical: the HL-LHC project, which remains CERN's primary goal in the medium term, reached a turning point in 2021, when the development and prototyping phases were succeeded by the industrial production and large-scale work phases, some of which are already nearing completion. The aim of the HL-LHC project is to increase the integrated luminosity of the LHC so that it produces ten times more collisions in twelve years than those that will have been produced by the end of 2025, when installation in the LHC tunnel is due to begin. The progress achieved in 2021 set the project on course for the start of operation during the fourth run, despite a delay of several months caused by the COVID-19 pandemic.

Construction of the HL-LHC's concrete and steel envelope was completed in 2021. Excavation of two underground caverns parallel to the LHC, designed to house the HL-LHC's equipment, progressed at a steady pace throughout the year. The caverns and tunnels near LHC Points 1 and 5, which cover an area of several hundred square metres, were completed in the autumn, and the first components of the technical infrastructure were lowered underground. The first four surface buildings on the two HL-LHC sites were constructed and delivered during the year. They will house various facilities, including the cooling systems for the upgraded accelerator.

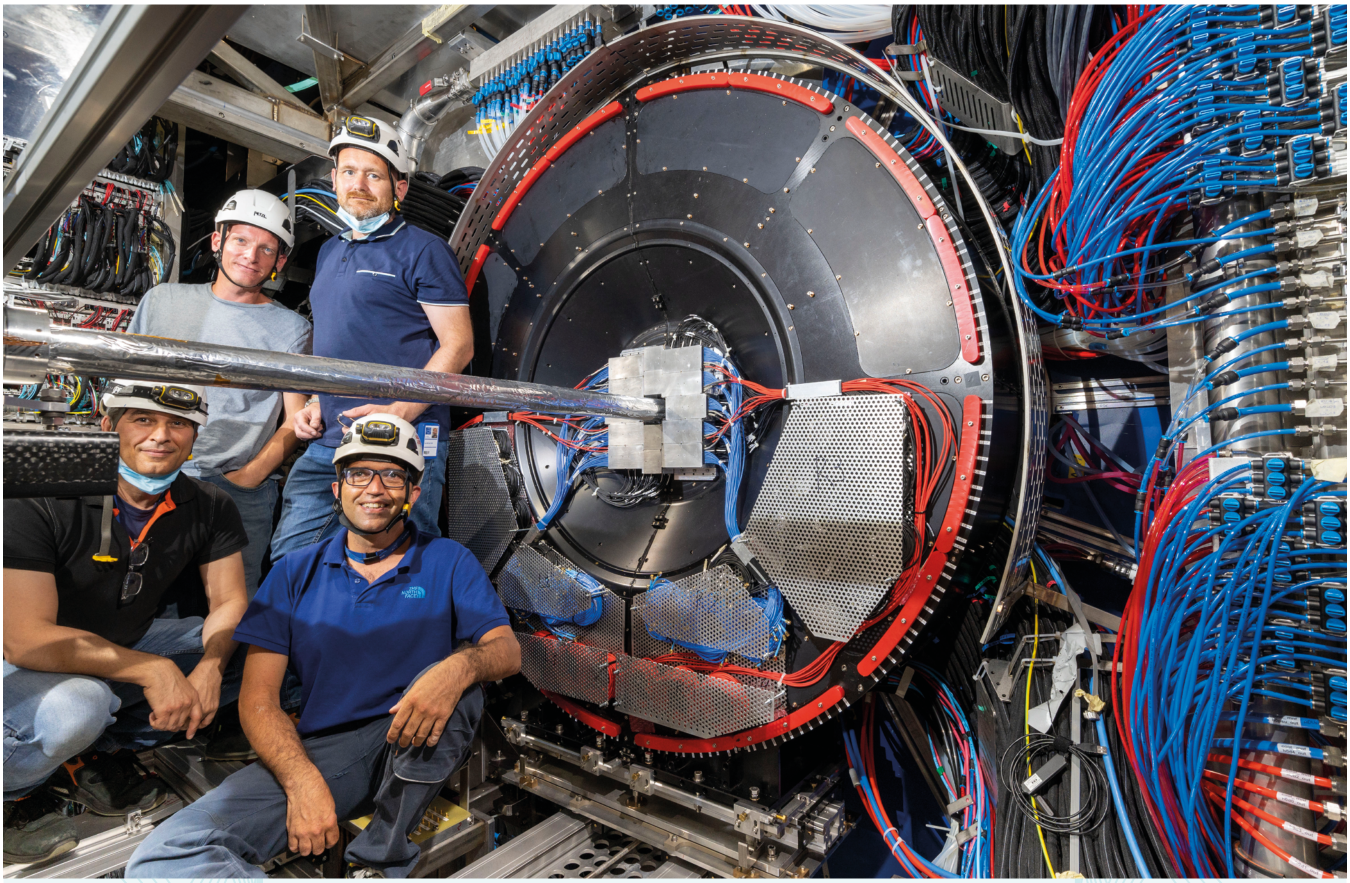
A new quadrupole magnet "MQXFA05" is tested at the Brookhaven National Laboratory, in the United States.

Innovative magnets, which are a key feature of the HL-LHC programme, are being designed, prototyped and produced to allow the new accelerator to correctly focus particle beams of extraordinarily high luminosity. New and more powerful quadrupole magnets, known as "triplets", will be used to focus the beams before they collide inside the ATLAS and CMS detectors. The short (4.2 metre) versions of these quadrupoles are being built in the United States, while the long (7.2 metre) versions are being designed and tested at CERN. The test of the first full-sized quadrupole at CERN in 2020 revealed a fault in one of the four magnet coils, which prevented the magnet from reaching its nominal energy of 7 TeV. In 2021, the magnet assembly procedures were reviewed and a new production process, taking the tests carried out on the failed magnet into account, was agreed. Further testing is planned for 2022. In parallel, production of the short magnets is continuing in the United States, and two new fully functional examples were produced in 2021. However, the production processes for future magnets had to be revised after performance limitations were detected in one of the four magnet coils of the last two magnets that had been built. Such adjustments are nothing unusual in the production of components of this kind. Other achievements relating to the HL-LHC magnet programme included the finalisation and successful testing of the first D1 prototype, a dipole "beam splitter" magnet, at KEK, Japan, and the assembly of its D2 counterpart at INFN in Genoa, Italy. The latter is due to be tested at CERN in 2022. Finally, following optimisation of prototypes designed at CIEMAT in Spain, industrial production of the nested-coil corrector magnets began, and production of the nine families of corrector magnets at the INFN LASA in Milan was completed towards the end of the year.

The design and construction of crab cavities is another crucial aspect of the HL-LHC programme. These radiofrequency cavities will be used to tilt the bunches of accelerated particles in order to perfect the superposition of two colliding bunches and thus maximise the luminosity at the collision point. In 2021, the construction of the first two RFD (radiofrequency dipole) crab cavities was finalised at CERN and tests confirmed their efficiency, while another type of crab cavity, the DQW (double-quarter wave) cavity, was successfully tested at the SPS.

Like the magnets, the crab cavities now benefit from a top-tier test centre outside CERN and its SM18 facility as, in 2020, the FREIA laboratory at Uppsala University in Sweden adapted its infrastructure to accommodate both types of components in optimal cryogenic and vacuum conditions. The HL-LHC project put this infrastructure to good use in 2021. In other good news for the project, the small multi-purpose CRANEbot robot, which was developed at CERN to carry out maintenance work in irradiated environments, has been proving its worth since February 2021. It will greatly facilitate the handling of equipment for the HL-LHC that cannot be done by technicians because of the level of irradiation.

A Double-Quarter wave cavity at CERN. This technology was successfully tested at the SPS in 2021.
(CERN-PHOTO-202106-077-9)



The installation of the FIT subdetector marked the end of installation works on the ALICE detector for Long Shutdown 2.
(ALICE-PHO-INSTALL-2021-001-3)

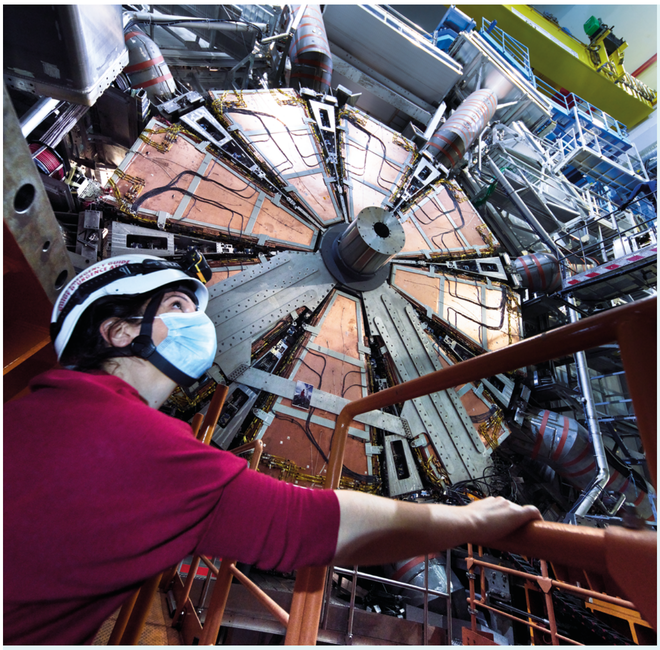
THE LHC EXPERIMENTS AT THE DAWN OF RUN 3

ALICE

Following the installation of the upgraded Time Projection Chamber (TPC), the new beam pipe and the Muon Forward Tracker (MFT) in 2020, the first half of 2021 was dedicated to the installation and pre-commissioning of the ITS2 (Inner Tracking Detector 2). This novel silicon pixel detector forms the heart of the ALICE upgrade and will allow unprecedented tracking and vertexing performance. The sharp increase in Pb–Pb (lead ion) collisions, together with a new continuous readout system, will increase the statistics for many physics topics by a factor of 100. The ALICE computing farm (Event Processing Nodes), which will be able to process all this data, was installed in January 2021. The ALICE upgrade installation work was completed in July with the installation of a final detector, the Fast Interaction Trigger (FIT). The following global commissioning culminated in very successful data taking during the pilot beam run in October 2021. In parallel with the upgrade and commissioning activities, the collaboration was busy preparing for future ALICE upgrades. Progress was achieved on two upgraded detectors planned for LS3: the ITS3, consisting of three layers of wafer-scale pixel sensors with extremely low materials requirements, and FOCAL, a highly granular forward electromagnetic calorimeter. Finally, in 2021, the ALICE collaboration prepared a letter of intent for ALICE3, an entirely new detector that will allow the full exploitation of the LHC for heavy-ion collisions in Runs 5 and 6.

ATLAS

The completion of the construction of ATLAS's New Small Wheels (NSW) and their installation in the ATLAS detector in the summer of 2021 was a major achievement for the collaboration and for CERN. A cornerstone in ATLAS's massive upgrade, the NSW subdetectors will give the experiment much more stringent selection criteria for muons, allow it to better handle high background and high pile-up rates and thus cope with the higher luminosity of the future HL-LHC. As well as reaching this milestone, the ATLAS collaboration completed all of the necessary upgrades in time to start commissioning in autumn 2021, which puts the experiment on track to start taking LHC proton collision data by mid-2022. Among the many achievements of the year, the new front- and back-end electronics for the Liquid-Argon Calorimeter were installed, involving the replacement of parts of the front-end boards and electronic crates. The near and far forward proton detectors (spectrometers that track protons in the forward region of the detector) were installed, incorporating a time-of-flight system in the far station featuring new photomultiplier tubes. On the software side, ATLAS physicists will now enjoy a sleeker and simplified readout architecture thanks to FELIX, a new readout system whose installation in 2021 was made possible by the efforts of the Trigger and Data Acquisition group (TDAQ). New data-analysis software based on multi-threading will also help



New Small Wheel (NSW) descent into ATLAS' "side A" of the experimental cavern. *(CERN-PHOTO-202107-094-113)*

to reduce the amount of storage resources needed for data analysis. Looking ahead to the next shutdown of the accelerators – which will be crucial in preparing ATLAS for higher luminosity – the design and production of next-generation detectors continued in 2021. Several of the new Inner Tracking Detector (ITK) components, including the 3D sensors and planar sensors, moved from final design to production. Prototypes of the front-end boards of the liquid-argon calorimeters were successfully tested, as were new components of the next-generation tile calorimeter. Progress was also made on the Muon System, whose small-diameter Monitored Drift Tube (sMDT) chambers entered production at the end of 2021.

CMS

Subdetector installation work in the CMS cavern progressed well throughout 2021, in time for the detector to be whole again by the time of the pilot beam test in October. The installation of the new beam pipe, a fragile component, was particularly challenging. This centrepiece of the detector was designed for the High-Luminosity phase of the LHC, was optimised to reduce radiation hazards, and was fitted out with a new set of vacuum pumps designed to facilitate maintenance. A few months later, a refurbished pixel tracker with improved resilience to radiation damage was wrapped around the beam pipe. Subdetectors that will measure luminosity at the collision point were also installed in September: the full Beam Radiation Instrumentation and Luminosity (BRIL) kit, whose technical design reports were submitted by the experiment in 2021, is scheduled to be installed during LS3 in preparation for the high-luminosity upgrade. The online and offline monitoring software was improved, as were the strategies aimed at selecting new topologies, such as long-lived particles, from the background noise. The timely rebuilding of the CMS detector allowed successful commissioning based on cosmic-ray data and a short period of proton–proton collisions at the injection energy. In 2021, as well as finalising the LS2 activities, CMS made progress in the development of the Phase 2 upgrades, the last round of detector upgrades before the leap to higher luminosities. In the muon system forward region, the first station of gas electron multiplier (GEM) chambers was installed, as were demonstrators for GEM and resistive plate chambers that will be tested during Run 3. In parallel, prototypes of new sensors for the forward calorimeter were successfully produced: these radiation-hard sensors will increase the resilience of the subdetector in the context of higher radiation rates. Finally, the outer tracker, CMS's next-generation silicon detector scheduled for installation during LS3, received new sensors and ASIC chips, while the barrel calorimeter reached an advanced stage of prototyping.

LHCb

At LHCb, unlike other LHC experiments such as ATLAS and CMS, most of the upgrades designed to prepare the detector for high luminosity were carried out during the second long shutdown, which came to an end in 2021. During Run 3, the LHCb detector will record collisions at ten times the previous rate. Almost the entire detector was dismantled and its various components were then upgraded through ambitious development projects and began to be reinstalled in the cavern in 2021. The highlights of 2021 included the installation of the beam pipe – whose conical shape is unique at the LHC – and of the SciFi subdetector – an exceptionally precise scintillating-fibre tracker that was installed in May. Lastly, the two RICH (ring-imaging Cherenkov) subdetectors, which identify charged particles, were installed on either side of the LHCb magnet in the autumn. The production and assembly of the components of the brand new VELO (Vertex Locator), a subdetector for tracking B mesons, took place in parallel, and the subdetector's installation is scheduled for 2022. 2021 also saw the implementation of a first-level trigger based on GPUs (graphics processing units) in addition to the usual CPUs (central processing units) that are involved in the second-level trigger, as well as the repair and successful testing of the coils of the detector's magnet.

A surveyor from CERN performs levelling measurements for the Future Circular Collider Feasibility Study.
(CERN-PHOTO-202105-071-3)

THE FUTURE CIRCULAR COLLIDER

The Future Circular Collider (FCC) Feasibility Study, which was launched in 2020 following the update of the European Strategy for Particle Physics, continued in 2021. The FCC, with a circumference of almost 100 km, would start out as an electron–positron Higgs factory for studying in detail the properties of this unique particle and how it interacts with other particles. In the longer term, the machine would be converted into a hadron collider of unprecedented energy (at least 100 TeV), giving physicists access to energy regions where as yet undiscovered particles might be found. The Feasibility Study, whose final organisational structure was approved by the CERN Council in June, focuses on the technical, financial and social aspects of building such an accelerator. The Study made some initial headway in 2021, particularly in relation to the machine's placement and system design and the mobilisation of international partners.

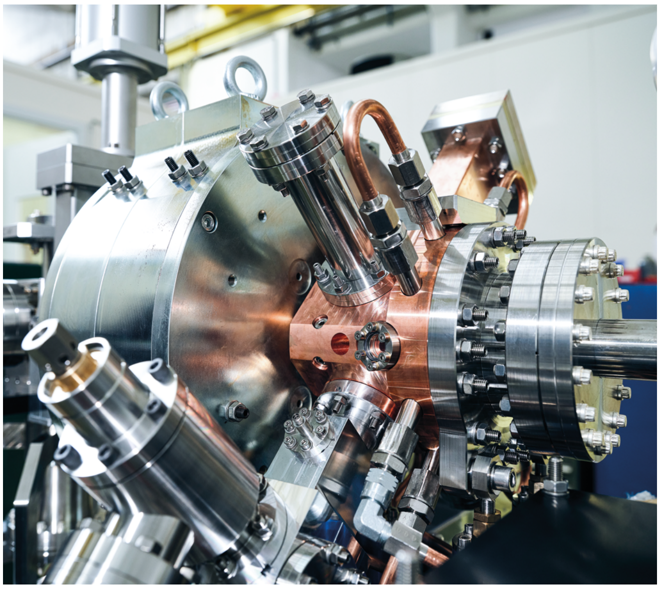
The proposed placement of the tunnel, which was the first major question mark for this large-scale project, was presented in June 2021 following in-depth studies of the terrain through which the accelerator would pass. The preferred option envisages a 91.2 km underground ring with eight sites on the surface. This scenario will form the basis for discussions with the Host States as well as for the geological surveys – which were launched in 2021 – of the areas identified as of the most challenging for the tunnel's construction.

The design projects for the FCC systems continued with the support of European institutes. Because of its scale, the future accelerator will rely on cutting-edge superconducting magnet and radiofrequency technology of unparalleled energy efficiency and cost-effectiveness. Two alternative designs for new radiofrequency cavities have been studied and R&D work has been carried out on klystrons, the tubes filled with electrons that, when placed in the centre of a radiofrequency cavity, produce the electric field that accelerates the charged particles. In parallel, a design study for the electron–positron collider's pre-injector was pursued in collaboration with the Paul Scherrer Institute (Switzerland) and with the support of IJClab (France) and INFN (Italy).

With the FCC Feasibility Study in its first year, its success relies on the growing mobilisation of international partners to achieve the technical results that satisfy the conditions required to build the accelerator. To this end, events like the online FCC Week in May 2021, which brought together 688 participants to address the project's challenges over the course of 128 different presentations, are encouraging signs for the groups involved in the project at CERN. The FCC Innovation Study workshop, a two-week event held at CERN, also demonstrated the enthusiasm of CERN's international scientific partners for the project. Speakers from DESY (Germany), INFN (Italy), CEA (France), LAPP (France), IJCLAB (France), PSI (Switzerland), SLAC (United States), KEK (Japan) and CLS (Canadian Light Source) helped sow the seeds for the innovations that will make the FCC possible. The involvement of international partners will also make the project more sustainable: through the "Mining the Future" competition, dozens of research institutes presented their ideas for smart and environmentally friendly ways to reuse the excess molasse rock that will be produced by the tunnel's excavation.

CLIC

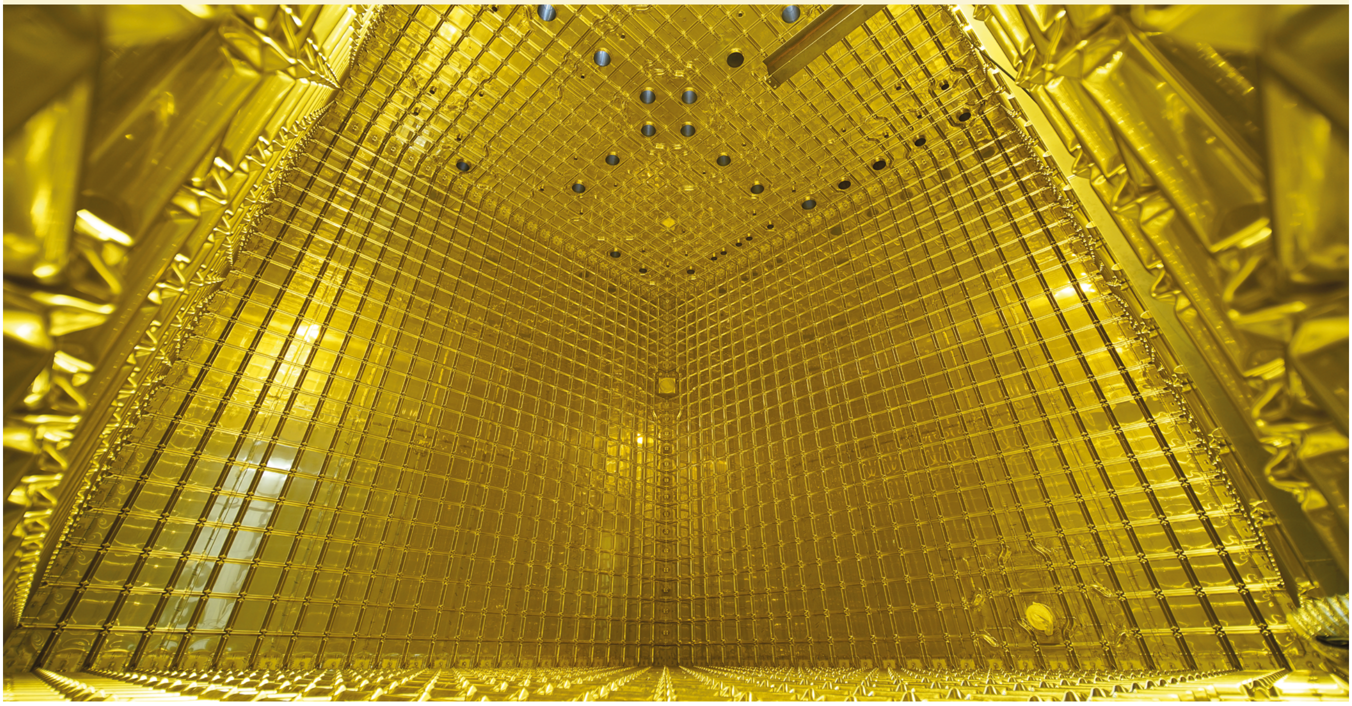
The Compact Linear Collider (CLIC) project has been developing technologies for several years with a view to the construction and operation of a high-luminosity electron–positron linear collider. The R&D work on key CLIC technologies is continuing in order to make sure that CLIC remains a viable option for a future collider at CERN. Thanks to this work, in 2021, CLIC continued to promote technological innovation in accelerator physics and in related domains that have strong synergies with accelerator physics. For example, the efforts to reach ever higher acceleration gradients (particularly through X-band technology) helped to push forward research in radiotherapy using electron beams. Most notably, the FLASH technique, which was born out of a collaboration between CERN and Lausanne University Hospital (CHUV) and is based on this X-band technology, was developed further and the initial work on a detailed conceptual design for a facility began.



This electron source for the CLIC study at CERN will be used to build up a prototype injector for CLEAR and the AWAKE project. *(CERN-PHOTO-202102-028-4)*

NEUTRINO RESEARCH

CERN is actively involved in neutrino research – a field of particle physics that has garnered more and more interest in recent years – through its participation in projects based in the United States and Japan. In line with the European Strategy for Particle Physics, the Laboratory is providing testing infrastructure and prototypes for these experiments, notably ProtoDUNE, a prototype of the future DUNE (Deep Underground Neutrino Experiment) facility, which will be constructed at LBNF (Long-Baseline Neutrino Facility) in the United States. CERN is providing two liquid-argon neutrino detector prototypes (a single-phase version and a dual-phase version with a layer of gaseous argon). In 2021, the CERN neutrino group used a large-scale prototype to demonstrate the validity of two concepts for the ProtoDUNE detector: the vertical-drift time projection chamber (TPC) and readout units based on a new technology. The excellent test results allowed this concept to be approved for the DUNE experiment's second far detector. In 2021, CERN also agreed to provide LBNF with a second cryostat for the vertical-drift detector, which will be ready for delivery at the end of 2023. Finally, the construction of an upgraded near detector (NP07) for the T2K experiment in Japan got under way.



Inside a ProtoDUNE liquid-argon neutrino detector prototype at the CERN Neutrino Platform. *(CERN-PHOTO-201710-248-1)*

The colossal North Area houses most Physics Beyond Colliders experiments. *(CERN-PHOTO-202104-058-16)*

PHYSICS BEYOND COLLIDERS

Since 2016, the Physics Beyond Colliders (PBC) programme has been studying possible ways to use CERN's installations for physics research projects that are compatible with the goals of the main experiments of the Laboratory's collider programme. In 2021, in the context of the PBC programme, studies aiming to increase the North Area's physics research potential continued. Their completion could make it possible to study certain very rare decays of neutral and charged kaons with more intense beams (through the KLEVER and NA62++ experiments) or to continue the hunt for very weakly interacting particles that may make up dark matter. In parallel, research and development towards the construction of the Beam Dump Facility (BDF) made great strides in 2021, notably with the first working demonstration of a new beam manipulation system using crystals that will significantly reduce beam losses during extraction. The installation of the BDF in other existing infrastructures at CERN is under study. The design of a polarised gas target around LHC interaction point 8 progressed during the year, as did the design of fixed-target experiments using single or double crystals, which could provide new data on the measurement of the dipolar magnetic and electric moments of certain charmed particles. Progress was also made on the Forward Physics Facility, an installation that could be located on the beamline, 600 metres from LHC interaction point 1, and would host a series of experiments dedicated to the search for light and weakly interacting particles "escaping" from the detectors installed at the interaction point. A document setting out the case for such an installation was published in 2021 and the evaluation of the characteristics of the detectors and the technical infrastructure is continuing. The PBC programme's Technology Working Group, in collaboration with the Quantum Technology Initiative (QTI) (p. 31), is supporting the review of a project to install an atomic interferometer in an LHC access shaft. The interferometer would be designed to detect gravitational waves and dark matter. The same group made good progress in developing radiofrequency cavities with coatings made of high-temperature superconducting materials for the detection of axions, another particle that may constitute the mysterious dark matter.

A series of studies on experiments that could be conducted using the intense photon beams produced by a gamma ray factory is being published in a special edition of the prestigious journal *Annalen der Physik*, and an international collaboration is being set up with a view to demonstrating the operating principle of such a gamma factory at the SPS.

AWAKE

The second run of AWAKE (Advanced Wakefield Experiment) began in 2021, following the second long shutdown of the accelerator complex. The experiment studies the use of proton beams to generate waves (wakefields) in a plasma cell, allowing electron beams to be accelerated with gradients hundreds of times higher than is possible with today's accelerators. Success came early in the new run, with the demonstration that self-modulation of the proton bunch can be seeded with an electron beam. In parallel, a prototype of the new electron source was installed in the CTF2, a testing infrastructure used by CLIC, in collaboration with the latter. It will be installed in AWAKE during the third long shutdown. Finally, the prototype of the new plasma source was tested at CERN and its commissioning will begin in 2023.

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Composition as of 31 December 2021

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Chair of the ISOLDE and Neutron Time-of-Flight Experiments Committee
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Chair of the European Committee for Future Accelerators
Professor K. Jakobs

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Dr U. Bassler

Chair of the Finance Committee
Dr U. Dosselli

Director-General
Dr F. Gianotti

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(Italy)

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Chair
Professor B. Åsman
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Members
One representative from each Member State

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At least two external experts, appointed by the Council

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Deputy Director for Accelerators and Technology	Malika Meddahi
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Theoretical Physics (TH)	Gian Giudice
Project and Study Management	
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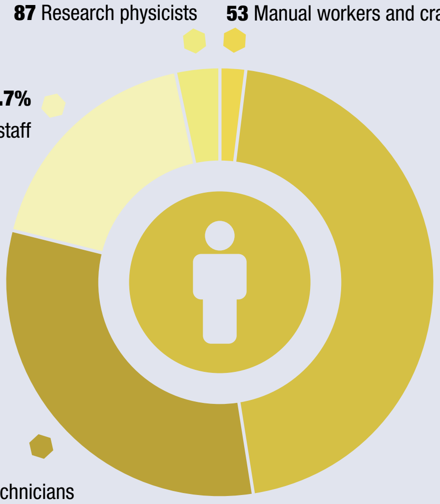
CERN Neutrino Platform	Marzio Nessi
Future Circular Collider (FCC) Feasibility Study	Michael Benedikt
High-Field Magnets R&D Programme (HFM)	Luca Bottura
High-Luminosity LHC (HL-LHC)	Oliver Bruning
Linear Collider Studies (CLIC and LCS)	Steinar Stapnes
Muon Colliders	Daniel Schulte
Physics Beyond Colliders (PBC)	Gianluigi Arduini
Science Gateway	Patrick Geeraert
Worldwide LHC Computing Grid (WLCG)	Simone Campana

CERN IN FIGURES

CERN STAFF

Total: 2676 people



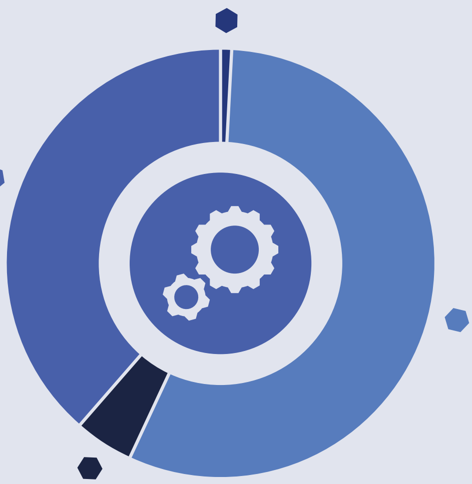
EVOLUTION OF STAFF MEMBERS

2017	2633
2018	2667
2019	2660
2020	2635
2021	2676

In addition to staff members, CERN employed 783 fellows (including 87 TTE technicians), trained 710 students and hosted 989 associates in 2021. CERN's infrastructure and services are used by a large scientific community of 11 175 users (p. 12).

CERN EXPENSES

Total expenses: 1228.4 MCHF



In 2021, more than 35% 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.

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Sixty-seventh 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-reports

The biennial Environment Report 2019–2020 is available at:
https://e-publishing.cern.ch/index.php/CERN_Environment_Report
The 2021 Knowledge Transfer annual report is available at:
http://kt.cern/annual-report
The 2021 CERN & Society annual report is available at:
https://cernandsocietyfoundation.cern/page/annual-reviews

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-2021
A glossary of useful terms is available at: https://cern.ch/go/glossary

Images:
Kenzi Foto: p. 6 (bottom right)
NASA: p. 8 (middle left)
Escuela Nacional Preparatoria Plantel and Liceo Scientifico Statale A. Scacchi: p. 9 (middle right)
Lena Ditte Nissen: p. 9 (bottom right)
NASA: p. 20
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Brookhaven National Laboratory, USA: p. 44

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