# Annual Report
# 2020

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

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

## MESSAGE FROM THE PRESIDENT OF THE COUNCIL

Never before has a CERN Open Council meeting garnered such a large audience as that of 18 June 2020. Over 3000 people connected from all over the world to hear the latest developments from CERN's governing body. Due to the COVID-19 pandemic, the Open Council was live-streamed for the first time, allowing the eagerly anticipated announcement of the latest update to the European Strategy for Particle Physics (ESPP) to be shared with the particle physics community worldwide.

After two years of preparatory work, the ESPP process entered its final stages in January with an open symposium in Bad Honnef, Germany. The resulting Strategy statements and Deliberation Document were discussed in detail during an exceptional online Council session on 25 May. However, the formal approval scheduled for the same day in Budapest, Hungary, had to be cancelled, and the Council resolution to update the ESPP was later adopted in June.

The highest priority for particle physics in Europe remains a successful high-luminosity phase of the LHC. Until the next ESPP update, this ambitious project encompassing both the accelerator and the experiments requires the highest level of engagement. The reward will be an exciting physics programme that will not only shed light on the Higgs boson, but also take our understanding to a new level in many areas of the field.

The coming years will also be crucial for the long-term future of CERN. To this end, recommendations from the updated ESPP are already reflected in the Medium-Term Plan presented to the Council by the Director-General. Key among these is a feasibility study for a 100-kilometre collider at CERN, along with a mandate to deliver plans for the construction and financing of the required tunnel by the time of the next ESPP update. In parallel, the European Laboratory Directors Group and the European Committee for Future Accelerators have been tasked with establishing roadmaps for accelerator and detector research and development. The implementation of these roadmaps at CERN and in Member State laboratories will lay the technological foundations for future programmes at CERN. Development of high-field magnets is of the highest importance, but alternative accelerator concepts must also reach a level of maturity that will allow them to be fully evaluated.

During the ESPP process, broader aspects both underpinning and emerging from our activities were widely discussed. Social and career prospects for future generations in our evolving field, and in society as a whole, form an important part of the update, along with European participation in global projects and the place of particle physics in the wider research landscape. Knowledge and technology transfer, public engagement, education and communication were flagged as vital for bridging the gap between publicly funded research and society. For the first time, the ESPP process made recommendations on the sustainable development and environmental impact of our field – an initiative echoed in the publication of CERN's first public-facing environment report in September.

My thanks go to all who participated in the ESPP update, in particular the Strategy Secretariat and its Chair, Halina Abramowicz. I would also like to express my gratitude to the CERN personnel and Management, as well as to the Member and Associate Member State delegations, for their invaluable support and cooperation. I hope that 2021 will see us overcome the pandemic, and I look forward to the next steps in the company of you all, as we build our insights into the deepest mysteries of nature.

Ursula Bassler

## MESSAGE FROM THE DIRECTOR-GENERAL

In a year marked by the unprecedented challenges wrought on society by COVID-19, CERN also faced unprecedented difficulties, with its primary goal being to protect the health of everyone on site. Thanks to the hard work and dedication of many services and people, and the exemplary flexibility of the personnel in complying with new safety measures and working procedures, we maintained a safe environment. As a result, great progress was made in the second year of Long Shutdown 2 (LS2) on upgrading the accelerator complex and the experiments for Run 3, and on preparing for the High-Luminosity Large Hadron Collider (HL-LHC) phase. The LHC Injectors Upgrade (LIU) project was successfully completed and, although extended teleworking and the development of safe-working protocols led to inevitable delays, we ended the year on track to bring the accelerator complex back into operation in 2021. In parallel, data analysis continued at a sustained pace over the year and produced beautiful physics results across the Laboratory's full experimental programme.

A highlight of 2020 was the update of the European Strategy for Particle Physics by the CERN Council. The updated Strategy sets ambitious goals, and I am very pleased that we were able to start to include the plans and resources needed for their implementation in the Laboratory's 2020 Medium-Term Plan, which covers the period 2021-2025.

Another important milestone in 2020 was the publication of CERN's first public-facing environment report. This represents a bold commitment to conduct our research in an environmentally responsible way. It includes far-reaching targets to reduce our impact on the environment over the coming years, and it is an undertaking to build a sustainable future for our research. Three projects that made headway in 2020 have a significant environmental protection component. Firstly, heat recovered from the LHC is being harnessed to heat a new local housing development. Secondly, construction of a new computer centre, with built-in heat recovery, was approved. And thirdly, construction began on the Science Gateway, our new education and outreach facility, which will generate its own electricity from solar panels.

In 2020, the value system of science proved its worth, with scientists taking centre stage as never before, most notably through the development of vaccines in record time. Although work of this nature is far removed from CERN's expertise, the particle physics community came together to join the global effort to combat the virus. The "CERN against COVID-19" task force coordinated grassroots initiatives to help in a wide range of areas, including the production of sanitiser gel and face shields, the development of a full-scale ventilator, and the provision of computing resources to those engaged in front-line research on the virus.

With 2020 being the last year of my first mandate as CERN's Director-General, I would like to thank the outgoing Directors, Frédérick Bordry (Accelerators and Technology), Eckhard Elsen (Research and Computing) and Martin Steinacher (Finance and Human Resources) for their excellent work and dedication in the service of the Organization and its community.

Details of 2020 at CERN can be found in the pages of this report. The great accomplishments described here were possible thanks to the competence, hard work and commitment of the CERN personnel, and to the strong and sustained support of our Member and Associate Member States. My deep gratitude, along with that of the whole Directorate, goes to them all, along with my personal thanks for the confidence that the Council has shown in me by entrusting me with a further five years as Director-General.

Fabiola Gianotti

# 2020 IN PICTURES

***With Long Shutdown 2 in full swing, in 2020 CERN, like the rest of the world, faced COVID-19-related challenges. Although many events were postponed, switching to safe mode didn't stop the Laboratory from working efficiently – from outstanding physics results to major improvements to the accelerators and experiments. Discover more in pictures.***

## 20 JANUARY

Particle physicists formulate the future of the field, during key discussions in Bad Honnef on the update of the European Strategy for Particle Physics.

## 20 JANUARY

His Excellency Mr Egils Levits, President of the Republic of Latvia, visits CERN.

(CERN-PHOTO-202001-016-41)

## 14 FEBRUARY

CNAO, a cancer therapy synchrotron that CERN helped to establish in Pavia, Italy, successfully performs the world's first proton treatment of a cardiac pathology.


## 19 FEBRUARY

ALPHA reports first measurements of certain quantum effects in antimatter, paving the way for future precision studies.

(CERN-PHOTO-201810-266-4)

## 12 MARCH

CERN updates its Open Hardware Licence, introducing three variants to cater to different collaborative models.

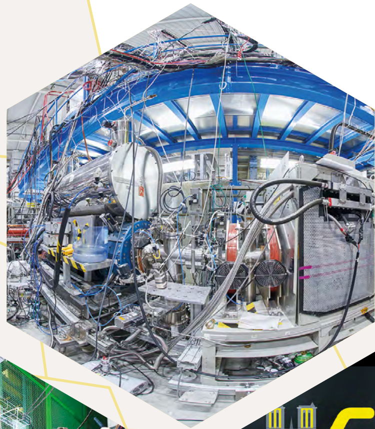
(CERN-HOMEWEB-PHO-2020-022-1)

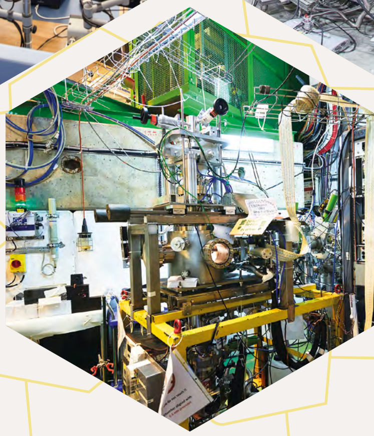
## 20 MARCH

CERN enters safe mode in response to the COVID-19 pandemic, with on-site activities limited to those essential for the safety and security of the site and equipment.
(OPEN-PHO-ACCEL-2020-002-3)

## 6 MAY

ASACUSA researchers create and study new exotic atoms at PSI using CERN experimental equipment.
(CERN-HOMEWEB-PHO-2020-056-1)






## 14 MAY

The CLOUD collaboration reveals a new mechanism behind urban smog, which could inform policies for reducing urban particle pollution.
(CERN-PHOTO-201909-278-3)

## 27 MAY

ISOLDE succeeds in performing the first-ever laser-spectroscopy measurements of a short-lived radioactive molecule.
(CERN-PHOTO-201911-394-20)

## 25-30 MAY

At the LHCP conference, the LHC experiments present results on new Higgs boson signatures, exotic hadrons with charm quarks and promising paths for new physics searches.

## 15 JUNE

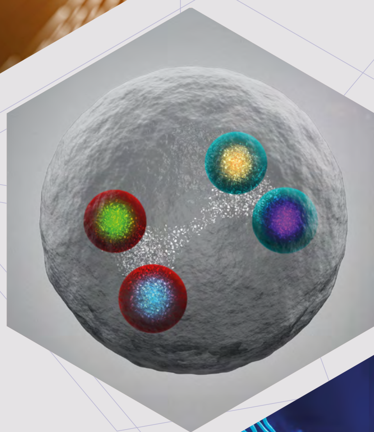
Two teams of high-school students from Switzerland and Germany win the 2020 CERN Beamline for Schools competition.
(OPEN-PHO-LIFE-2020-006-4)


## 19 JUNE

At its 199th session, the CERN Council announces the update of the European Strategy for Particle Physics, outlining a vision for the future of the field.

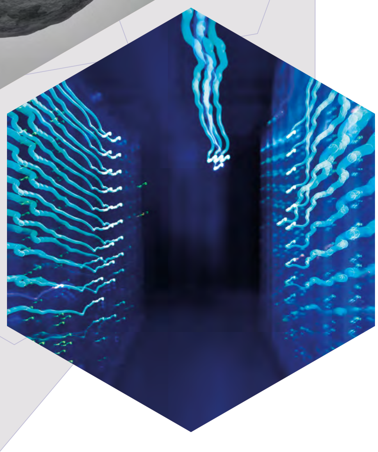

## 19 JUNE

Representatives of CERN and of the Government of Estonia sign an Agreement admitting Estonia as an Associate Member in the Pre-Stage to Membership of CERN.
(CERN-PHOTO-202006-088-9)



## 1 JULY

The LHCb collaboration discovers a new type of tetraquark – an exotic particle made up of four charm quarks.



## 22 JULY

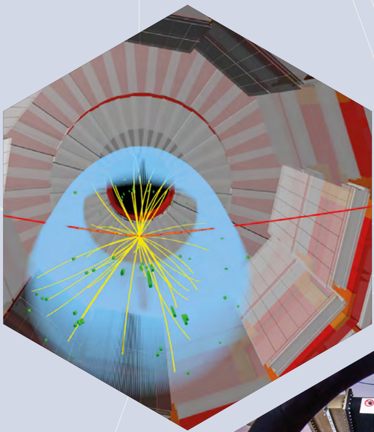
CERN, SKA, GÉANT and PRACE collaborate on the next generation of high-performance computers.
(CERN-CO-1008294-02)

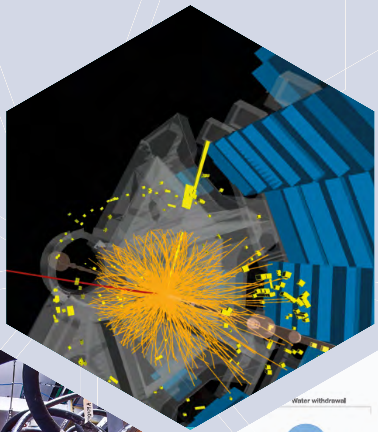
## 3 AUGUST

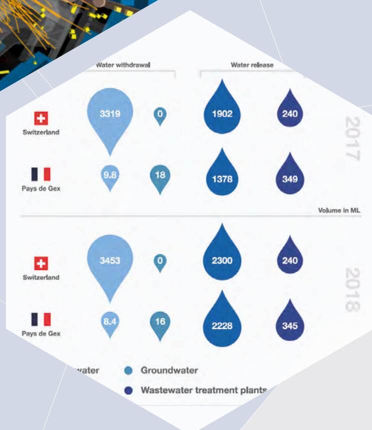
ICHEP2020: the ATLAS and CMS experiments announce new results, which show that the Higgs boson decays into two muons.
(OPEN-PHO-EXP-2020-002-1)

## 5 AUGUST

ICHEP2020: the ATLAS experiment reports the observation of photon collisions producing weak-force carriers and provides further insights into their interactions.
(ATLAS-PHOTO-2020-031-1)








## 20 AUGUST

Linac4 takes over from the retired Linac2 as the first accelerator in the LHC injection chain.
(CERN-PHOTO-201704-093-10)

## 9 SEPTEMBER

CERN publishes its first public environment report detailing the status of CERN's environmental footprint, along with objectives for the coming years.

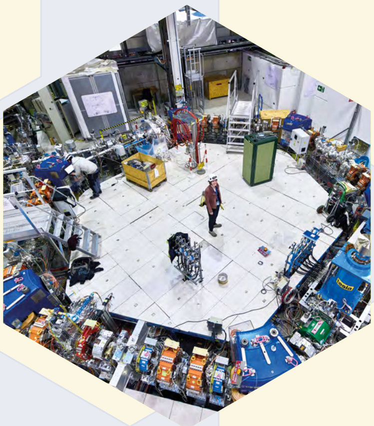
## 18 SEPTEMBER

The International Academy of Digital Arts and Sciences awards the 2020 Webby Honoree title to CERN's communications team for the first 360° live video, streamed from the CMS cavern.

(CERN-PHOTO-202009-119-2)


## 1 OCTOBER

Science Gateway construction gets the green light, following receipt of official permission from the Geneva authorities.



## 28 OCTOBER

ELENA injects $H^-$ ions and delivers them to the GBAR and ALPHA experiments for the first time.

(CERN-PHOTO-201804-086-10)

## 10 NOVEMBER

Swiss artist Chloé Delarue and Chilean artist Patricia Domínguez are awarded the Simetría residency at CERN and ALMA-ESO.

## 23 NOVEMBER

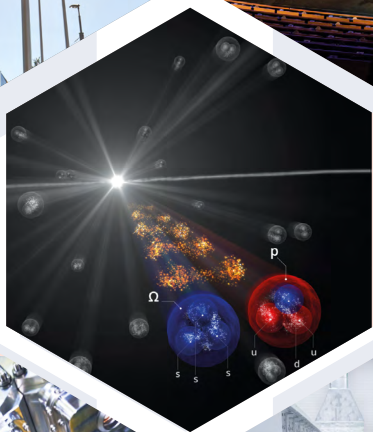
All five CERN-coordinated projects submitted to the Horizon 2020 Research Infrastructure calls are approved for European Union funding.
(CERN-PHOTO-201809-249-16)

## 30 NOVEMBER

CERN launches the Sparks! serendipity forum, a new science innovation forum, beginning with the theme of artificial intelligence (AI).
(OPEN-PHO-ACCEL-2020-003-1)


## 9 DECEMBER

The ALICE collaboration shows how proton–proton collisions at the LHC can reveal the strong interaction between hadrons, opening an avenue for high-precision studies of the strong force.




## 11 DECEMBER

The PS Booster receives its first beam after a major upgrade during Long Shutdown 2.
(CERN-PHOTO-202012-170-1)

## 11 DECEMBER

CERN announces a new open-data policy for LHC experiments in support of open science.
(IT-PHO-CCC-2021-001-13)

# CERN JOINS THE FIGHT AGAINST COVID-19

***In March, CERN's Director-General establishes the "CERN against COVID-19" task force to coordinate ideas and contributions from the CERN community of over 18 000 people worldwide to the fight against COVID-19. Throughout this process, CERN stays in close contact with the medical community through, for example, the Laboratory's collaboration agreement with the World Health Organization. Here is a short summary in pictures of some of the many initiatives drawing on scientific and technical expertise and facilities at CERN, in the Member States and beyond, which were carried out in coordination with health institutions and experts from relevant fields.***

**27 March: CERN establishes a task force to identify and support contributions from the Organization to combat the COVID-19 pandemic.**

## HELPING THE LOCAL COMMUNITY

CERN's Fire and Rescue Service supports Swiss and French ambulance drivers.

(CERN-PHOTO-202004-072-2)
(CERN-PHOTO-202004-062-1)

(CERN-PHOTO-202004-066-5)
(CERN-PHOTO-202004-067-5)

CERN produces and delivers personal protective equipment to local organisations on the front line: face shields, protective panels and 6500 litres of hydro-alcoholic liquid.

(CERN-PHOTO-202005-074-45)
(CERN-PHOTO-202004-058-11)

## MEDICAL DEVICES

Physicists and engineers from the LHCb collaboration, supported by many CERN departments, develop the High-Energy Ventilator.

(CERN-PHOTO-202008-107-12)

(CERN-PHOTO-202005-077-5)

Designs for 3D-printed masks developed at CERN are published under the CERN Open Hardware Licence.


CERN supports the Mechanical Ventilator Milano (MVM) project, spearheaded by the Global Argon Dark Matter collaboration and the OpenBreath project, which aims to develop and produce a scalable low-cost lung ventilator.

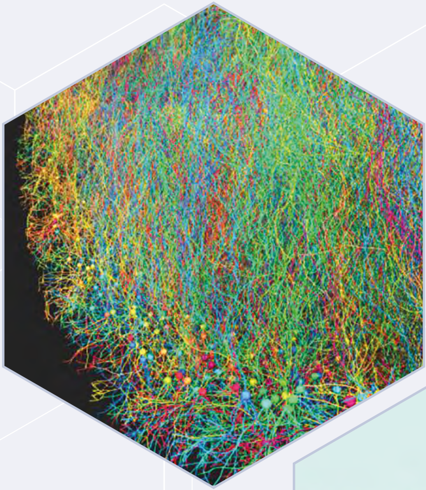
## COMPUTING AND DATA ANALYSIS

zenodo
Research. Shared.

OpenAIRE

Zenodo and OpenAIRE contribute to the call for action by preserving and sharing all COVID-19-related data sets, software, preprints and any other research objects that could help the scientific community to find solutions to this universal problem.

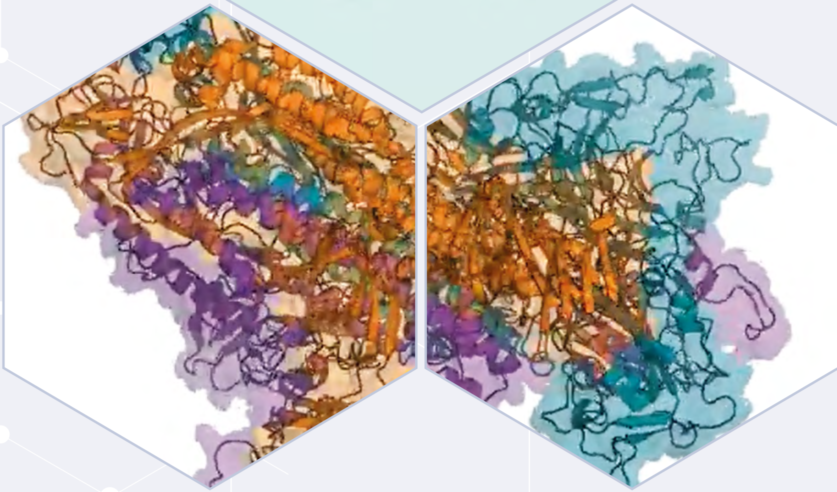
CERN partners with epidemiologists at the University of Geneva to model COVID-19 infection and propagation rates and the virus transmission in closed spaces.

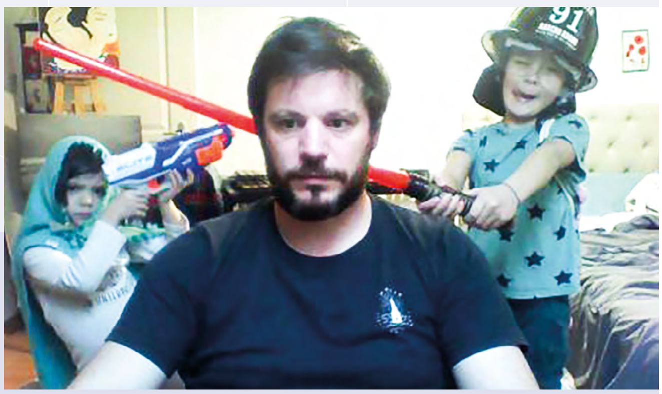


*An example of large-scale simulation using BioDynaMo.*

CERN computing resources are deployed in support of a Swiss-Government-sponsored versusvirus hackathon.


CERN and LHC computing sites support the *Folding@home* volunteer-computing initiative, a distributed computing platform for simulating the dynamics of protein molecules. CERN contributes about 10 000 computer cores from its main data centre.





*One of the winners of the Background Challenge competition launched by the CERN Bulletin in April 2020.*

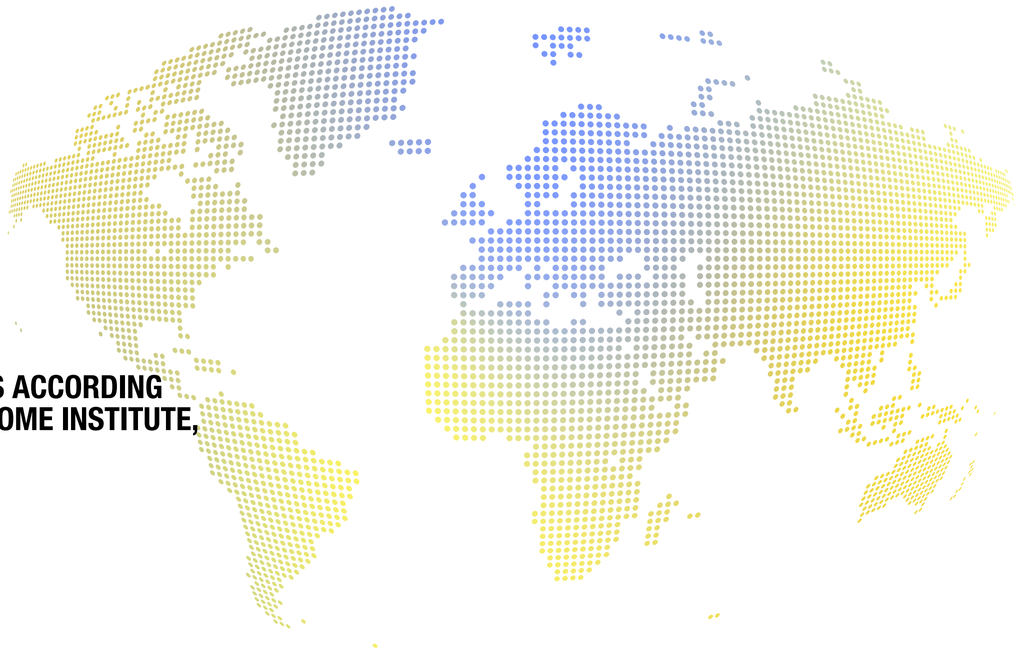
## INFORMING AND ENGAGING THE CERN COMMUNITY DURING COVID-19

Regular CERN-wide communication keeps all members of the personnel informed of the COVID-19 measures in place at CERN, connected to each other for support to stay well during the pandemic, and engaged with the activities of the Laboratory, thus ensuring operations continue in complete safety.

A dedicated website containing all the relevant information on the pandemic is set up and regularly updated. It includes news, tips and advice for staying safe, well and connected to colleagues. Four online town hall meetings with the Director-General and CERN Management are organised, with ample time for questions and answers. Video messages by the Director-General, Directors and Heads of Department are produced and shared with the community. The CERN Bulletin moves to a weekly frequency during safe mode (March–May), and weekly newsletters dedicated to COVID-19-related topics are sent out (from September onwards).

# A LABORATORY FOR THE WORLD

***A veritable centre of excellence for international scientific cooperation, CERN was once again a hive for a lively, industrious and multicultural community of scientists in 2020. Despite the many challenges associated with the COVID-19 pandemic, this large family of 16 400 people managed to remain united and committed to ensuring the smooth operation of the Laboratory's many activities. The 2600 members of the personnel continued their work to develop, construct and operate the accelerator and detector complex, the Organization's nervous system, while contributing to the analysis of the data that was produced. This colossal infrastructure and the plethora of data also served a research programme conducted by almost 11 400 users of 110 different nationalities working for institutes in 76 countries.***



## BREAKDOWN OF CERN USERS ACCORDING TO THE COUNTRY OF THEIR HOME INSTITUTE, AS OF 31 DECEMBER 2020

### NUMBER OF USERS: 11 399

### MEMBER STATES (6632)

**Austria** 82 – **Belgium** 122 – **Bulgaria** 37 – **Czech Republic** 221 – **Denmark** 35 – **Finland** 79 – **France** 794 – **Germany** 1185 – **Greece** 138 **Hungary** 67 – **Israel** 63 – **Italy** 1388 – **Netherlands** 166 – **Norway** 78 – **Poland** 272 – **Portugal** 80 – **Romania** 99 – **Serbia** 35 – **Slovakia** 66 **Spain** 325 – **Sweden** 96 – **Switzerland** 329 – **United Kingdom** 875

### ASSOCIATE MEMBER STATES IN THE PRE-STAGE TO MEMBERSHIP (27)

**Cyprus** 11 – **Slovenia** 16

### ASSOCIATE MEMBER STATES (390)

**Croatia** 38 – **India** 151 – **Lithuania** 13 – **Pakistan** 35 – **Turkey** 124 – **Ukraine** 29

### OBSERVERS (3071)

**Japan** 211 – **Russian Federation** 1021 – **United States of America** 1839

### OTHER COUNTRIES (1279)

**Algeria** 2 – **Argentina** 15 – **Armenia** 10 – **Australia** 23 – **Azerbaijan** 2 – **Bahrain** 2 – **Belarus** 26 – **Brazil** 108 – **Canada** 196 – **Chile** 22 **Colombia** 15 – **Cuba** 3 – **Ecuador** 4 – **Egypt** 14 – **Estonia** 26 – **Georgia** 35 – **Hong Kong** 20 – **Iceland** 3 – **Indonesia** 7 – **Iran** 13 – **Ireland** 6 **Jordan** 5 – **Kuwait** 2 – **Latvia** 6 – **Lebanon** 17 – **Malaysia** 4 – **Malta** 3 – **Mexico** 49 – **Montenegro** 5 – **Morocco** 18 – **New Zealand** 11 – **Oman** 1 **People's Republic of China** 334 – **Peru** 2 – **Puerto Rico** 2 – **Republic of Korea** 132 – **Singapore** 3 – **South Africa** 57 – **Sri Lanka** 8 – **Taiwan** 50 **Thailand** 16 – **United Arab Emirates** 2

(CERN-PHOTO-202001-011-4)

CERN is a laboratory firmly rooted in Europe but with a resolutely global orientation. In 2020, the Organization continued to strengthen its ties with numerous states, institutes and laboratories all over the world. Talks aimed at enlarging the Organization within Europe resulted in the signature of an agreement with Estonia in June 2020, which paved the way for the country to become an Associate Member State in the pre-stage to Membership in February 2021, when the agreement entered into force. The process towards the accession of Latvia as an Associate Member State continued in parallel. In the framework of CERN's international outreach policy, the United States was granted Observer status in respect of the High-Luminosity LHC project. The Organization also signed an international cooperation agreement with North Macedonia and a scientific collaboration agreement with the Brazilian Centre for Research in Energy and Materials. CERN is staunchly committed to enriching and driving forward the research it hosts through partnerships like these, which promote the exchange of ideas and knowledge.

*CERN signs an agreement with the Brazilian Centre for Research in Energy and Materials, intensifying collaboration with Brazil.* (CERN-PHOTO-202012-166-17)


*The CERN Alumni network celebrated its third anniversary in June during an online event live from the Linac4 tunnel.* (CERN-VIDEO-2020-032-001)

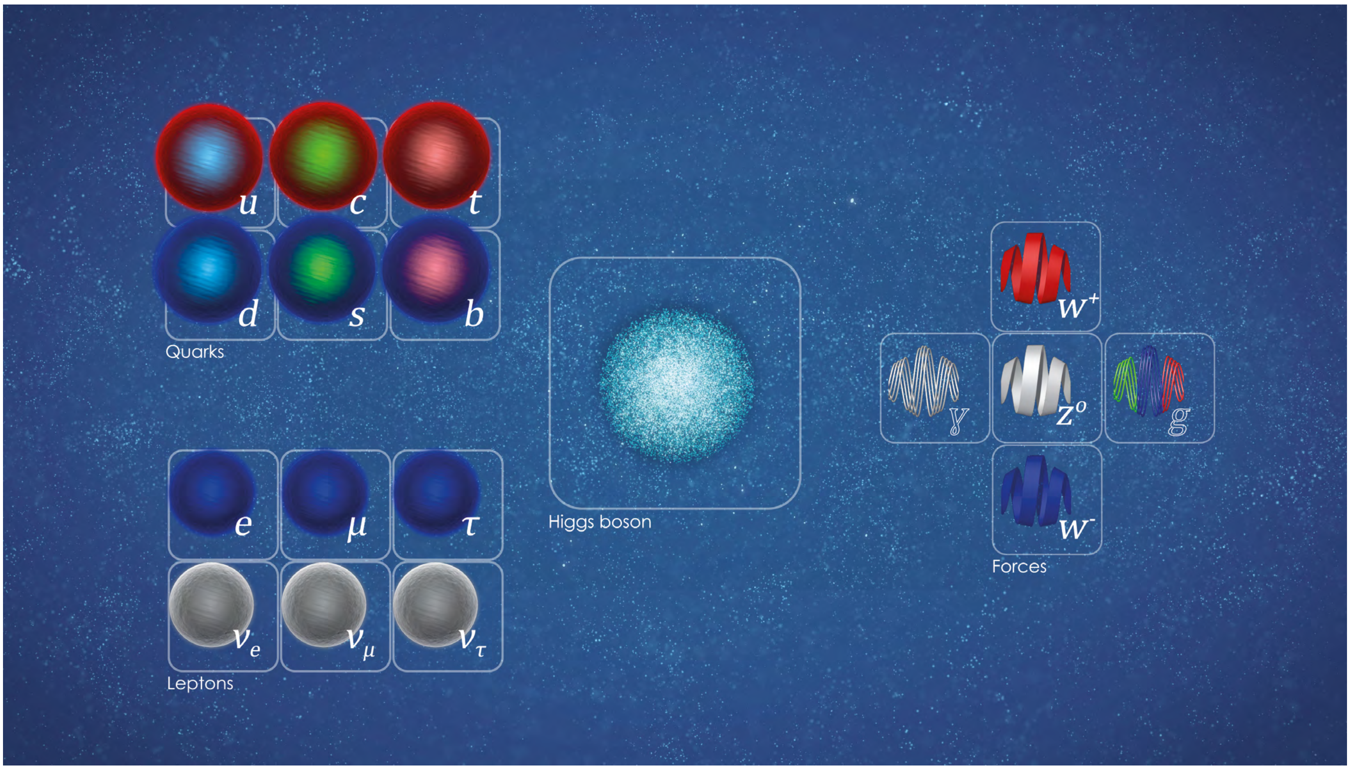
CERN's international renown also relies on a dynamic network of alumni that brings current and former members of the personnel together and, through mutual aid and skill sharing, helps them to use the experience acquired within the Organization to find enriching careers in a wide range of fields. A melting pot of people with very different profiles, all united by their attachment to the Organization, the network fosters the CERN community spirit both within and beyond the Laboratory. Three years ago, the network was officially launched as the *CERN Alumni* programme, which by the end of 2020 had no fewer than 6583 members in over 100 countries and nine regional groups based in Austria, Greece, Italy, Netherlands, Switzerland, the United Kingdom and the United States. The diversity of alumni profiles is reflected in the many different events organised by the network. In 2020, a series of online events for the network's members took place in spite of the constraints associated with the COVID-19 pandemic: the "*News from the Lab*" series, providing information about specific aspects of CERN's mission, and the successful "*Moving Out of Academia to…*" workshops, which offer an opportunity to explore possible career moves. The latest in the series, "*Moving Out of Academia to MedTech*", was held in September. These events bring the members of this dynamic network closer together and help to make it an ideal place for forging connections and sharing experiences.

# EXPLORING THE NATURE OF THE UNIVERSE

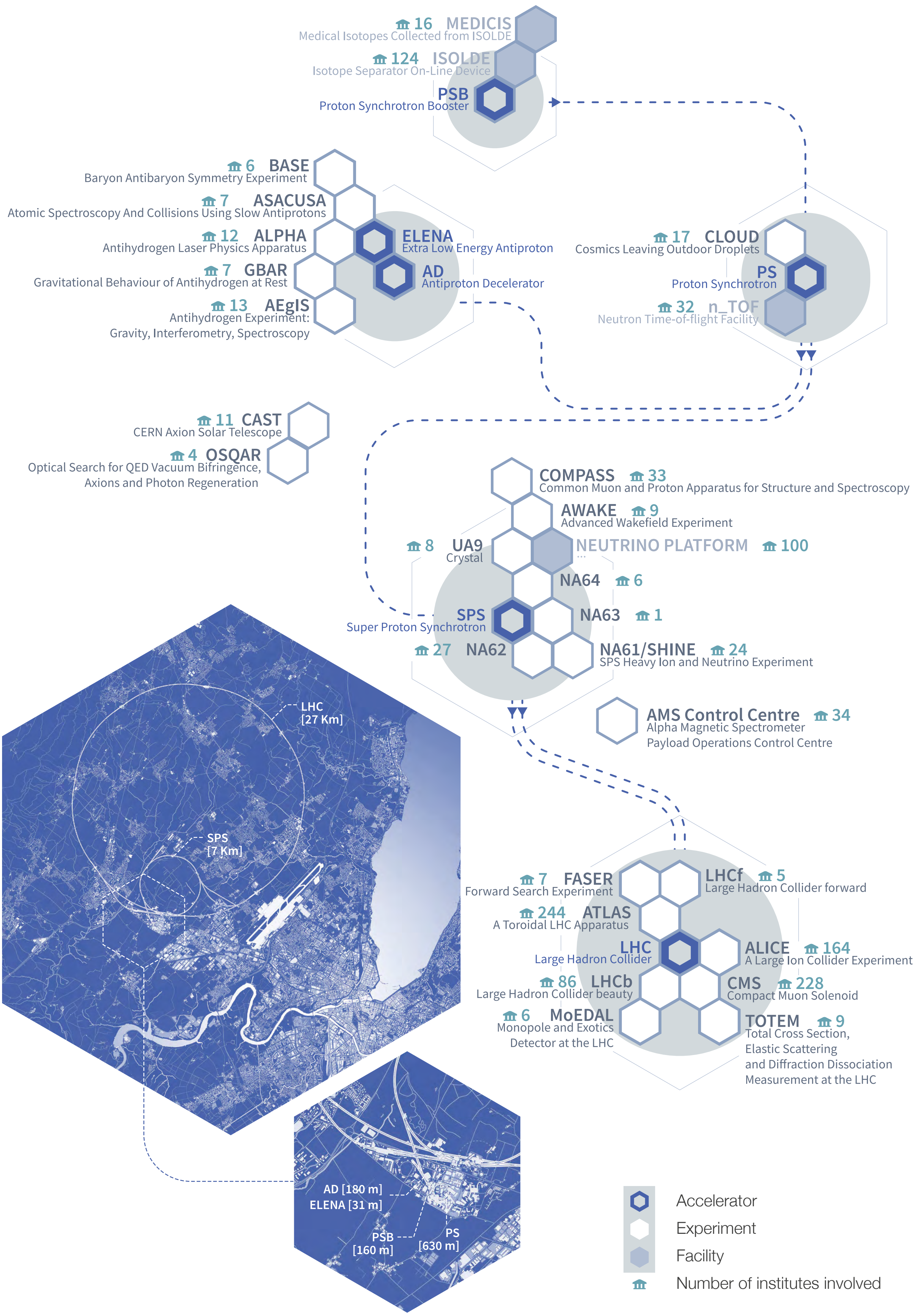
***CERN explores the fundamental structure of the universe by operating a sophisticated complex of accelerators that collide beams of particles or direct them onto fixed targets. The results of these collisions are recorded by giant detectors and analysed by thousands of scientists at CERN and beyond.***

## CERN'S ACCELERATOR COMPLEX AND THE EXPERIMENTS THAT IT FEEDS

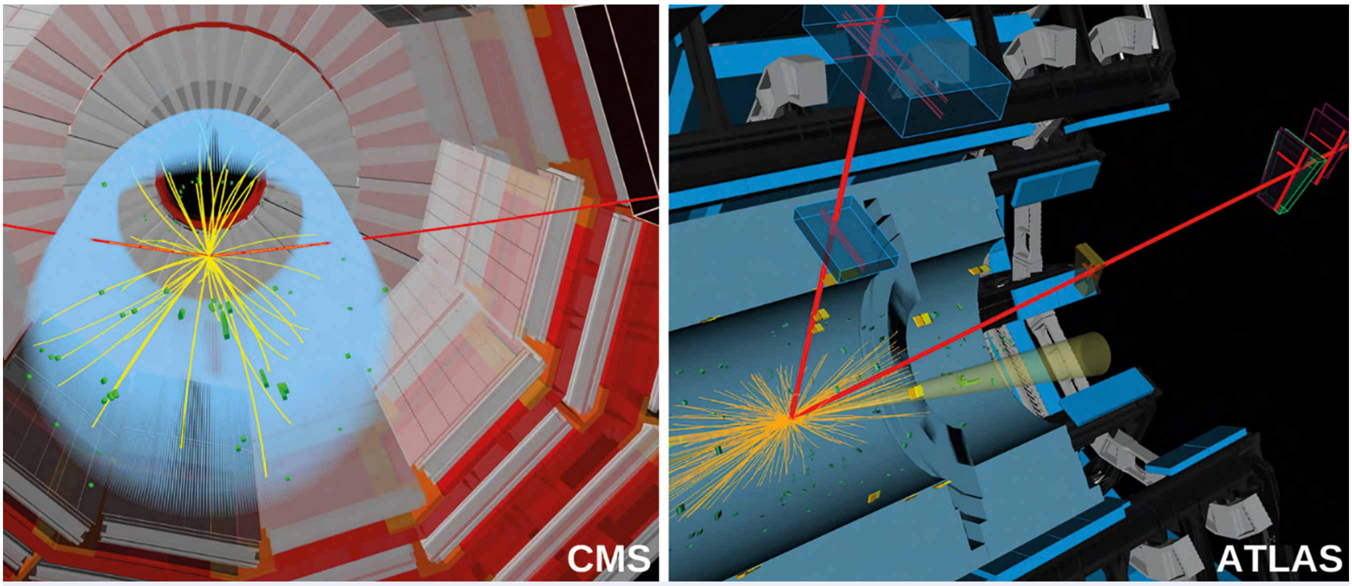
The Large Hadron Collider (LHC) is CERN's flagship machine. It collides proton beams at the highest energies ever created, and the results of these collisions are recorded by seven experiments – ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL and TOTEM – and soon also by FASER, the newest LHC experiment. The year 2020 was the second year of the Laboratory's ongoing long shutdown, during which the accelerator complex and experiments are undergoing intensive maintenance and upgrade work. However, despite the shutdown and the COVID-19 pandemic, 2020 was a very productive year for CERN. In addition to the completion of the process leading to the update of the European Strategy for Particle Physics (see p. 47), 2020 saw many remarkable physics results based on the analysis of data taken before the shutdown by both the LHC and the non-LHC experiments. The results include the first indications that the Higgs boson interacts with second-generation particles, the observation of a new form of matter–antimatter asymmetry in strange-beauty particles, and the demonstration of a technique to reveal the dynamics of the strong interaction between composite particles called hadrons. It was also a special year because 30 March 2020 marked ten years of the LHC physics programme, which has seen almost 3000 scientific papers published by the LHC experiments.




*Particles of the Standard Model of particle physics.* *(OPEN-PHO-CHART-2015-001)*




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




*Displays of candidate events for a Higgs boson decaying into two muons, as recorded by CMS (left) and ATLAS (right).*
*(OPEN-PHO-EXP-2020-002-1)*

*ATLAS AND CMS PRESENTED THE FIRST INDICATIONS THAT THE HIGGS BOSON INTERACTS WITH A MUON AND THUS WITH A SECOND-GENERATION FERMION.*

## THE HIGGS BOSON AND THE SECOND GENERATION

The ATLAS and CMS collaborations have been studying the Higgs boson and how it interacts with other particles ever since they discovered this special particle in 2012. In the Standard Model, the Higgs boson is responsible for the masses of the elementary particles. As such, 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 physics phenomena. ATLAS and CMS study the Higgs boson's interactions by looking at how the boson transforms, or decays, into lighter particles or how the boson is produced in association with other particles. The two experiments have previously observed the interaction of the Higgs boson with other bosons and with the heaviest elementary fermions. Fermions (quarks and leptons) come in three generations of increasing mass, and ATLAS and CMS have observed the interaction of the Higgs boson with the heaviest, third generation of fermions – the tau lepton and the top and bottom quarks. But the weaker interactions of the Higgs boson with the next lighter fermions – the muon and the charm and strange quarks – have remained elusive.

In 2020, ATLAS and CMS continued their detailed exploration of the Higgs boson and presented the first indications that the boson interacts with a muon and thus with a second-generation fermion. CMS achieved evidence that the Higgs boson decays to two muons with a significance of three standard deviations, whereas ATLAS attained a significance of two standard deviations. The combination of both results would increase the significance well above three standard deviations, providing strong evidence for the Higgs boson decay to two muons.

ATLAS and CMS also detected new signatures of the Higgs boson. ATLAS presented the result of its search for a rare process in which a Higgs boson transforms into a Z boson and a photon (γ), whereas CMS presented the result of its first search for rare Higgs transformations also involving a Z boson but accompanied by a ρ (rho) or ϕ (phi) meson.

Other Higgs highlights include searches for signs of Higgs transformations into "invisible" particles that could make up dark matter, which accounts for more than five times the mass of ordinary matter in the universe. ATLAS obtained an upper limit on the probability that a Higgs boson could transform into invisible particles known as weakly interacting massive particles, or WIMPs, while CMS obtained results from a new search for Higgs transformations to four leptons via at least one intermediate "dark photon", also setting limits on the probability of such a transformation occurring at the LHC.

## TESTING THE STANDARD MODEL AND ITS EXTENSIONS

The LHC collaborations continue to subject the Standard Model and its extensions to detailed scrutiny. In 2020, LHCb observed a form of matter–antimatter asymmetry known as time-dependent CP violation in $B^0_s$ mesons, which contain a beauty antiquark and a strange quark. The result represents a further milestone in the study of the differences between matter and antimatter, adding to the previous LHCb observation of time-integrated CP violation in these mesons. In the time-dependent form, CP violation varies with the particle's lifetime due to the spontaneous oscillation of the particle into its antiparticle and back. In the case of the $B^0_s$ mesons, this oscillation takes place three thousand billion times per second, but the excellent resolution of the LHCb detector made it possible to observe the effect of these oscillations.

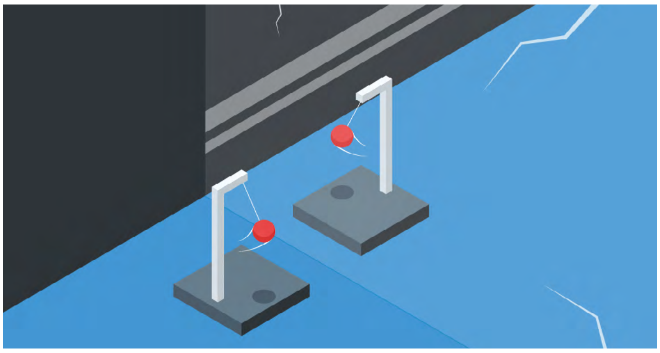
The LHCb collaboration also obtained the world's best measurement of an angle, the γ angle, in a triangle linked to the Cabibbo-Kobayashi-Maskawa matrix, which quantifies the strength of the interactions between quarks of different type and possible CP violation in quarks. In addition, LHCb discovered several new composite particles made up of quarks, including new beauty baryons and two exotic four-quark particles, or tetraquarks: a tetraquark made up of four charm quarks and a tetraquark with only one charm quark. The new exotic particles are an ideal "laboratory" for studying the strong interaction that binds protons, neutrons and atomic nuclei.

Other LHCb results include further investigations of the intriguing tensions with the Standard Model, or "anomalies", that have been seen in certain transformations of B mesons. For example, LHCb presented a new analysis of data from the decay of a $B^0$ meson into a $K^*$ meson and a pair of muons. In previous analyses of this decay, LHCb found a deviation from Standard Model predictions in one parameter, technically known as $P_5'$, calculated from the distribution of the angles of the $B^0$ decay products with respect to the parent $B^0$. In the new study, the LHCb team added new data to their analysis and still saw a deviation from Standard Model calculations in $P_5'$ as well as other parameters. As with previous related analyses, the result has not yet reached the level of solid proof, but it adds important information to the global effort to try to unravel the origin of these anomalies.

Highlights from ATLAS, in addition to the Higgs results, include two studies where the LHC was used as a photon collider. One study established the observation of photon collisions producing pairs of W bosons, which carry the weak force. The result confirms one of the main predictions of electroweak theory – that force carriers can interact with themselves – and provides new ways to probe it. Another study resulted in the direct observation and measurement of two photons turning into matter, specifically into a pair of leptons. Such measurements are important tests of how light interacts with matter at the highest laboratory energies. Other highlights were new limits on long-lived supersymmetric leptons, which superseded the previous best limits set by the LEP collider; a precise measurement of the phenomenon of lepton flavour universality suggesting that a previous discrepancy measured by the LEP collider in W boson decays may be due to a fluctuation; and a new search for dark matter that set the most stringent limit on dark matter of any collider experiment so far.

Highlights from CMS, again in addition to the Higgs results, include the first observation of the simultaneous production of three W or Z bosons. The phenomenon is extremely rare, but it provides physicists with a tool to probe and confirm the existence of the so-called quartic self-interaction between these bosons. The collaboration also observed for the first time the decay of the $B^0_s$ meson into a ϕ meson and a candidate for a tetraquark known as $\chi_{c1}(3872)$, finding that the rate at which $B^0_s$ decays into these two particles is about twice as low as that of the previously observed $B^+$ meson decay into $\chi_{c1}(3872)$, and the $K^+$ meson. This intriguing difference could provide insight into the nature of $\chi_{c1}(3872)$. Other highlights include the first measurement of the rate at which a W boson and a photon are produced in proton–proton collisions at an energy of 13 TeV, which agreed with the Standard Model expectation; some of the tightest bounds yet on the existence of leptoquarks that would interact with third-generation quarks and leptons, which allowed part of the leptoquark-mass range that could explain the B-meson anomalies to be excluded; and searches for long-lived particles decaying to jets that set competitive limits in a large range of theoretical models.

The year 2020 also saw results from the smaller LHC experiments: LHCf, MoEDAL and TOTEM. Achievements include LHCf's measurements of quantities related to the production of photons and neutrons in proton–proton collisions at small angles from the collision line; MoEDAL's results from the first direct search for particles with both electric and magnetic charges; and TOTEM's publication of measurements of proton–proton cross sections from energies between 2.7 and 13 TeV. Installation of the newest smaller LHC experiment, FASER, which was approved in 2019 and will search for light and weakly interacting particles, is ongoing and should be completed in 2021.



*A CP-symmetry transformation swaps a particle with the mirror image of its antiparticle. LHCb observed a time-dependent breakdown of this symmetry in the decays of the strange-beauty meson (red sphere on the left), which oscillates into its antiparticle (oscillation illustrated by the pendulum motion).*
*(CERN-HOMEWEB-PHO-2020-121-4)*

## ALICE MATTERS

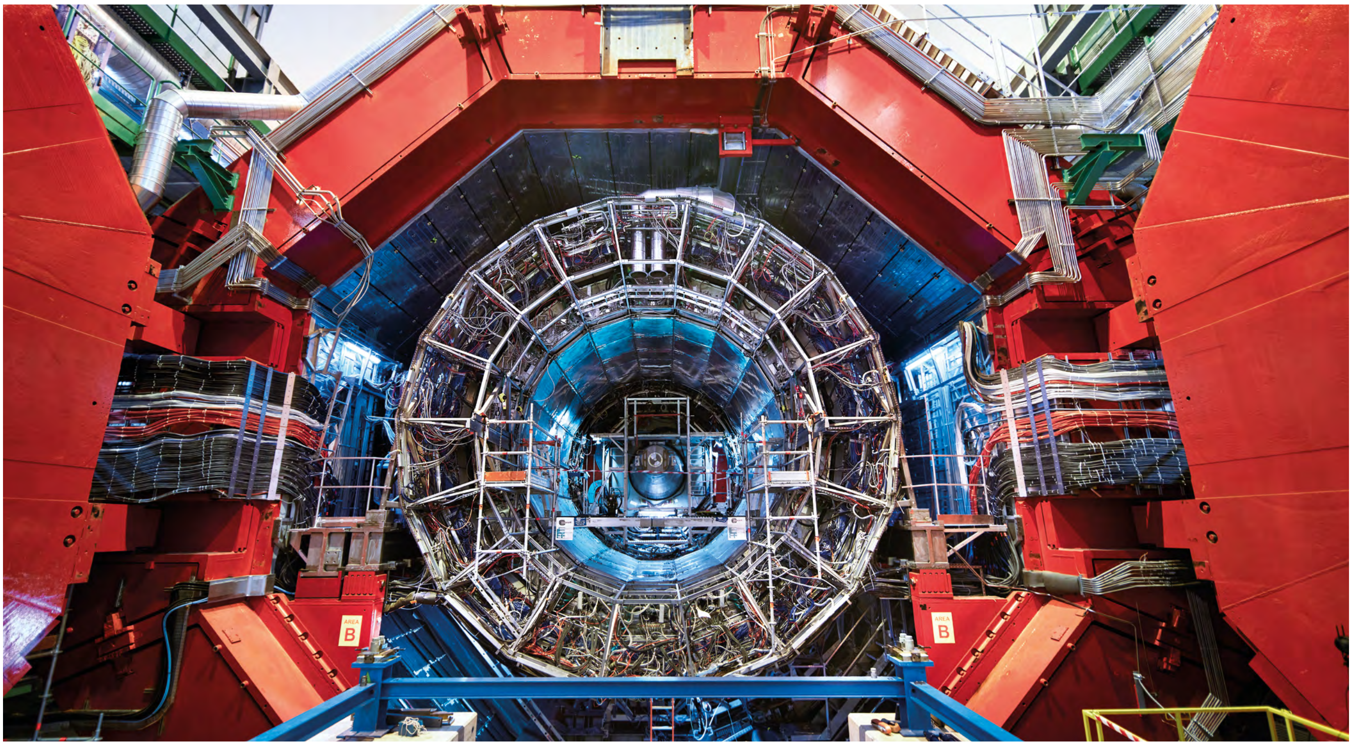
The LHC also collides lead nuclei and other heavy ions such as xenon nuclei. These collisions recreate the quark–gluon plasma, a dense state of deconfined quarks and gluons that is thought to have existed shortly after the Big Bang. The recreated plasma cannot be observed directly, but the LHC experiments can deduce its properties and effects from the signatures the plasma leaves on the particles produced in the collisions. In 2020, ALICE, which specialises in these collisions, measured the elliptic-shaped flow of hadrons containing a charm quark, either bound to a light quark (forming a D meson) or to an anticharm (making a J/ψ meson) in lead–lead collisions. ALICE found that, at low hadron momentum, the elliptic flow of D mesons is not as large as that of pions, which contain only light quarks, whereas the elliptic flow of J/ψ mesons is lower than both. The results indicate that the heavy charm quarks are dragged by the plasma's expansion, but likely to a lesser extent than light quarks, and that both D and J/ψ mesons at low momentum are in part formed by the binding of flowing quarks. Another ALICE measurement, of the flow of electrons originating from decays of B hadrons, which contain a bottom quark, indicated that bottom quarks are also sensitive to the elongated shape of the plasma.

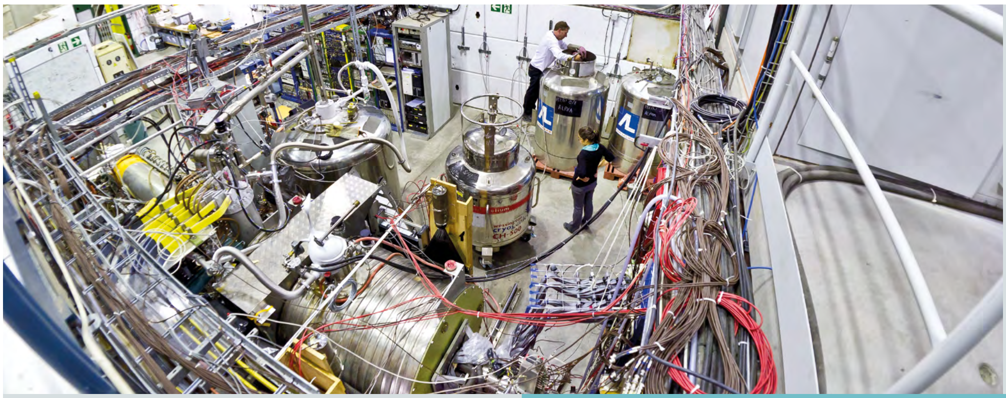
ALICE  presented measurements of the production of muons originating from decays of hadrons containing heavy quarks, in collisions of lead nuclei and of the smaller xenon nuclei. The measurements showed that both of these collision systems display a suppression in muon yield relative to proton–proton collisions. The suppression is caused by the energy loss of the heavy quarks that traverse the plasma, and it was found to be the same in lead and xenon collision events that produce a similar number of particles.

ALICE also obtained notable results based on proton–proton collisions. In one study, ALICE measured the production and annihilation probabilities of antideuterons (the antimatter counterparts of deuterium nuclei) in proton–proton collisions, providing a fundamental basis for modelling the production and absorption of antideuterons in interstellar space. Such modelling is required to interpret data from experiments that are on the hunt for such antideuterons, which could be generated by dark-matter annihilations or decays or by other sources, including collisions of high-energy cosmic rays with the interstellar medium.

In another study, ALICE showed how a technique based on measuring the momentum difference between hadrons produced in proton–proton collisions can reveal the dynamics of the strong interaction between these particles. The technique had previously allowed ALICE to study interactions involving several types of hyperons – hadrons with one or more strange quarks. In 2020, the team used the technique to uncover with high precision the interaction between a proton and the Omega hyperon, which contains three strange quarks. The result allows for a comparison with predictions from calculations known as lattice quantum chromodynamics, and provides a solid testbed for theoretical work.

*ALICE showed how proton–proton collisions at the LHC can reveal the strong interaction between hadrons.* (CERN-PHOTO-202008-104-64))





*The ALPHA experiment in CERN's Antiproton Decelerator hall.* *(CERN-EX-1011301-01)*

*ALPHA REPORTED THE FIRST MEASUREMENTS OF THE FINE STRUCTURE AND THE LAMB SHIFT IN THE ENERGY STRUCTURE OF ANTIHYDROGEN.*

## THEORY INSIGHTS

In 2020, CERN's Theoretical Physics department conducted cutting-edge research supporting the Laboratory's activities and serving the international theoretical physics community. This research covered many fields, from string theory and quantum field theory to collider physics, cosmology and astroparticle physics.

This research led to the submission of over 280 papers to the arXiv preprint server. Notable examples among the many influential results include precise calculations of processes in the Standard Model; an effective method based on machine learning to indirectly search for new physics phenomena at the LHC; various studies concerning dark matter, including how it can produce black holes at the centre of celestial bodies; the interpretation of results from the North American Nanohertz Observatory for Gravitational Waves in terms of a stochastic background of gravitational waves produced by cosmic strings; a possible resolution of a tension in measurements of the Hubble constant, which represents the rate at which the universe is currently expanding; and the development of analytical methods for deriving non-perturbative constraints on the structure of particle scattering.

The department actively participated in the physics studies related to the European Strategy for Particle Physics, and it made fundamental contributions to the LHC Physics Centre at CERN and to all working groups on the physics of the LHC and on the proposed colliders CLIC (Compact Linear Collider) and the FCC (Future Circular Collider). The department also played a leading role in new physics research initiatives in the context of the Neutrino Platform (see p. 52) and Physics Beyond Colliders (see p. 53).

Owing to the COVID-19 pandemic, in 2020 the department hosted fewer people than in previous years: 178 visiting scientists (20 associates, 116 paid visitors and 42 unpaid visitors). The number of theory institutes held by the department was also affected, with only three programmes taking place in 2020. However, the department organised a rich and successful programme of virtual scientific activities, from seminars to small workshops to open discussion sessions.

## ANTIMATTER ADVANCES

CERN's Antiproton Decelerator (AD) provides low-energy antiprotons to experiments investigating the properties of antiprotons, antiprotonic atoms and antihydrogen. Such studies allow ever more detailed comparisons between the behaviour of matter and antimatter in order to precisely test a fundamental symmetry in the Standard Model and a fundamental principle in general relativity. In 2020, the AD hosted five experiments: ALPHA, AEgIS, ASACUSA, BASE and GBAR. All of these experiments have now been connected to the new ELENA ring, which slows down antiprotons even further than the existing AD so that they are more easily trapped by the experiments. In 2020, several technical upgrades to the experiments got under way, and will continue in 2021, with the aim of increasing their measurement potential once the accelerator complex is up and running again.

Highlights from results published in 2020 include ALPHA's first measurements of two quantum effects known as the fine structure and the Lamb shift in the energy structure of antihydrogen, the antimatter counterpart of hydrogen. The measurements are consistent with theoretical predictions of the effects in "normal" hydrogen and pave the way for more precise measurements of these and other fundamental effects.

Another result was ASACUSA's creation at the Paul Scherrer Institut – using experimental equipment from CERN – of a predicted but never before verified exotic "pionic helium" atom as well as first measurements of how it absorbs and resonates with laser light. The new atom consists of a nucleus from the isotope helium-4, an electron and a negatively charged pion in a high-lying energy state. The results mark the first time laser spectroscopic measurements have been made on an exotic atom containing a meson. Laser spectroscopic measurements of exotic mesonic atoms could be used to determine with high precision the mass and other properties of the constituent mesons, as well as to place limits on possible new forces involving mesons.

*A section of the ISOLDE experimental hall.* (CERN-PHOTO-201911-394-9)

## NEWS FROM THE WORLD OF NUCLEI

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 research, including nuclear and atomic physics, solid-state physics and life sciences. These exotic beams can be re-accelerated using the REX/HIE-ISOLDE linear accelerators, which can accelerate radioactive isotopes to energies close to 10 MeV per nucleon (proton or neutron). Owing to the ongoing shutdown, no experiments were performed at ISOLDE in 2020. Nonetheless, many upgrades were made to the experiments and many results were obtained from analyses of data taken prior to the shutdown.

A highlight was the measurement of the electron affinity of the element astatine, the rarest naturally occurring element on Earth (there are only 70 milligrams in the Earth's crust at any given time). The electron affinity is the energy released when an electron is added to a neutral atom in the gas phase to form a negative ion, and it is one of the most fundamental properties of a chemical element. The result is important for both fundamental and applied research: as well as giving access to hitherto unknown properties of this element and allowing theoretical models to be tested, the finding is of practical interest because astatine is a promising candidate for the creation of compounds for cancer treatment by targeted alpha therapy.

Another noteworthy result was the finding that the nucleus of the radium isotope $^{222}$Ra has a stable pear shape, while $^{228}$Ra instead oscillates between a pear shape and its mirror image. These results allowed researchers to conclude that so far there are only three cases in nature – $^{222}$Ra, $^{224}$Ra and $^{226}$Ra – where there is incontrovertible evidence for nuclear pear shapes. Such nuclei are useful for testing existing nuclear theories, and they could be used to search for an electric dipole moment in particles, in particular when they are part of molecules such as radium monofluoride. ISOLDE's first-ever laser-spectroscopy measurements of radium monofluoride, published in 2020, are an important step in that direction.

ISOLDE also stepped into a nearly unexplored region of the nuclear chart with a first study of the neutron structure of the mercury isotope $^{207}$Hg, which is a relatively close neighbour of nuclei involved in a process that is responsible for producing approximately half of the nuclei heavier than iron.

## SPACE UPDATE

Attached to the International Space Station and operated from a control centre at CERN, the Alpha Magnetic Spectrometer (AMS-02) detector continues to surprise with its observations of cosmic rays – charged particles that travel through space with energies of up to trillions of electronvolts. The year 2020 began with the successful completion of a six-month-long series of spacewalks – unprecedented in complexity for a space intervention – to replace the AMS cooling system, which has extended the lifetime of the experiment. Later in the year, the AMS team reported measurements of how the fluxes of heavy primary cosmic rays – the heavy nuclei of neon, magnesium and silicon – change with rigidity, a measure of a charged particle's momentum in a magnetic field. They found that the neon, magnesium and silicon fluxes display unexpectedly


*The AMS detector on the International Space Station.*

identical rigidity dependence above 86.5 GV, including an also unexpected deviation above 200 GV from the single-power-law dependence predicted by the conventional theory of cosmic-ray origin and propagation. In addition, the observed rigidity dependence is surprisingly different from that of the lighter primary helium, carbon and oxygen cosmic rays, which had been previously measured by AMS. The new measurements have again challenged the conventional theory of cosmic-ray origin and propagation.

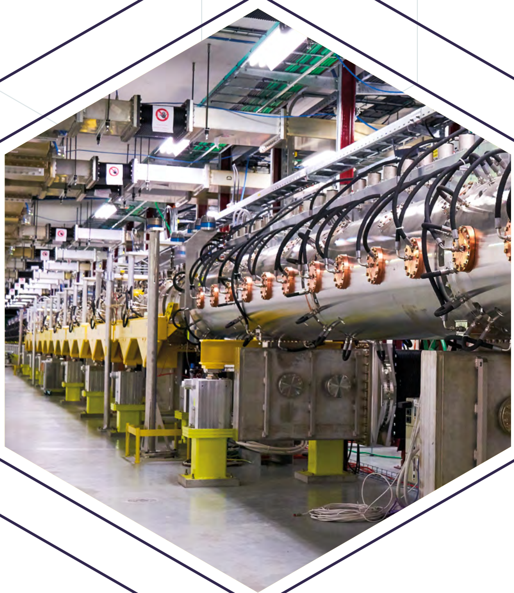
## FIXED-TARGET TERRITORY AND BEYOND

Other CERN-based experiments, many of which are fed by beams from the PS Booster and the PS and SPS accelerators, have also made great advances. One is CLOUD, a unique experiment that can study aerosol and cloud formation in an ultra-pure chamber. In 2020, in a result that could help shape policies for reducing air pollution, the CLOUD collaboration revealed a new mechanism that drives winter smog episodes in cities. Other advances made during the year include particle measurements for neutrino and cosmic-ray experiments and investigation of the quark–gluon plasma in heavy-ion collisions in fixed-target mode (NA61/SHINE); studies of rare kaon decays and searches for new heavy neutral leptons (NA62), with the first significant evidence seen for the ultra-rare decay of a positively charged kaon into a pion and a neutrino–antineutrino pair; studies of radiation processes in strong electromagnetic fields (NA63); searches for dark-sector particles (NA64), including the first NA64 search for axions and axion-like particles; measurements of neutron-induced processes relevant to nuclear physics and astrophysics (n_TOF); studies of the hadron structure with COMPASS and of its future successor, AMBER, which was approved in December 2020; and searches for chameleon particles and axions (CAST).

*CLOUD revealed a new mechanism that drives winter smog episodes in cities.* *(CERN-PHOTO-201909-278-1)*

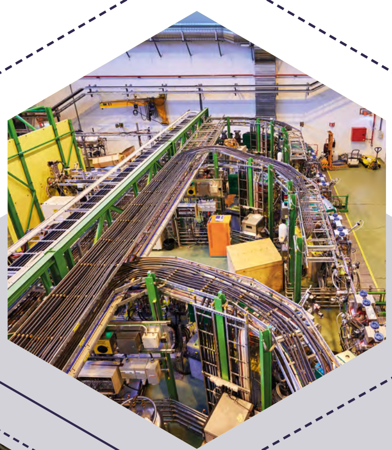
# DISCOVERY MACHINES

***2020, the pivotal year of the second long shutdown (LS2) of CERN's accelerator complex, really put the teams to the test. The COVID-19 pandemic took its toll on the already hectic schedule of equipment maintenance, renovation and replacement due to take place during LS2. Despite the difficult situation, the LHC Injectors Upgrade (LIU) project and the upgrades needed in preparation for Run 3 of the LHC and the High-Luminosity LHC (HL-LHC) continued to advance, largely thanks to the unfailing commitment of all the teams.***



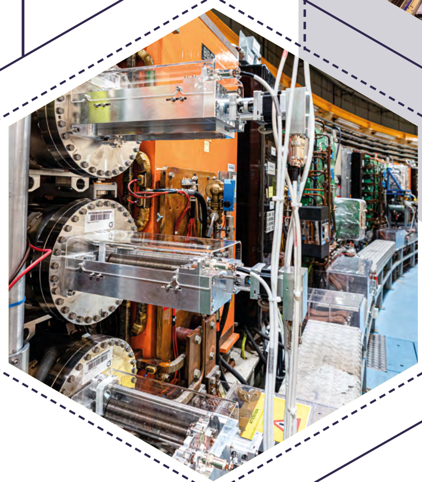
### LINEAR ACCELERATOR 4 (LINAC4)

The commissioning of Linac4 continued. In August, beams at 160 MeV passed through the whole machine. In December, Linac4 supplied beam to the PS Booster for the first time.
(CERN-PHOTO-201704-093-2)



### ISOLDE

ISOLDE's front ends and tape station were replaced. One of the HIE-ISOLDE linear accelerator's cryomodules was reinstalled after undergoing repairs and a series of tests.
(CERN-PHOTO-201911-394-11)

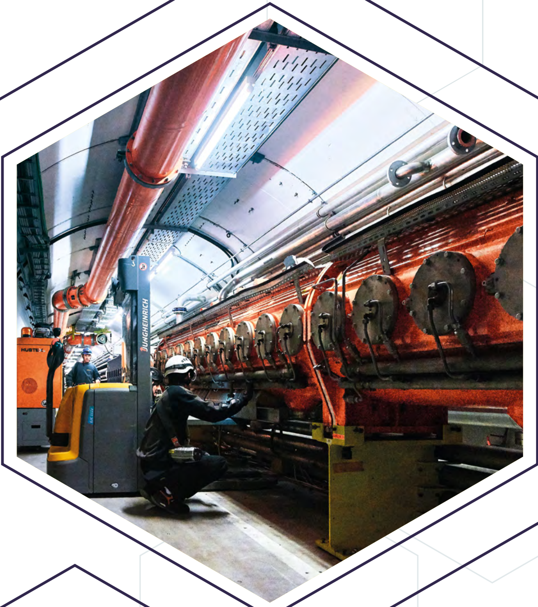


### PS BOOSTER (PSB)

Some 40% of the machine was replaced or upgraded. In December, the Booster received its first beam from Linac4, marking the first-ever connection between the two accelerators. (CERN-PHOTO-202006-085-9)

## SUPER PROTON SYNCHROTRON (SPS)

Upgrade work on the acceleration system was completed. The new beam dump was installed at Point 5.
(CERN-PHOTO-201902-032-12)

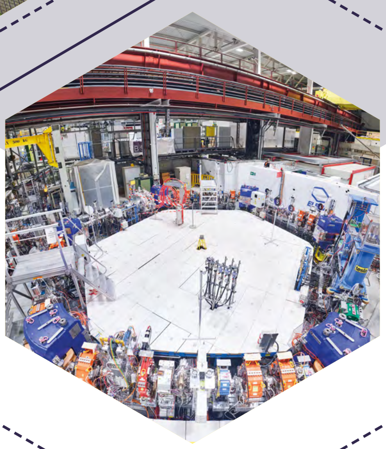


## LARGE HADRON COLLIDER (LHC)

As part of the DISMAC project, the electrical insulation of the last of the 1232 LHC diodes was completed. Five of the eight LHC sectors were cooled down at the end of the year. The LHC's two external beam dump systems were upgraded.
(CERN-PHOTO-202101-019-2)

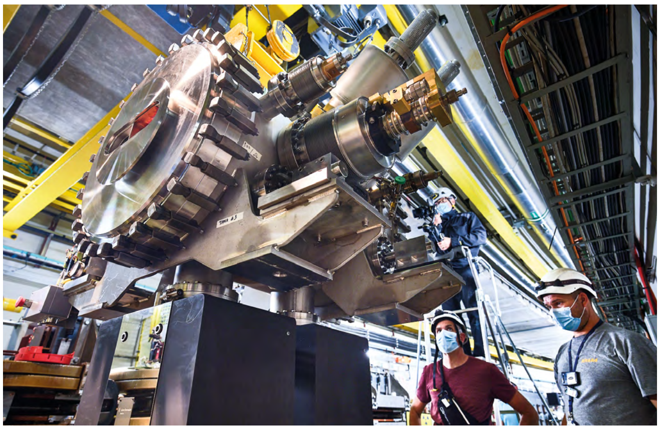
## PROTON SYNCHROTRON (PS)

The PS injection system was equipped with a new septum magnet and a new kicker magnet. Two new internal beam absorbers were installed in the machine.
(CERN-PHOTO-202004-081-3)



## ANTIPROTON DECELERATOR (AD) AND ELENA

$H^-$ ions were injected and circulated in the new ELENA decelerator before being extracted for the first time and sent to the GBAR, BASE, ASACUSA and ALPHA experiments.
(CERN-PHOTO-201611-300-1)



*The new septum magnet and a bumper magnet during installation in the PS injection line.*
*(CERN-PHOTO-202006-090-13)*

## RESTART OF THE FIRST INJECTORS

CERN's accelerator complex is gradually coming out of two years of hibernation, during which maintenance and repair work has been carried out. In the summer, the second long shutdown came to an end for **Linear Accelerator 4** (Linac4), CERN's newest accelerator. During the machine development phase, which ended in mid-August, low-energy negative hydrogen ion ($H^-$) beams passed through the initial part of the accelerator for the first time in 2020. On 20 August, the first beams at the nominal energy of 160 MeV (compared to 50 MeV for Linac2) passed through all the accelerating structures to a dedicated absorber at the other end of the machine.

Linac4, the first link in the proton accelerator chain, shapes $H^-$ ion beams differently to its predecessor, Linac2. The Proton Synchrotron Booster (PSB), the accelerator downstream of Linac4, receives $H^+$ ions by means of an innovative injection system that works through charge exchange. This technology limits particle loss during injection and produces very bright beams. The energy spread of the beams can also be adjusted to correspond to the acceptance of the Booster.

The **Proton Synchrotron Booster** (PSB), a racing car that was completely transformed during LS2, was recommissioned soon after Linac4. In December, the Booster received its first beam from Linac4, marking the first-ever connection between the two accelerators.

A whole host of the Booster's components, from the engine (the power supply and converters) to the accelerator (the radiofrequency cavities), the steering (the magnets), the injection system, the cooling circuit and the control and safety systems – around 40% of the machine! – were replaced or upgraded.

The aims of the work on this nearly 50-year-old accelerator were twofold: to inject and accelerate particles arriving at higher energies from Linac4 and to double the brightness of the beam – in other words, the concentration of particles.

In order to preserve this brightness in the Proton Synchrotron (PS), the next accelerator in the chain, the Booster will increase the energy up to 2 GeV (compared to 1.4 GeV previously), thanks to its all-new main acceleration and power supply system. The electrical repulsion between particles of the same charge (Coulomb repulsion) lessens as the energy increases: the energy helps to keep the particles bunched and therefore to maintain brightness. And with more brightness comes more luminosity, making the Booster one of the keys to increasing the LHC's luminosity.

To receive particles arriving from the Booster at an energy of 2 GeV, the system of injection into the **Proton Synchrotron** (PS) needed a new septum magnet and a new kicker magnet. These two magnets bend the trajectory of the proton beams entering the PS from the Booster so that they follow a circular path.

The new septum magnet, which was installed in the spring, is based on the principle of Foucault currents; this is the first time that this kind of septum magnet has been used at CERN. In the PS, the septum magnet works in conjunction with five bumper magnets and a kicker magnet, which together make up the injection system. The septum magnet bends the trajectory of the beam from the Booster to the PS ring. The bumper magnets modify the orbit inside the PS so that its position and angle correspond to those of the beam coming out of the septum. Finally, the kicker magnet, located downstream, places the injected beam onto the nominal orbit. The kicker magnet was installed in January, replacing its predecessor, which had been in service since 1979.

The PS's acceleration systems were extensively upgraded, and all the radiofrequency (RF) cavities, the transverse feedback and the low-level RF systems were modified to provide the beam intensities required for the HL-LHC.

In June, the PS was fitted with two new internal beam absorbers, the result of five years of development work as part of the LHC Injectors Upgrade (LIU) project. The core of the absorber is made of two materials, isostatic graphite and a copper, chromium and zirconium alloy, the second denser than the first, through which the beam passes one after the other. Each absorber is encased in an armoured steel and concrete structure, which helps to absorb the beam. The absorber works differently to those typically used at CERN. Particles are usually deflected by a kicker magnet, which steers them towards a static absorber. Instead, the PS's new absorber moves to meet the beams, oscillating to block the vacuum chamber so that the particles' trajectory does not need to be deflected.

On Friday, 23 October, the keys to the PS were handed back to the operations team, marking the start of the equipment's commissioning.

*The PS's two new internal beam absorbers, encased in an armoured steel and concrete structure (green), were installed in the accelerator in June.*
*(CERN-HOMEWEB-PHO-2020-094-1)*

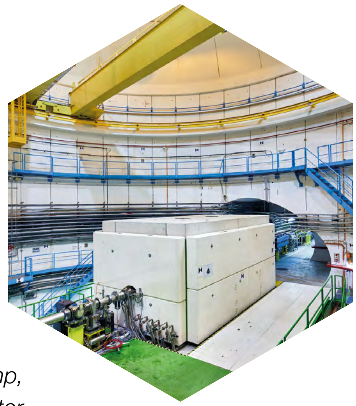
*The East Area, one of CERN's oldest facilities, has been transformed into a cutting-edge research centre.*
*(CERN-PHOTO-202101-009-1)*

In the **East Area**, which is supplied by the PS, progress was made on the main consolidation work, with the installation and commissioning of the new extraction line from the PS and new power converters, as well as a new beam dump. The new ventilation system for the primary area was installed and major work was carried out on the cooling, ventilation and electrical distribution systems. In addition, the experiment area was modified for the CLOUD experiment.

On 4 December, precisely on schedule, the members of the Accelerator Coordination and Engineering group handed over the keys to the **Super Proton Synchrotron** (SPS) to the Operations group, marking, as for the PS, the beginning of the equipment commissioning phase.

The modifications to the machine's acceleration system were completed in 2020. This new system, based on highly innovative radiofrequency transistor power amplifiers that are more powerful than any produced elsewhere, will make it possible to accelerate more intense beams. The accelerating cavities were reinstalled following the required modifications, while the 32 towers containing 10 240 transistors were commissioned. In parallel, the beam control systems were upgraded.

The new SPS beam dump, which replaces that located at Point 1 of the accelerator, was installed at Point 5. This absorber, developed in the framework of the LIU project, is a 10-metre-long device made of an assortment of high-density materials designed to absorb the entire power of the SPS beam. The absorber is encased in an armoured structure made of concrete, iron and marble.



*The new SPS external beam dump, located at Point 5 of the accelerator.*
*(CERN-PHOTO-202011-158-5)*

*The Linac3 micro-oven is closed after being refilled with lead.*
*(CERN-PHOTO-202011-154-1)*

## LINAC3 EQUIPMENT UPGRADE

**Linear Accelerator 3** (Linac3), constructed in 1994, is the departure point for ions, usually lead nuclei, which are used either for collisions in the LHC or for fixed-target experiments.

To produce ion beams, oxygen gas and lead vapour are injected into the source plasma chamber. A microwave is applied to create the plasma in which the lead and oxygen ions are ionised; the plasma is confined by a magnetic field. To evaporate the lead, Linac3 uses a micro-oven. In 2020, the Linac3 team developed and tested a new configuration of this oven, with the aim of improving its performance.

In addition, Linac3 was equipped with a new extraction system – the system that takes lead ions from the plasma chamber – that will allow the extracted beam to be more precisely adjusted and could also increase its intensity.

*One of the four HIE-ISOLDE cryomodules with its five radiofrequency cavities.* *(OPEN-PHO-ACCEL-2016-016-7)*

## THE NUCLEAR PHYSICS FACILITIES LEVEL UP

In the **ISOLDE** target area, which is supplied by the PSB, the front ends were replaced with a new generation of these devices, enabling more exotic radioactive isotopes to be produced. Another important upgrade was the replacement, after 40 years of operation, of the tape station, which is used to sample and identify radioactive isotopes. The new instrument greatly reduces the sampling time for short-lived isotopes and is equipped with more powerful detectors.

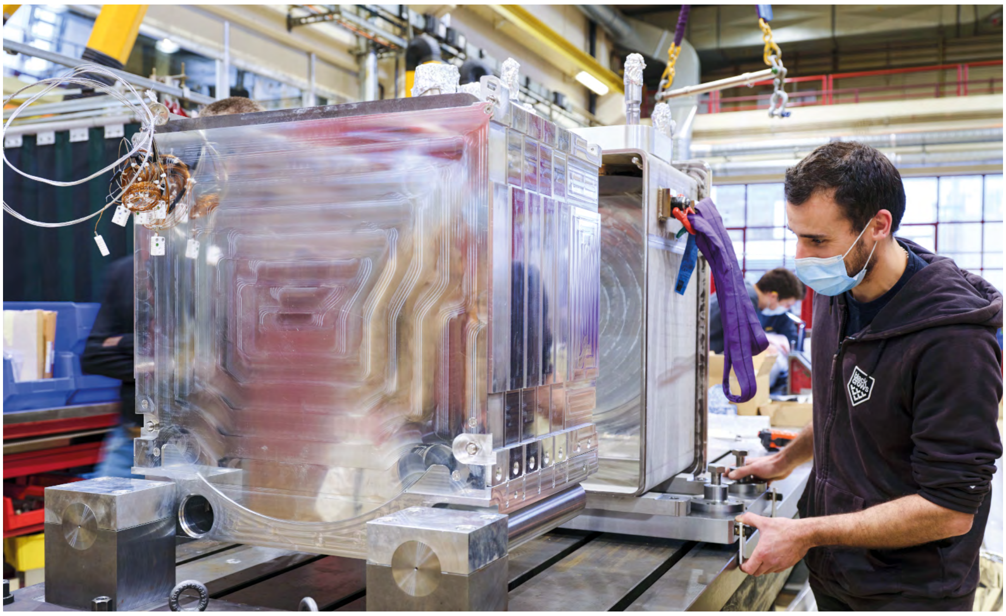
Located in the ISOLDE hall, **HIE-ISOLDE** (High Intensity and Energy Isotope Mass Separator On-Line), the compact linear accelerator for heavy isotopes, comprises 20 superconducting radiofrequency cavities arranged in four cryomodules, each cooled to around 4 kelvins. This machine accelerates radioactive isotopes to up to 15% of the speed of light. At this energy, the nuclei can fuse or exchange nucleons with the atoms of the targets with which they collide.

In 2020, one of its four cryomodules, which had been found to be faulty after commissioning, was reinstalled following repairs and a series of tests. In the autumn, a stable neon beam from an independent source was injected into the machine, confirming that it was functioning correctly.

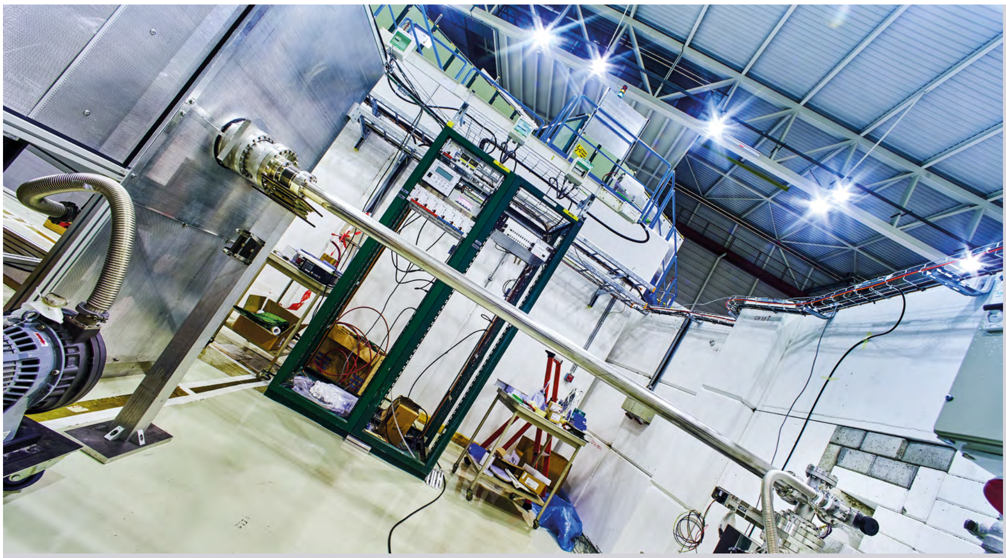
The electron gun of the REX-EBIS charge breeder, which supplies the normal-conducting REX-ISOLDE and superconducting HIE-ISOLDE linacs with highly charged ions, was completely redesigned. In addition, new diagnostic boxes were installed along the length of REX-ISOLDE and will provide valuable information on unexplained beam losses that were recorded before LS2.

The ISOLDE nuclear materials handling laboratory now has an extension to house the “nano-lab”, a unique infrastructure designed for the development of innovative materials for the ISOLDE targets.

The construction of the new target for the **neutron time-of-flight** (n_TOF) facility, which studies nucleus–neutron interactions, was completed. The target will be installed at the beginning of 2021 and expects to receive its first beams from the PS in July 2021. Several upgrades and improvements were also successfully completed in the target area and on the neutron beamlines. The power converters and the control systems of the proton transfer line towards the n_TOF target were also upgraded.



*Construction of the new n_TOF target.* *(CERN-PHOTO-202010-175_02)*



*Transfer line connecting the ELENA ring (behind the wall on the right) to the GBAR experiment (left).*
*(CERN-PHOTO-201708-192-11)*

## ELENA SUPPLIES ITS FIRST EXPERIMENTS

**ELENA** (Extra Low Energy Antiprotons), CERN's new deceleration ring, again injected and circulated $H^-$ ions from an independent source and, for the first time, sent them to the GBAR, BASE, ASACUSA and ALPHA experiments.

ELENA is the new keystone of the antimatter factory. It receives antiprotons from the **Antiproton Decelerator** (AD) at an energy of 5.3 MeV and decelerates them to 0.1 MeV, which will enable the experiments to trap almost 100 times more antiprotons than previously.

The new GBAR experiment was connected to ELENA in 2017. Since November 2018, LS2 has been spent dismantling and then replacing the transfer lines between ELENA and ALPHA, AEgIS, ASACUSA and BASE, and installing new lines to the future antimatter factory experiments.

These new transfer lines use innovative technologies: the old electromagnets have made way for dipole and quadrupole electrostatic plates, which are enough to guide particles that have been slowed down to such an extent. By not using these magnet systems, the antimatter factory has opted for a solution that is economical and frees up space to increase the number of quadrupoles and thus further focus the beam to make it less sensitive to interference.

Innovations have also been made in the instrumentation: the new beam observation monitors allow the beam to be measured precisely by intercepting only part of it. Obtained at the end of the year, the first diagnostics of the beam of $H^-$ ions travelling through the new lines to the experiments are very promising.

## THE LHC COOLDOWN HAS BEGUN

The consolidation work on the **Large Hadron Collider** (LHC) is almost complete. In January, the DISMAC (Diode Insulation and Superconducting Magnets Consolidation) project teams reinforced the electrical insulation of the last of the 1232 diodes. The final diode box was rewelded in February. Following the insulation work, other teams carried out electrical and quality assurance tests and closed the interconnections one by one. Due to the COVID-19 pandemic, the work had to be put on hold in the spring, resulting in a delay of around three months. The final interconnection was closed in July.

Eight pressure tests (one per LHC sector) were then performed, the last in sector 6-7 on 27 October. They revealed no mechanical issues in the machine.

However, the electrical tests performed during cooling and the metrology checks uncovered a few non-conformities. The DISMAC project's Special Interventions team is responsible for the repairs and corrections, which will be carried out at the beginning of 2021. None of these non-conformities appears to be critical.

Nonetheless, the cooldown of the first LHC sector began in the autumn, and was successfully completed on 15 November. The sector was cooled with superfluid helium to a temperature of 1.9 K (-271.3 °C), the nominal operating temperature. Four other sectors were then also cooled. The three remaining sectors will be cooled in 2021, enabling the whole of the LHC to operate under its nominal cryogenic conditions.

*One of the LHC's spare external absorbers is extracted from the tunnel to undergo upgrades in preparation for Run 3 of the accelerator. (CERN-PHOTO-202001-018-15)*

Work on the accelerator's two external beam dump systems began at the start of February. During Run 2, the maximum internal temperature of the absorbers climbed to 1000 °C in barely 100 microseconds after each beam dump. After LS2, when the LHC beams will be even more intense, the temperature could rise to 1500 °C. To cope with this, the LHC's beam dumps are equipped with an 8-metre-long graphite absorber contained in a stainless steel tube, itself encased in iron shielding filled with nitrogen gas.

After ten years of operation, the beam dump systems were showing signs of fatigue. In preparation for Run 3 of the LHC, the decision was taken to upgrade the two spare absorbers.

One of the main modifications made was to the support system of the absorbers, which will now be suspended from high-resistance steel cables to provide better shock absorption. The upgrade work also included the installation of new titanium-alloy beam "windows" that trap the graphite part of the absorber in its nitrogen atmosphere. In addition, the transfer line from the LHC was physically disconnected from the absorber to prevent the propagation of vibrations in the ultra-high-vacuum beam pipe leading from the accelerator.

The work was completed at the beginning of October. During the next run, instruments fitted to the upgraded absorbers will collect data that will guide the design of the absorbers for the future High-Luminosity LHC (HL-LHC).

During LS2, upgrade work was also carried out on the Point 4 refrigerator, which dates from the time of the previous accelerator, the Large Electron–Positron Collider (LEP). The renovations increased its cooling power from 16 kW to 18 kW at 4.5 K in preparation for the HL-LHC.

The Point 4 refrigerator is crucial for the HL-LHC because, as well as cooling sectors 3-4 and 4-5, it will also cool the sections housing the radiofrequency cavities, which require a considerable amount of cooling. To achieve this important extra 2 kW, the four turbines and heat exchangers of the two cold boxes at Point 4 have been replaced with higher-performing equivalents.

*At Point 4, the cold box located on the surface measures around 6 metres in length and 3 metres in diameter. All of its components are vacuum-insulated to limit thermal radiation. (CERN-PHOTO-201912-412-4)*

## A NEW SCHEDULE FOR LS2

The COVID-19 lockdown period, which resulted in a shutdown of activities on the CERN site and the closure of many partner institutes, followed by a gradual restart, naturally had an impact on the Long Shutdown 2 (LS2) schedule. In June, a new schedule for the LS2 activities was drawn up, anticipating that the first low-intensity test beams will circulate in the LHC at the end of September 2021, four months later than the date planned before the COVID-19 crisis.

No changes were made to the schedule beyond 2022. A normal year-end technical stop is planned to take place in 2023-2024. LS3 is scheduled to start at the beginning of 2025.

*The CERN Data Centre is the heart of CERN's entire scientific, administrative and computing infrastructure. (IT-PHO-CCC-2018-001-12)*

## COMPUTING: UPGRADES AND CONTINUITY

Computing is essential not only to process the data supplied by the experiments, but also for the smooth running of the activities of all CERN's departments, from engineering to administration and human resources. While the COVID-19 pandemic situation did not prevent computing teams from meeting most of their 2020 objectives, many activities had to be rearranged and reprioritised. In parallel, computing services also ensured the continuity of CERN's activities by providing the community with the infrastructure and connections to work remotely.

Across all systems, videoconference connections quadrupled during CERN's COVID-19 response, which required extensive adaptations. A new videoconference service was successfully piloted and deployed in 2020. CERN's response to the pandemic also led to significant expansion of the LoRaWAN infrastructure in 2020, as required for the deployment of the Proximeter devices, which are designed to warn people if they get too close and to log such close contacts for follow-up should any of those involved test positive for the coronavirus.

The year 2020 was key for preparing all computing services for Run 3. Much of the network, database, server and storage maintenance and upgrade work required for Run 3 could only be performed during Long Shutdown 2. It was also the year in which the NXCALS (next-generation accelerator logging) project moved into full production mode in preparation for the next LHC run. For this mission-critical project, the database team invested enormous effort in developing the right administrative tools and monitoring systems, which are now useful to many other projects.

In 2020, about 40 tonnes of new hardware were installed in the CERN Data Centre, and 25 tonnes were retired. Since 2012, CERN has regularly donated computing equipment that no longer meets its highly specific efficiency requirements but is still more than adequate for less exacting environments. In 2020, 117 servers from the CERN Data Centre and six network switches were donated to Fayoum University in Egypt, while 254 server chassis were donated to LHCb. In addition, CERN Data Centre hardware that was about to be retired was used for the *Rosetta@Home* and *Folding@Home* projects to perform protein-folding simulations.

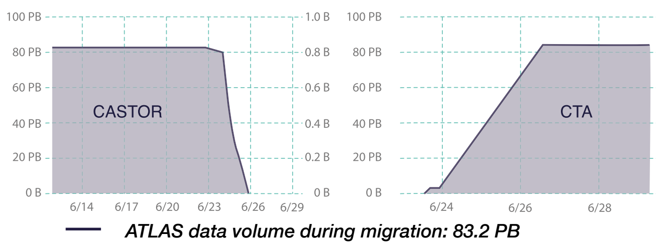
Finally, a major undertaking in 2020 was the successful tender for the design, construction, operation and maintenance of a new, energy-efficient Data Centre to be built on the CERN Prévessin site. The award of the contract was adjudicated at the December 2020 meeting of the CERN Finance Committee.

## DATA STORAGE CONSOLIDATION

Over the last ten years, requirements have evolved and a new disk system – EOS – was developed for online storage and data analysis. During 2020, the EOS physics clusters delivered 2.5 exabytes of physics data for analysis, reconstruction and software validation. However, as EOS does not provide offline storage and data archival, a new project, the CERN Tape Archive (CTA) project, was conceived as the tape back-end to EOS. CTA saw its first deployments in 2020 for the ALICE, ATLAS and CMS experiments, which involved the migration of over 200 petabytes of data.

Besides the introduction of CTA, CERN also prepared for Run 3 by installing a new tape library in the Data Centre and by upgrading FTS, its File Transfer Service. FTS, which distributes the majority of LHC data across the Worldwide LHC Computing Grid (WLCG) infrastructure, benefitted from several significant performance improvements. It is now also supporting CTA and is used by more than 35 experiments at CERN and in other data-intensive scientific disciplines. In 2020, FTS transferred to WLCG about one billion files and more than one exabyte of data.

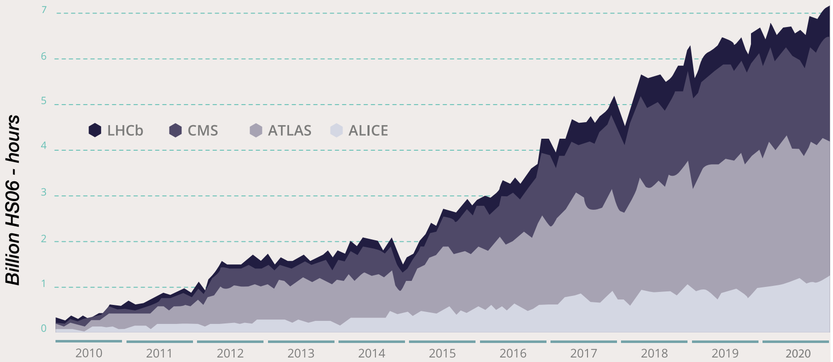
***Total data (ATLAS)***




*On 29 June, the CERN Tape Archive (CTA) officially entered production after 83 petabytes of ATLAS data initially stored in CASTOR were successfully migrated to CTA.*

## THE WORLDWIDE LHC COMPUTING GRID (WLCG) EVOLVES

WLCG was highly stable and reliable in 2020, supporting the timely delivery of high-quality physics results by the experiment collaborations. Even though they were not taking data, the four LHC experiments nevertheless continued to use all of the WLCG services and resources at full capacity for storage and analyses. The levels of central processing unit (CPU) time used reached new peaks during the year. The total amount of storage used approached one exabyte, split approximately equally between tape and disk media.




***Evolution of the overall core processor time delivered by WLCG***

*As the graph shows, the total CPU time delivered by WLCG (expressed in billions of HS06 hours per month, HS06 being the HEP-wide benchmark for measuring CPU performance) is continually increasing. In 2020, WLCG pooled the computing resources of about one million cores.*

## PREPARING FOR THE FUTURE

Looking to the future, the High-Luminosity LHC (HL-LHC) will bring a major increase in computing requirements compared with the upcoming Run 3. That demand exceeds extrapolations of technology progress within a constant investment budget, in terms of both storage and computing capacity. Various partnerships, collaborations and projects worked actively in 2020 to tackle those challenges. The work on the use of graphics processing units (GPUs) also continued.

CERN openlab, the unique public–private partnership whereby CERN collaborates with leading ICT companies and other research organisations, supported a record 34 joint R&D projects in 2020, which have great potential to provide solutions for CERN's future ICT challenges.

In 2020, a new collaboration on high-performance computing (HPC) was set up in which CERN joined forces with SKAO, the organisation leading the development of the Square Kilometre Array radio-telescope; GÉANT, the pan-European network and service provider for research and education; and PRACE, the Partnership for Advanced Computing in Europe. Its aim is to overcome challenges related to the use of HPC to support large, data-intensive science projects, thus helping research communities to unlock the full potential of the next generation of hardware.

The WLCG team is leading the DOMA (data organisation, management, access) project, which aims to prototype the concepts of a "data lake", whereby data can be streamed on demand to processing centres rather than being pre-placed there. The CERN team is leading a work package, within the EU-funded ESCAPE project, to demonstrate this data lake technology. During its first mandate, the DOMA access working group produced an activity report that provided input for the HL-LHC computing review in May 2020. A full dress rehearsal exercise took place on 17 November 2020 and demonstrated the capability of the data lake pilot to address the needs of many different scientific communities by running realistic workflows in a 24-hour period. Some 10 scientific disciplines, 10 sites and about 50 scientists participated in the exercise and successfully shared a common infrastructure and a common data management framework for the first time under realistic conditions.

Last but not least, CERN's external networking capacity was also further developed in 2020, which resulted in the doubling of the bandwidth available for transfers to sites connected to LHCONE and the introduction of a first 400-gigabit-per-second link, which will be used to prepare the WLCG for the significantly higher data rates expected in the HL-LHC era.

## SCIENCE IN THE CLOUDS

Over 90% of the Data Centre's computing resources are provided using a private cloud that is based on OpenStack, an open-source project to deliver a massively scalable cloud operating system. Ten years after its creation, this cloud provided over 300 000 physical and hyper-threaded cores in the CERN Data Centre in 2020.

The CS3MESH project, coordinated by CERN, started in January 2020. It enables service providers to deliver state-of-the-art connected infrastructure to boost scientific collaboration and data sharing according to FAIR (findable, accessible, interoperable and reusable) principles. The project delivers the core of a scientific and educational infrastructure for cloud storage services in Europe through a lightweight federation of existing sync/share services (CS3) and integration with multidisciplinary application workflows.

During 2020, CERN was involved in or successfully submitted 16 projects that received funding from the European Commission as part of the establishment of the European Open Science Cloud (EOSC). The EOSC initiative was proposed by the European Commission in 2016 with a view to building a competitive data and knowledge economy in Europe. EOSC will provide 1.7 million European researchers and 70 million professionals working in science, technology, the humanities and social sciences with a virtual environment offering open and seamless services for the storage, management, analysis and reuse of research data. CERN became a member of the recently formed EOSC Association in 2020, where it has a mandate to represent the European intergovernmental research organisations that make up EIROforum.

## OPEN SOURCE FOR OPEN SCIENCE

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

In 2020, the CERN Open Data portal, which allows the LHC experiments to share their data, benefitted from several new open-data releases. ATLAS released its first 13 TeV data samples, while CMS completed 2010-2011 proton–proton data and released new heavy-ion physics data samples. The coverage of non-LHC particle physics increased with the new OPERA electron–neutrino and charm hadron production data sets. December 2020 was marked by the publication of the CERN Open Data Policy, which aims to empower the LHC experiments to adopt a consistent approach towards the openness and preservation of experimental data. Several CERN technologies are being developed with open access in mind. Zenodo, the free open-data repository co-developed by CERN and available to all sciences, is one example. In 2020, Zenodo's growth was astonishing, having six times more visitors than the previous year, with a total of 15 million visits. As a contribution to the fight against COVID-19, a special community was created in Zenodo, the homepage rebranded and special fast-track support lines added to help anybody needing to share COVID-related data sets.

The MALT project, which was launched in 2018 with the aim of mitigating anticipated increases in software licence fees by transitioning to open-source products, brought several projects to fruition in 2020, with the implementation of the new CERN single sign-on (SSO), two-factor authentication and CERNphone. Some additional services such as Mattermost, CodiMD and Discourse, to name just a few, were also made available over the last two years.


*Participants of the online Inverted CERN School of Computing 2020.*

## THE CERN SCHOOL OF COMPUTING TURNS 50

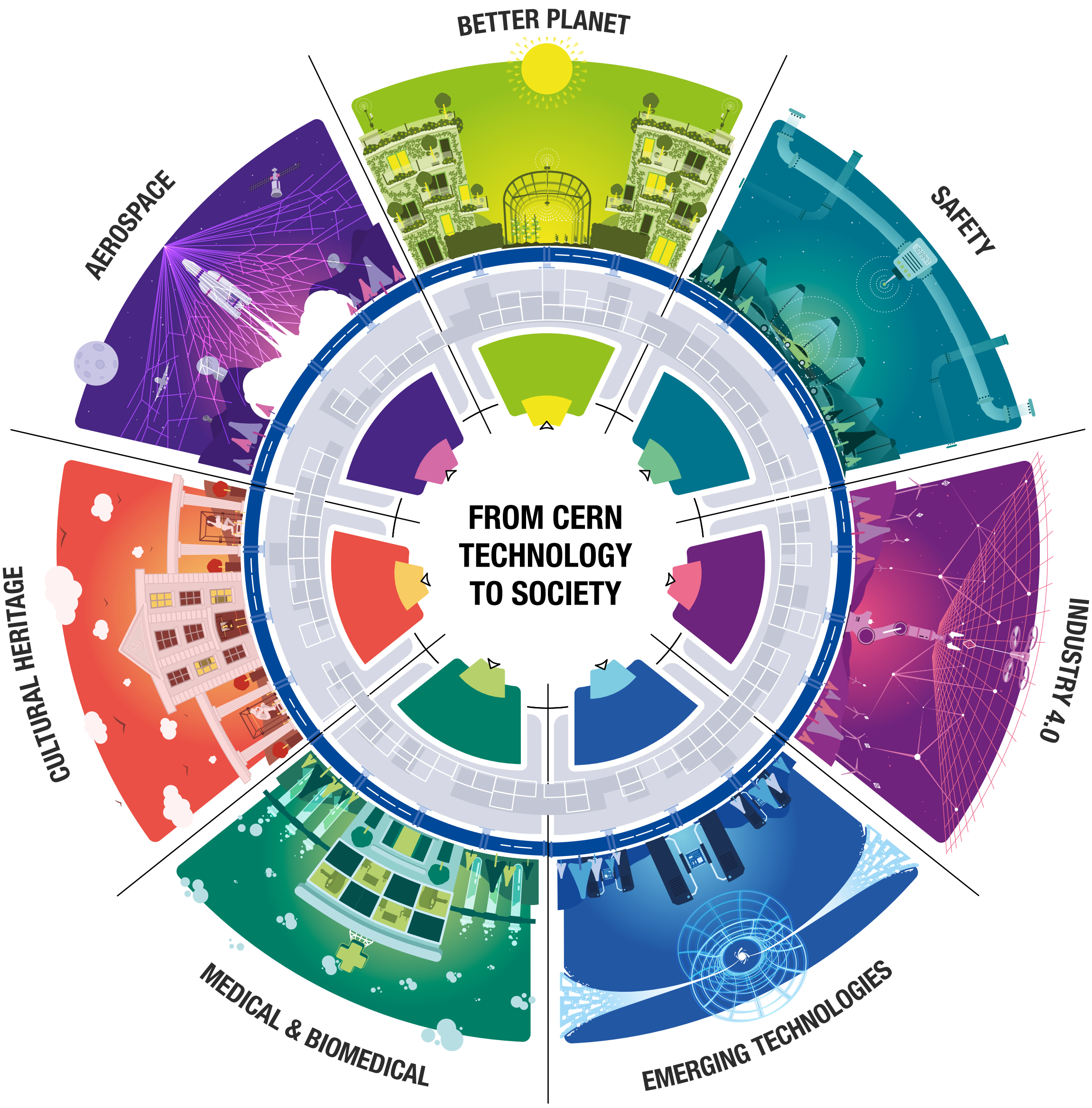
The CERN School of Computing (CSC), which fosters the dissemination of knowledge and learning in the field of scientific computing, celebrated its 50th birthday in 2020. Since the first CSC in Italy in 1970, the school has visited 24 countries and been attended by more than 2900 students from five continents and 80 nationalities.

Its mission is to create a common culture in scientific computing among scientists and engineers involved in particle physics and other sciences.

The CSC normally runs three schools per year. Due to the pandemic, both the Thematic School and the Main School had to be cancelled in 2020. However, the Inverted School (where the students become the teachers) went ahead as a virtual event in September and received a record of more than 1300 registrations. Each online class was attended by several hundred people.

# ACCELERATING INNOVATION

***In its quest to answer some of the biggest questions in the universe, CERN pushes the frontiers of accelerator, detector and computing technology. The resulting developments find applications beyond particle physics, in diverse areas such as medical and biomedical technologies, cultural heritage and environmental solutions. CERN actively cooperates with experts in science, technology and industry, and with governing bodies to foster this transfer of knowledge, drive innovation, and promote economic development in its Member States, thereby maximising the positive impact of CERN in society.***




*CERN's three pillars of technology are accelerators, detectors and computing. Behind these, lie a great number of areas of expertise. These technologies, and the human expertise associated with them, translate into positive impact across industries beyond CERN.*

## FROM CERN TO SOCIETY

Many novel technologies emerge from tools and techniques developed at CERN for particle physics. By identifying key technologies with potential societal impact, CERN seeks out opportunities to work with industry leaders in a range of fields of application. It would be impossible not to mention how, in 2020, this process allowed CERN to put its technology and knowledge at the service of the global efforts against COVID-19; some examples are featured in Chapter 2 “2020 in pictures” (pp. 6-15). This chapter features a few other knowledge-transfer success stories from the past year.

*Close-up of Compact Linear Collider prototype technology, on which the future electron FLASH facility design is based.*
*(CERN-PHOTO-202008-108-13)*

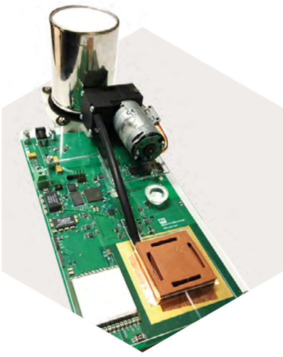
*Above left: Graphic combining energy spectra measured by the RToo scanner. Above right: RToo scanning the painting* The Madonna and Child.

### A PIONEERING NEW CANCER RADIOTHERAPY FACILITY

CERN continues to support the application of technology developed for accelerators, detectors and computing systems to solutions for present and future health challenges. One such challenge is obtaining high-energy electrons for FLASH radiotherapy, a highly targeted form of cancer treatment that is capable of reaching deeper into the patient’s body with fewer side effects than traditional radiotherapy. In September 2020, CERN and the Lausanne University Hospital (CHUV) announced that they would be collaborating on an innovative facility that will use CLIC (Compact Linear Collider) accelerator technology to accelerate electrons to very high energies to treat tumours up to 15 to 20 cm in depth.

### A LONG-LOST PAINTING BY RAPHAEL, REDISCOVERED

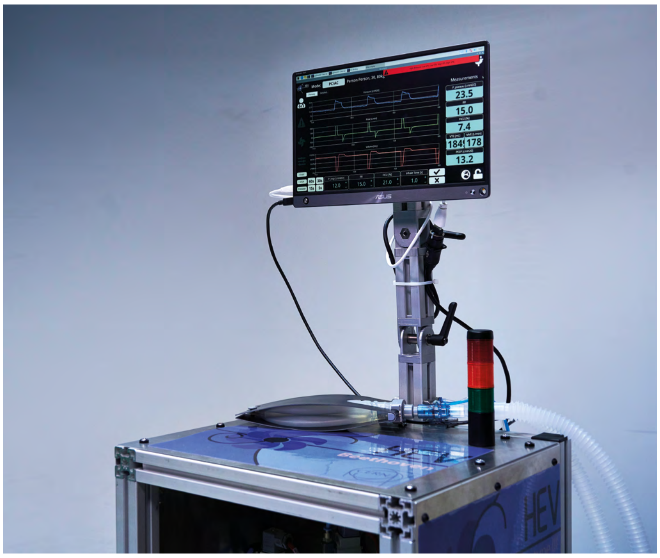
In the past, particle physics technology has allowed researchers to authenticate artwork through its composition, without affecting the object under analysis. The latest example is *The Madonna and Child*, a painting on canvas from a private collection. The Czech start-up InsightART successfully helped attribute the painting to the Renaissance master Raphael, using RToo, a state-of-the-art robotic X-ray scanner that uses Timepix photon detectors. InsightART obtained 11 high-resolution images taken at different X-ray wavelengths, enabling experts to acquire more information about the painting and earning InsightART the ArtTech Prize 2020.



*Prototype radon-monitoring device RaDoM, which will drive mitigation measures based on real-time data.*

### ENVIRONMENTAL SOLUTIONS BASED ON CERN TECHNOLOGY

CERN’s considerable intellectual resources are helping tackle another colossal challenge: creating a healthier and more sustainable planet. In 2020, technologies developed at CERN contributed to environmental monitoring through the spin-offs PlanetWatch and BAQ. PlanetWatch announced the activation of over 100 environmental sensors in Milan and Taranto (Italy) to help detect local air-pollution peaks and identify local air-pollution triggers. CERN and BAQ signed a licence agreement on the RaDoM (Radon Dose Monitor) technology – an innovative radon-monitoring prototype that includes a cloud-based service to collect and analyse data, control measurements and drive mitigation measures based on real-time data, which could help prevent diseases like lung cancer in the future.



*Particle physicists proposed the High-Energy Ventilator to help combat COVID-19. The design for this novel ventilator was developed by members of the LHCb collaboration.* *(CERN-PHOTO-202008-107-3)*

## A CULTURE OF INNOVATION SUPPORTED BY KNOWLEDGE-TRANSFER FUNDING

The CERN Knowledge Transfer fund and the CERN Medical Applications budget are two funding mechanisms to encourage CERN personnel to harness the full potential of CERN technology to have a broader positive impact. From financing higher-education fellowships to taking different commercial applications of CERN technology into society, these mechanisms have provided various projects with the support needed to let innovation take root. In 2020, two noteworthy projects were: the High-Energy Ventilator (HEV), a fully functional, high-quality medical ventilator for use in and out of intensive care units, and compatibility software to allow CERN's power-converter digital controls to be deployed in other accelerator facilities, such as the synchrotron facility SOLEIL, which is currently undergoing major upgrades for future research.

*IN 2020, CERN WAS AWARDED PRIZES FOR INSPIRING CURIOSITY ABOUT BIG SCIENCE, AND FOR MITIGATING THE IMPACT OF COVID-19 ON PROCUREMENT CONTRACTS.*

## DOING BUSINESS WITH CERN

Procurement is a fundamental aspect of CERN's economic impact in its Member States: advancements in accelerators, detectors and computing take shape through successful business collaborations, helping drive innovation in a variety of industries. In 2020, CERN continued the extensive procurement activities for the High-Luminosity Large Hadron Collider, for the CERN Science Gateway (with contracts signed for its construction and for the design, supply and installation of its exhibitions), and for the design, construction, operation and maintenance of the new data centre on the Prévessin site. Globally, CERN's procurement activities included 30 000 orders of various types, 62 invitations to tender, 114 price enquiries above 50 000 CHF, and the signature of 230 contracts, of which 139 were collaboration agreements. The expenditure on various orders and contracts totalled 441 MCHF (approximately 37% of the budget) in 2020.

In 2020, the CERN Procurement Service participated in industry events hosted in Denmark, France, India, Spain, Sweden and Turkey, and organised the France@CERN industrial exhibition, held virtually for the first time. At the Big Science Sweden Conference 2020, CERN was awarded the "Big Science Sweden Influencer: Research Facility" prize.


*The 2020 EIPM Peter Kraljic Prize for Excellence, awarded to the CERN Procurement and Industrial Services.*

Despite these impressive numbers, the global health crisis had an impact on CERN's procurement activities in 2020, due to the restrictions imposed in the Member States and Host States to curtail the spread of COVID-19. With CERN operating in safe mode, measures were taken to mitigate the impact of this transition on contractors, such as supporting unemployment claims and aiming to fulfil contractual obligations pragmatically and in the spirit of partnership with contractors. In recognition of their work in response to the COVID-19 pandemic, the CERN Procurement and Industrial Services were awarded the 2020 Peter Kraljic Prize for Excellence in the "Master of Business Continuity" category by the European Institute of Purchasing Management (EIPM).

*Participation in EU projects strengthens CERN's links with universities, research institutes, laboratories, industry and decision-makers in its 23 Member States and beyond.*
*(CERN-PHOTO-201809-249-15)*

## INTERNATIONAL COLLABORATION FOR SCIENCE

CERN cultivates close collaborations with both academia and industry through its participation in projects co-funded by the European Commission (EC) under Horizon 2020. In 2020, CERN was involved in 41 Horizon 2020 projects and coordinated 11 (including AIDA-2020, ARIES and ATTRACT), with corresponding EC contribution for CERN of 28.6 million euros. In addition, all five CERN-coordinated projects submitted to the Research Infrastructures programme were approved for funding, all with a strong knowledge-transfer component associated with co-innovation and the transfer of technology from particle physics laboratories to industry. These range from future accelerators (I.FAST) and detectors (AIDAinnova) to radiation testing facilities (RADNEXT), medical isotopes (PRISMAP), and detection and imaging technologies (ATTRACT2), corresponding to 70 million euros of EC contribution. In total, 20 projects involving CERN were selected for funding in 2020.

CERN also concluded its one-year chairship of the European Intergovernmental Research Organisation Forum (EIROforum) in 2020, with highlights including the launch of a new working group on the environment and sustainability, the publication of a guide on innovation and technology transfer, and participation in events like the European Research and Innovation Days in September. EIROforum brings together eight of Europe's largest research organisations (CERN, EMBL, ESA, ESO, ESRF, European XFEL, EUROfusion and ILL).

## ATTRACT PHASE 2: A PROJECT COORDINATING THE FUNDING OF DISRUPTIVE INNOVATION

ATTRACT brings together Europe's fundamental research institutions and industrial communities to lead the next generation of detection and imaging technologies. During Phase 1, 170 breakthrough ideas received funding and their results were presented at the ATTRACT Conference, held virtually in 2020 but based in Brussels. Building on that success, ATTRACT Phase 2 will fund the most promising technology concepts for scientific, industrial and societal applications. Phase 2 will scale up support for young innovators, offering 400 of them (rather than the 100 of Phase 1) the opportunity to prototype their solutions based on the technology of ATTRACT-funded projects. It will also deliver a first-of-its-kind socio-economic study of an innovation ecosystem in the making and make a concerted effort to address public and private stakeholders in exploring potential models to streamline innovation funding.

ATTRACT

# INSPIRING AND EDUCATING

***Education and outreach are key to generating long-term support for CERN's mission, for particle physics and for scientific research. Each year, CERN's public engagement and education activities share the work of the Laboratory with young and old alike, across CERN's Member States, Associate Member States and beyond. These activities empower all generations to make sense of the science and technologies underpinning research at CERN, and inspire students to pursue careers in science and engineering.***

***In 2020, despite the cancellation of many on-site activities due to COVID-19, CERN continued to reach audiences across the globe. Some activities were recalibrated for online delivery; several new activities were developed. Many will continue in the future as a complement to the crucial on-site and in-person offer.***

*The Swiss winning team of the 2020 Beamline for Schools competition, in CERN's S'Cool LAB. The other 2020 winning team carried out their experiment at DESY, in Hamburg.* (OPEN-PHO-LIFE-2020-006-20)

## ENGAGING LOCALLY AND GLOBALLY

CERN is a much-favoured visitor destination, receiving an average of 150 000 visitors per year. Due to the COVID-19 pandemic, guided tours of CERN were cancelled as of March 2020, and CERN's permanent exhibitions were closed. As a result, only 27 000 visitors came to CERN for on-site tours. Only four public events were held in the Globe of Science and Innovation (compared to 27 in 2019).

However, engagement with visitors continued, with a concerted move to online formats. Virtual talks by CERN guides were set up for schools and the general public. From April to the end of the year, over 7000 participants enjoyed 315 presentations about CERN, in 10 different languages, with opportunities for questions and answers. The majority (75%) of participants were from schools.

Despite the constraints imposed by COVID-19, a total of 37 visits by decision-makers from CERN Member States, Associate Member States and other countries took place, either on-site or online.

The COVID-19 pandemic did not stop CERN's flagship travelling exhibition *Accelerating Science* from travelling to Turkey and continuing its run in Estonia, reaching an estimated 52 000 visitors in both countries.

For exhibitions – on-site and travelling – 2020 was a year for improving the existing materials.

Work progressed at several visit itineraries (the Antiproton Decelerator, ATLAS and LHCb), with exciting new exhibition content opening in 2021 at ATLAS and LHCb. CERN's travelling exhibition was updated. Significantly, a new online portal bringing together all the information about CERN's travelling exhibition offer was developed and launched.

Engaging with CERN's neighbours continues to be an important part of the Laboratory's outreach efforts. For the International Day of Women and Girls in Science, 2793 students from 135 classes in the local area had the opportunity to hear from 67 women about their jobs at CERN, EPFL and the University of Geneva.

The dialogue between arts and science continued, with several of the Arts at CERN programme commissions being shown in leading art museums worldwide, including the Centre Pompidou (Paris), Tate Modern and Serpentine Galleries (London), the New Museum (New York) and the Museum of Contemporary Art (Chicago).

*COVID-19 IMPACTED ON-SITE ACTIVITIES, BUT CERN CONTINUED TO REACH AUDIENCES ACROSS THE GLOBE.*


*Sparks!, the serendipity forum at CERN, was launched in November 2020 via an online event, beginning with the theme of the first edition – artificial intelligence – scheduled for September 2021 at CERN.*
*(OPEN-PHO-ACCEL-2020-003-10)*

## CURATING SERENDIPITY FOR KNOWLEDGE AND INNOVATION

Sparks! is a new annual two-day multidisciplinary science innovation forum and public event. It brings together scientists from diverse fields around the world, decision-makers, representatives of industry, philanthropists, ethicists and the public.

At the online launch event, CERN researchers, artificial intelligence (AI) pioneers and leading AI researchers (confirmed as speakers for Sparks! in 2021) discussed how prevalent the use of AI is in our daily lives, its use in research fields such as medicine, astronomy and climatology, and how society wants to use AI in the future.

The online launch was well received on social media, with metrics above the average for CERN posts. The video, published as a "premiere", received 7100 views, a peak of 265 simultaneous viewers and more than 760 hours of watching time. A tweet announcing the launch event had a reach of almost 250 000. More than 900 positive answers were collected on the professional platform LinkedIn, and the stories created for Instagram had a reach of close to 22 000.

## WORLDWIDE MEDIA INTEREST

Efforts continued in 2020 to sustain interest in and knowledge of CERN and the contribution of Member and Associate Member States to the Laboratory's achievements in the global media landscape.

As with many other on-site activities, media visits were affected by the COVID-19 pandemic. Only 76 visits took place, for 180 journalists (compared to 554 media visits for over 1100 journalists in 2019). Almost all the media visits took place in the first three months of the year.

Despite these constraints, media interest remained high in 2020, with over 270 requests from journalists and just over 129 000 press clippings throughout the year across the globe. Of the 23 press/media updates of 2020, 12 focused on physics results from the LHC and other CERN experiments.

A highlight of the year was the online Q&A with media that was held for the announcement of the update of the European Strategy for Particle Physics in June 2020 (see box to the right). This event was one of three such online Q&A sessions with journalists in 2020.

## COMMUNICATING THE UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

In close collaboration with the European Particle Physics Communication Network (EPPCN), several resources were developed to communicate about the 2020 update of the European Strategy for Particle Physics.
The scientific community was invited to view the online Open Council via webcast. A core press release was adapted by each Member State to their specific context. News stories were published on CERN and Member States' websites, and an online Q&A with selected journalists was held on 19 June with the President of the CERN Council, CERN's Director-General and the Scientific Secretary of the European Strategy Group. In addition, a Q&A talking points document was prepared for EPPCN members, Council delegates and Member States' stakeholders.

The Open Council on 19 June had over 3000 viewers. A total of 19 media outlets from 11 countries participated in the Q&A session. The decision to update the Strategy was reported in news outlets across the globe, with 409 clippings between 17 and 24 June, and an overwhelmingly positive/neutral sentiment (78%). For the same period, there were around 4000 mentions on social media.

## A GROWING DIGITAL PRESENCE

CERN's already strong digital presence grew in 2020, as many of the outreach and education activities moved online, supplemented by new initiatives on social media.

The CERN home website counted 9 million pageviews from 3.6 million visitors, and engagement with CERN's presence on social media increased by 107%.

Three live broadcasts covering key Long Shutdown 2 milestones were produced and broadcast simultaneously on several social-media platforms. The "lives" elicited almost 50 000 reactions (engagement) and reached up to 1100 simultaneous viewers.

The *CERN Courier* magazine's move to an online-first publishing model continued to produce impressive results. The magazine is estimated to have reached 100 000 readers in 2020, who enjoyed two special issues, 100 news stories, 20 conference reports, 18 opinion pieces and interviews, 6 career articles and 15 arts reviews.

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

Construction of the CERN Science Gateway started in December, with all the administrative processes for construction completed and the main contract adjudicated.

Development of the content for the Science Gateway's exhibitions, laboratories and public spaces is making significant progress. An international kick-off workshop, including participants from CERN's Member States, on content for the Science Gateway education labs generated over 300 ideas for activities tailored to different age groups. Detection, computing and magnets were identified as the first themes for development of modules for the labs. Three consortia were selected and approved to design, build and install all elements of the three exhibitions "Discover CERN", "Our Universe" and "Quantum World". The exhibitions will incorporate many of the 65 individual

*Rendering of the preliminary design by iArt/Finzi Pasca for part of the "Discover CERN" exhibition.*

hands-on exhibits that were developed with the involvement of 90 CERN scientists and engineers. Artist Julius von Bismarck was chosen to create the main artwork for the "Exploring the Unknown" commission following an international competition organised with the Arts at CERN programme. Front-end audience research and evaluation continued; the findings are feeding into the design and build of the exhibitions.

The building design was finalised with the architect team, including the specifications of the auditorium and reception.

Fundraising efforts continued: 77 MCHF out of a total requirement of 87 MCHF has been raised exclusively through external donations.

## EMPOWERING TEACHERS AND STUDENTS

Teachers are pivotal ambassadors for CERN; they take back inspiring ideas from their participation in CERN's teacher programmes to pass on to students and other teachers. Due to COVID-19, only three national teacher programmes, with 80 participants, were held in January and February 2020 (compared to 904 participants in 31 teacher programmes in 2019).

Each year, several thousand students have the opportunity to experience first-hand the cutting-edge research at CERN. Again due to COVID-19 restrictions, S'Cool LAB was closed as of March, and the remaining six high-school student internship programmes (Belgium, Denmark, Greece, Italy, Romania and Switzerland) were postponed to 2021.

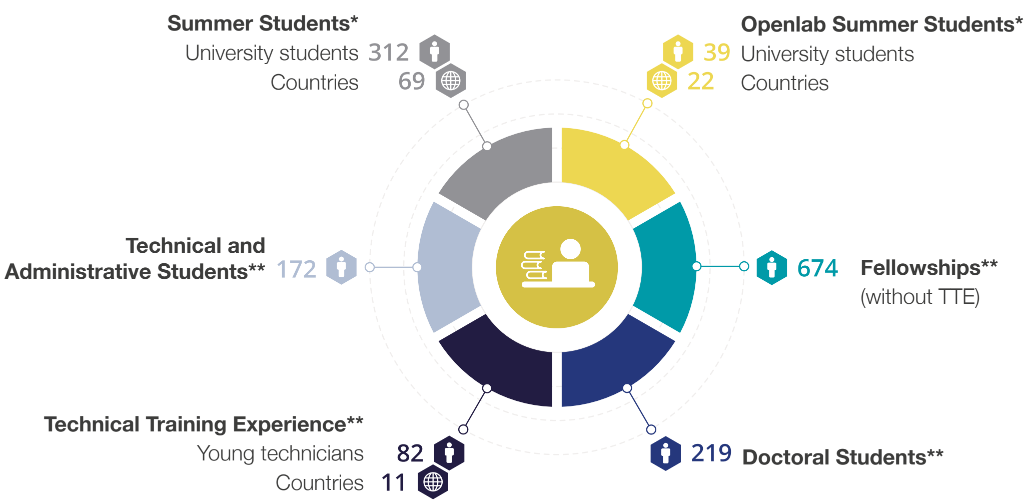
Nevertheless, S'Cool LAB activities and experiments were made available on social media over an 11-week period. The DIY experiments generated significant interest (10 000 likes and 280 000 views on Facebook and Twitter). An online particle physics course for 14 to 19 year olds was developed, aimed at introducing students to the central models of particle physics.

Despite the COVID-19 constraints, the Beamline for Schools competition went ahead successfully, with a record participation of more than 1300 students who competed in 198 teams from 47 countries (including 8 new countries). The two winning teams were from Switzerland and Germany. Due to the long shutdown at CERN, the experiments proposed by the winning teams were carried out at DESY, in Hamburg, Germany. COVID-19 prevented the Swiss team from travelling to DESY; they were instead welcomed at CERN and worked remotely with the German team at DESY on their experiment.

## TRAINING YOUNG RESEARCHERS

CERN offers students and postgraduates a rich working and learning environment, providing them with excellent technical skills and international experience, which make them highly qualified for business and industry in CERN's Member and Associate Member States. Despite the COVID-19 pandemic, in 2020 this key mission continued unabated, albeit remotely for many: some 750 fellows and over 390 doctoral, technical and administrative students, 144 trainees and some 160 short-term interns all joined the Organization to take advantage of these unique opportunities to work and learn. In addition, 351 summer students were selected from more than 90 countries, but given that the programme had to be adapted to an online format, only a subset were able to participate in the virtual projects on offer.

### 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 31.12.2020

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

# A SUSTAINABLE RESEARCH ENVIRONMENT

***CERN strives to ensure the well-being and safety of everyone using, visiting or living in the vicinity of its facilities, while minimising its impact on the environment.***

## ENVIRONMENTALLY RESPONSIBLE RESEARCH

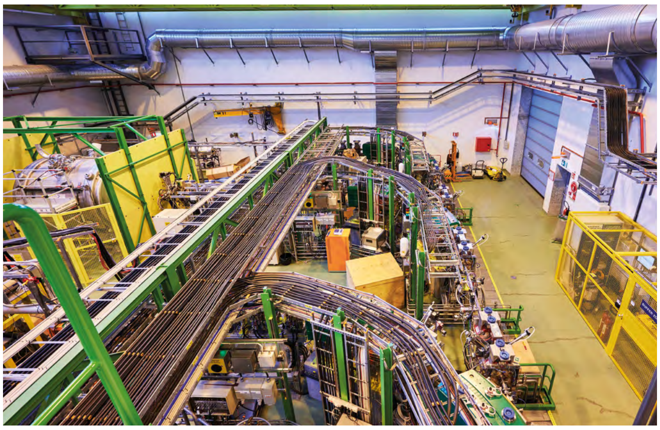
In 2020, CERN released its first public environment report, prepared according to the Global Reporting Initiative Standards for sustainability reporting. The report covers 2017 and 2018 and details the current status of CERN's environmental footprint, along with objectives for the coming years. One of the objectives is to reduce CERN's direct greenhouse gas emissions by 28% by the end of 2024, which CERN Management have endorsed and financed. A report covering 2019 and 2020 is set for publication later in 2021.

In 2020, the CERN Environmental Protection Steering board (CEPS) implemented and completed the Organization's Environmental Protection strategy for 2016-2020 and drew up the strategy for 2021-2025. During the year, CEPS also launched working groups on the use of fluorinated gases, waste management and biodiversity, as well as initiating a carbon emission assessment of mobility, duty travel, catering and procurement.

*In 2020, the Organization discovered a new variety of orchid species on its sites, the lady's tresses, making a total of 16. Most common on the sites are the pyramidal orchid, shown here.* (OPEN-PHO-LIFE-2018-006-3)

## INCREASED TRACEABILITY FOR CHEMICALS

In April 2020, the Organization launched a new tool for chemical safety – the CERN Chemical Register for Environment, Health and Safety (CERES). This web tool gives a global overview of all chemicals present on CERN's sites, complete with safety information and the precise location of and data on chemical and environmental risk assessments, including the mitigation measures in place. CERES allows for the complete traceability of chemicals at CERN. By providing better access to information and triggering preventive and protective measures, CERES enhances chemical safety at CERN.



*ISOLDE was the first pilot case of the Fire-Induced Radiological Integrated Assessment (FIRIA) project.* (CERN-PHOTO-201911-394-11)

## NEW FIRE SAFETY ASSESSMENTS

In 2019, CERN launched a three-year project – the Fire-Induced Radiological Integrated Assessment (FIRIA) – to assess fire-induced conventional and radiological risks to life, the environment and property, taking into account the complexity and specific characteristics of each CERN facility. In 2020, the risk assessment for ATLAS was carried out using the FIRIA methodolgy and a report regarding ISOLDE, the project's first pilot case, was finalised.

Over the course of this project, a number of collaborations have been set up, involving Lund University in Sweden, the National institute of Standards and Technology (NIST) in the United States and the Future Circular Collider fire safety study.

## REVITALISATION OF THE NANT D'AVRIL

In 2020, CERN co-signed a charter initiated by WWF Geneva for the revitalisation of the Nant d'Avril, the second largest affluent to the Rhône in the Geneva basin. The project aims to improve water quality and biodiversity all along the waterway.

The Nant d'Avril, like all the watercourses in the region, suffers from a summer drought. Thanks to water from the CERN cooling tower systems and the CAD-Vergers district heating system, the watercourse will remain well supplied.

In addition to improving water quality, the project will boost the biodiversity of the entire watershed, including by reopening some sections that are underground and building natural riverbanks. These actions will promote recolonisation by some target species, namely the brown trout, the fire salamander and the grass snake. Work will get under way in 2021 and the project will run until 2033.

*CERN CO-SIGNED A CHARTER IN 2020 TO HELP IMPROVE LOCAL WATER QUALITY AND BIODIVERSITY.*

## COVID-19

The year 2020 was dominated by the COVID-19 pandemic. CERN always strives to adopt the highest standards in matters of safety. Its overarching objective remains to safeguard the health and safety of everybody on the CERN sites while enabling the Laboratory to continue operating effectively.

Before entering safe mode in mid-March, the Organization established a COVID-19 helpline for its personnel. The helpline handles calls regarding any medical situation related to COVID-19, such as assessment of the caller's state of health, contact tracing and regular contact with people in quarantine. Since it was established, the helpline has received over 8000 calls, 3000 of which required action by CERN's Medical Service.

Since May, a vast set of measures has been in place to limit the risk of COVID-19 transmission. The fact that CERN straddles the French–Swiss border creates a need for a consistent set of measures for the whole Organization that is compatible with both Host States' regulations. CERN's measures have proven robust and foresighted and, due to the continous evolution of the situation in the Host States, the instructions were updated throughout the year.

The CERN Health, Safety and Environmental Protection unit undertook an extensive review of the existing literature on COVID-19, which culminated in the development of a simplified mathematical model to simulate the airborne spread of SARS-CoV-2 in indoor settings such as offices, meeting rooms and restaurants. The COVID Airborne Risk Assessment tool (CARA) is available through a web application and provides a quick and easy way to assess whether or not the current COVID-19 measures in a specific setting are sufficient to prevent airborne transmission.

# BUILDING TOMORROW AND BEYOND

***The year 2020 was decisive for the future of the Organization. The update of the European Strategy for Particle Physics set out the major long-term orientations, while work for the High-Luminosity LHC continued.***

*An artist's impression of the Future Circular Collider (FCC). (OPEN-PHO-ACCEL-2019-001-27)*

*THE STRATEGY UPDATE MAPS OUT CERN'S MAIN SCIENTIFIC ORIENTATIONS FOR THE FIRST HALF OF THE TWENTY-FIRST CENTURY.*

## UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Laying the groundwork for the future of particle physics research is part of CERN's mandate. In 2020, the Organization set out plans for its near- and long-term future aligned with the recommendations of the updated European Strategy for Particle Physics (ESPP).

Introduced in 2006 and updated in 2013 and 2020, the ESPP is the scientific deliberation process that lays the foundations for the future of particle physics in Europe. CERN is one of the primary drivers and beneficiaries of these future plans, in cooperation with other research institutes in CERN's Member States and beyond.

Following a participatory process with the broadest possible involvement of the particle physics community, the final document, prepared by the European Strategy Group, was made public in June 2020. The update foregrounds the full exploitation of the LHC and of its high-luminosity upgrade (HL-LHC) as the focal point of European particle physics in the coming years. It also underscores continued support of long baseline experiments in Japan and the United States, in collaboration with international partners, and that Europe should keep the door open to participating in other headline projects that will serve the field as a whole, such as the International Linear Collider.

The ESPP update identifies an "electron–positron Higgs factory" as the highest-priority collider after the LHC, which would allow the properties of the Higgs boson to be measured with extremely high precision. For the long term, the ESPP recommends that CERN conduct a technical and financial feasibility study of a future energy-frontier (100 TeV) hadron collider, with an electron–positron collider as a possible first step.

The update of the ESPP reaffirms the importance of ramping up R&D programmes for advanced accelerator, detector and computing technologies. These are necessary prerequisites to deliver the near- and long-term future research programmes envisaged in the ESPP.

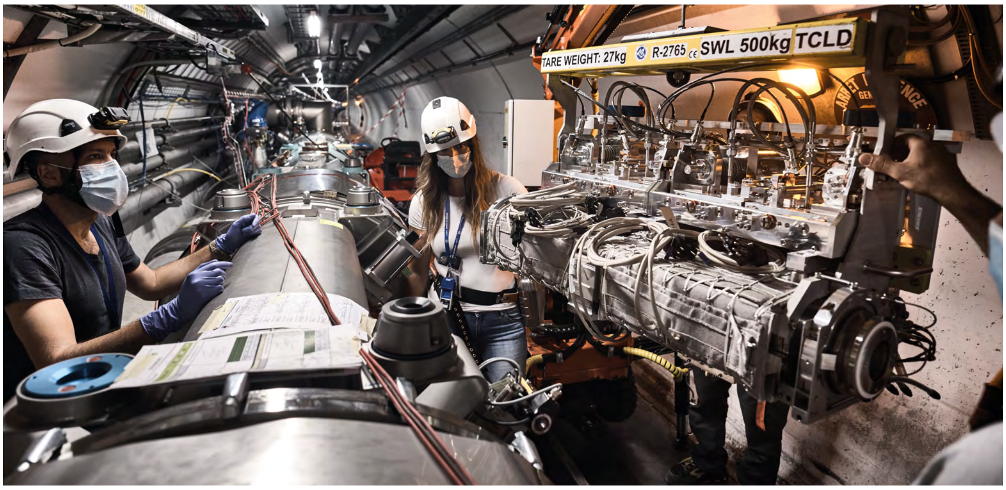
Studies, research and work continued in 2020 with a view to building the future envisioned in the ESPP: one in which Europe maintains a leading role in particle physics and in the innovative technologies developed within the field.

## THE HIGH-LUMINOSITY LHC

The High-Luminosity LHC (HL-LHC) project is on track to begin operation during Run 4, in mid-2027. This project will increase the integrated luminosity of the LHC so that the accelerator produces ten times more collisions in the ten years starting from 2027 than all the collisions produced up to 2024. In 2020, work continued to develop innovative equipment for high-luminosity operation, as well as to excavate the tunnels that will house that equipment. Project leader Lucio Rossi retired in 2020 after ten years in charge of the HL-LHC, handing the reins to Oliver Brüning in July.

The civil-engineering work for the HL-LHC made good headway, with the excavation of galleries near the LHC tunnel at Points 1 and 5 and their underground connections to the accelerator, which will house some of the new equipment. Despite a three-month delay due to the COVID-19 pandemic, the excavation work was completed, with the exception of the drilling work for the superconducting links and for the electrical connections for the radiofrequency cavities, which is planned for Long Shutdown 3. The first equipment was installed in the new caverns, while construction of the buildings continued on the surface.

*The construction of new underground structures that will house HL-LHC equipment near Point 1 of the LHC progressed significantly in 2020.* (CERN-PHOTO-202009-121-1)




*A TCLD collimator is installed at Point 7 of the LHC.*
*(CERN-PHOTO-202007-102-1)*

Major efforts are under way to protect the equipment from the increased radiation that will result from high luminosity. In 2020, one of the two new segmented injection protection absorbers known as the TDIS (target dump injection segmented) absorbers was installed at one of the two injection points between the SPS and the LHC; its twin will be installed at the other injection point in 2021. These absorbers, which will replace the old TDI (target dump injection) absorbers, will protect the LHC from radiation damage in the event of malfunctions at the time of injection. In parallel, the manufacturing process for the TANB (target absorber neutral B) absorber was validated: this small absorber will protect the superconducting magnets in the IR8 area around the LHCb experiment. The TCLD (target collimator long dispersion suppressor) collimators – part of the fleet of new collimators that will help with equipment protection – were installed on either side of Point 7 of the LHC to protect the ALICE experiment from the radiation of the future HL-LHC. The final low-impedance collimators were delivered to CERN in December. Lastly, a great deal of work went into automating the installation of modules containing equipment in areas that are subject to high levels of radiation.

The upgraded collider will be equipped with around a hundred new magnets of 11 different types. Work continued on developing superconducting magnets made from niobium–tin, a compound that will allow stronger magnetic fields to be achieved. New quadrupole magnets known as "triplets" will focus the beams more intensely before they cross at the heart of the ATLAS and CMS experiments. Quadrupoles measuring 4.2 metres in length are being produced in the United States, while longer versions measuring 7.2 metres are being made at CERN. The first full-sized CERN quadrupole, assembled in 2019, was tested, achieving an energy of 6.5 TeV. A coil failure put a halt to the tests, but the magnet concept was validated thanks to the short model, which exceeded the required field. The first two quadrupole magnets manufactured in the United States passed the cold tests. The production of two 11-tesla dipole magnets at CERN was completed, but performance degradation observed during the tests led to the decision to postpone their installation to the next long shutdown. Meanwhile, several innovative magnet models under development were shown to be effective, including small superferric quadrupoles developed at INFN (Italy) and KEK (Japan), a prototype corrector magnet with a nested coil architecture produced at CIEMAT (Spain) and tested at CERN, and a D2 corrector magnet now being industrially produced in China. Lastly, the remote alignment system developed in 2020 will make it possible to maintain the alignment of some of the quadrupole magnets.

Innovative transmission lines are required to deliver electricity to some of the HL-LHC equipment. Superconducting magnesium diboride wires are being developed to transport intensities of up to 100 000 amps. In 2020, a prototype set a new record for transporting electricity, carrying 54 000 amps over 60 metres (27 000 amps in each direction).

*A niobum–tin quadrupole magnet for the HL-LHC project achieved a peak magnetic field of 11.4 T during a test at Brookhaven National Laboratory, in the United States.*

Lastly, work on the crab cavities, which will tilt the beams to allow frontal collisions and thereby maximise the number of collisions, continued as planned, with the construction of two crab cavities completed. They will be installed in the SPS ready to be tested in 2023.

## THE LHC EXPERIMENTS MOVE TOWARDS HIGH LUMINOSITY

### ALICE

During Run 3, the ALICE detector will collect one hundred times more data than ever before. The collision rate will be six times higher (50 kHz) than during Run 2. This jump will be made possible by a complete upgrade of the detector and its data acquisition and processing systems. In 2020, several completed subdetectors were installed in the cavern.

The completely redesigned Time Projection Chamber (TPC), a giant tracker, was installed in August. Now equipped with Gas Electron Multiplier (GEM) systems and new readout electronics, the TPC will continuously record the tracks left by the particles flying through the heart of the detector. The Miniframe structure, measuring 12 metres in length and weighing 14 tonnes, was lowered into the cavern in November. It houses ALICE's support systems (power, cooling, gas and controls), as well as those of the inner tracker. The upgraded Fast Interaction Trigger (FIT) and the Muon Forward Tracker (MFT) were also reinstalled on the Miniframe. The MFT subdetector complements the current muon spectrometer by giving it higher resolution. The innovative new Inner Tracking System (ITS) was finalised and is due to be installed in early 2021.

Lastly, considerable progress was made on the integrated online/offline (O2) system, with the finalisation of the cabling in the counting room and the setting up of the computer centre, which will boast 250 servers.

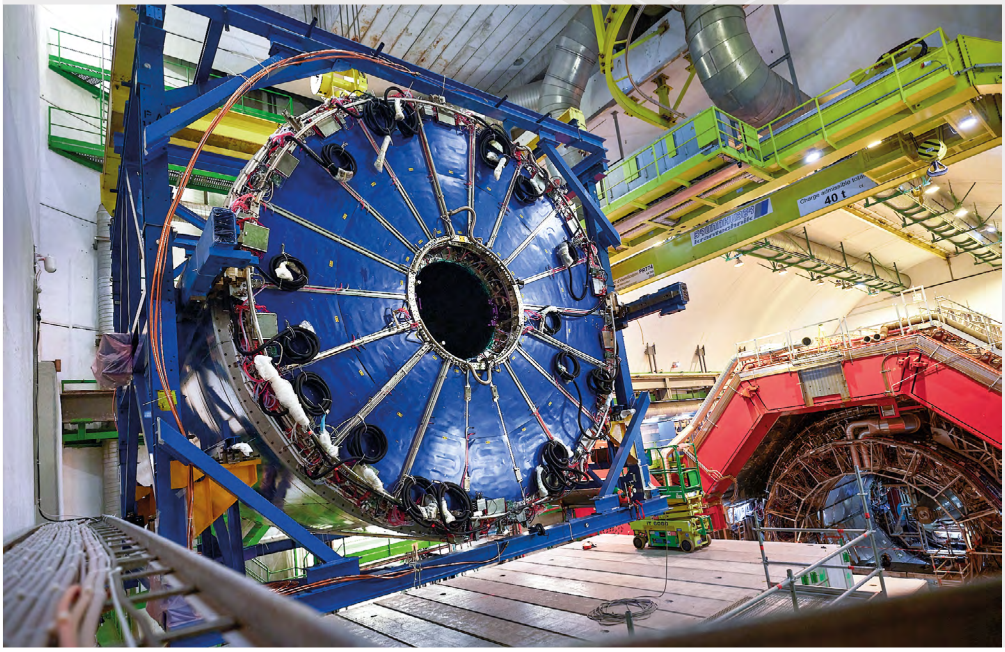
*With 54 000 amps transported over a length of 60 metres, this electrical transmission line for the HL-LHC is the most powerful ever built.* (CERN-PHOTO-202002-043-5)

### ATLAS

Upgrades to the readout electronics of the liquid-argon calorimeter progressed significantly with the replacement of the front-end boards. Upgrades to the calorimeter electronics are under way in order to increase the level of segmentation for the level-1 trigger system.

Maintenance and consolidation work on the tile calorimeter is entering its final phase: the regular maintenance of the front-end electronics is almost complete and the installation of the cold-insulation valves is beginning.

The new "small" muon wheels, which will improve muon identification, are still under development. They are each made up of 16 sectors with two types of chambers, i.e. small-strip thin gap chambers (sTGC) and MicroMegas. By the end of 2020, nine completed sectors had been mounted on the support disc of one of the small wheels.




*The ALICE detector (in the background) stands ready to receive the Time Projection Chamber (left).*
*(CERN-PHOTO-202008-104-78)*

The ATLAS Forward Proton (AFP) time-of-flight detector, installed 200 metres either side of the collision point in 2017 to study protons emitted at very small angles, was completely overhauled. New long-life photomultiplier tubes are being trialled. The detector's time resolution is better understood than ever.

Upgrade work is under way on the acquisition and readout systems, including the installation and commissioning of the Front-End LInk eXchange (FELIX), the system that acts as the interface between the detectors' front-end electronics, the trigger system, the acquisition system and the LHC clock, and whose purpose is to simplify the readout architecture. The readout systems, the online and offline monitoring servers and the file-storage servers and their operating systems are also undergoing upgrades. New trigger software is being developed and a new analysis model that will considerably reduce the size of the analysis formats is also being developed for Run 3.

The control room came back to life for a special "Milestone Week" to collect data from a cosmic-ray run that was captured by many of the subdetectors.

## CMS

The upgrade of the muon detection system was completed in December 2020, with the installation of the first layer of GEM detectors and upgrades to the front-end electronics and the cathode-strip chambers in the endcap. Maintenance and repairs were carried out on all the muon detectors, and the drift-tube chambers were tested using prototypes of the Phase II readout system.

The new inner layer of the pixel tracker was delivered ready for installation in 2021. The consolidation of the rotating shielding in order to adapt it to the new vacuum chamber that will be installed in early 2021 is going well.

The projects linked to the detector, such as the upgrade of the magnet safety system and the freewheel thyristor, as well as infrastructure projects such as the preparation of the $CO_2$ pump room, are all on schedule to receive the test beam in September 2021.

All the design and prototyping projects progressed well in 2020, particularly those related to integrated circuits; presentation of the final prototypes began in 2020 and will continue in 2021. Series production of some sensors and of the application-specific integrated circuits (ASIC) began. Lastly, the level-1 trigger project was approved.

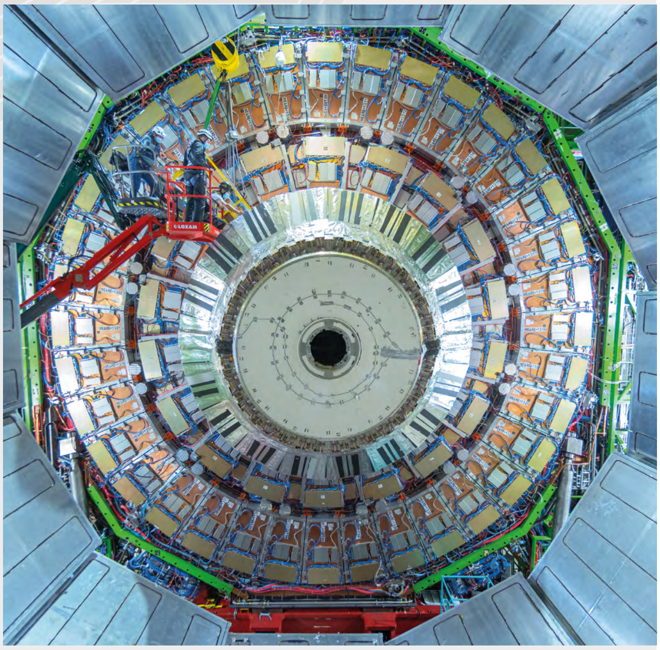
## LHCb

During Run 3, the LHCb detector will record collisions at ten times the previous rate. To achieve this objective and prepare the detector for high luminosity, subdetectors are currently being built.

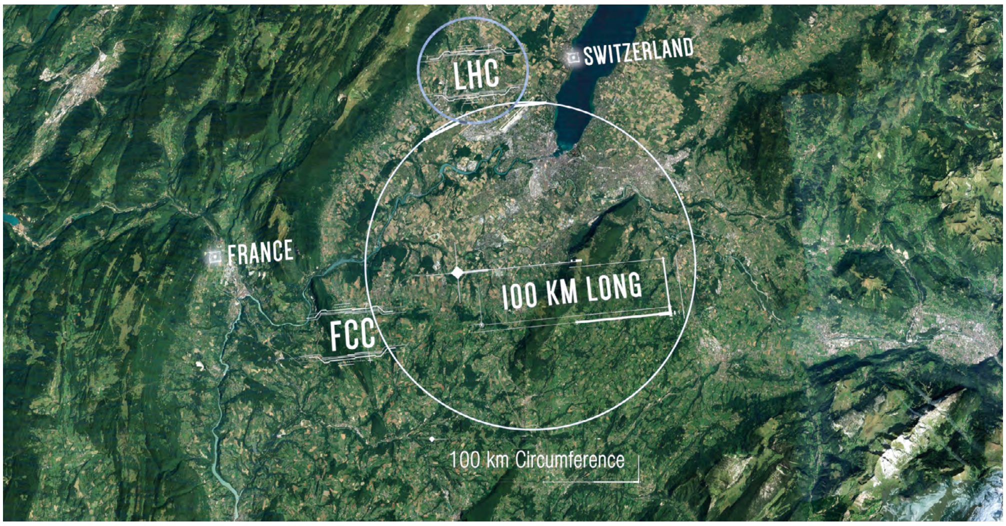
The construction of the VELO, SciFi, UT and RICH subdetectors is progressing apace, despite the slowdown caused by the COVID-19 pandemic. Significant progress was also made on the installation of the new electronics for the muon subdetector. Shielding elements were installed in the central part of the detector to reduce the radiation to the muon detectors.

An issue with the LHCb magnet's coil supports was corrected; a test demonstrated that the magnet was fully operational. The general infrastructure and the common electronics were largely completed.

The experiment's computing infrastructure is currently being used for Monte Carlo simulations and physics data analysis, while the fibre-optic infrastructure for the experiment's modernised readout system was installed in the new modular data centre.



*The final GEM (Gas Electron Multiplier) is installed in the CMS detector.* (CERN-PHOTO-202009-116-17)




*Proposed location of the FCC in the Franco-Geneva region.*
*(OPEN-PHO-ACCEL-2019-001-33)*

## THE FUTURE CIRCULAR COLLIDER

The update of the ESPP recommended that CERN carry out a technical and financial feasibility study of a 100 km Future Circular Collider (FCC), with an electron–positron Higgs and electroweak factory as a first stage, followed by a hadron collider at the highest possible energy (100 TeV). The electron–positron Higgs factory (FCC-ee) would allow the properties of this unique particle and its interactions with other particles to be studied in detail, and could put physicists on the road to physics beyond the Standard Model.

FCC-ee could be transformed into a hadron collider (FCC-hh) in the same tunnel, in much the same way as the LHC was constructed in the tunnel of the former Large Electron-Positron (LEP) collider. FCC-hh would be capable of reaching unprecedented energies, giving physicists access to energy regions where as yet unidentified particles might be found. Given the technological challenges of the project, the ESPP recommends that the European particle physics community intensify its research and development work into the innovative technologies that underpin the physics reach of high-energy colliders.

In 2020, as part of this feasibility study, the FCC team began to analyse the project's environmental impact by developing an evaluation procedure in collaboration with the Member States, as well as its socio-economic impact in collaboration with international partners. The EuroCirCol conceptual design study, funded by the European Union's Horizon 2020 (H2020) programme, was also completed during the year, with the submission of the final report and the approval of the FCC Innovation Study, which is the continuation of the EuroCirCol project and will support international R&D activities for the FCC.

Research and development on the key technologies, such as superconductivity and cryogenics, continued in 2020 with support from H2020 funding via the MSCA EASITrain initiative. Considerable efforts were invested, inter alia, in superconducting radiofrequency cavities and high-efficiency klystrons, which are being studied by international collaborations. Finally, research on the collider architecture with a view to optimising the location of the collider culminated in two alternative proposals involving rings of 96 km and 92 km, respectively.

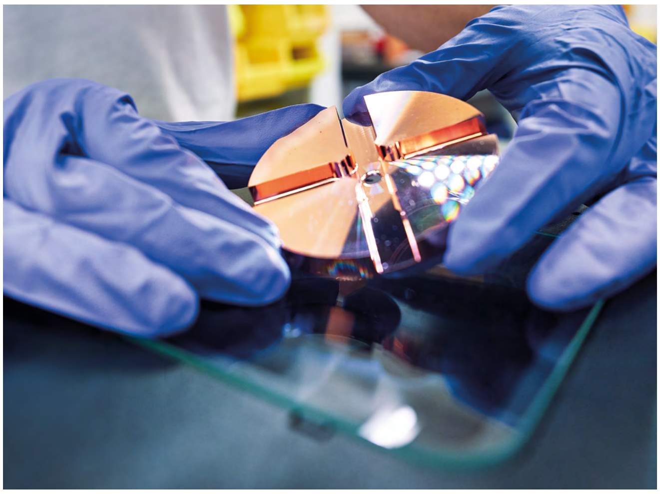
Also as part of the feasibility study, an investigation of the geology of the Geneva area was launched in 2020. A 3D geological model was developed in collaboration with the University of Geneva and other partners, while the physical geodesy was studied and a geodetic infrastructure developed with ETHZ, the Swiss Federal Office of Topography (Swisstopo) and the Territorial Engineering Institute of the Vaud School of Management and Engineering (HEIG-VD).

## LINEAR COLLIDERS

For several years, the Compact Linear Collider (CLIC) project has been developing technologies with a view to the construction and operation of a high-luminosity electron–positron linear collider to be realised in three stages, from 380 GeV to 3 TeV, based on an innovative two-beam acceleration concept. Research and development on key technologies for CLIC will continue in order to maintain CLIC as an option for a future collider at CERN. In addition, CLIC continues to be the source of many technological innovations for accelerator physics that are finding applications in related fields.

In 2020, the CLIC research programme continued, with the particular goal of reaching ever higher acceleration gradients over shorter and shorter distances. Significant progress was also made with respect to nano-beams, luminosity and energy efficiency, the optimisation of beam parameters and research on high-efficiency radiofrequency systems.

This research programme will feed into the preparatory studies for the possible International Linear Collider (ILC) in Japan. The ESPP gives the go ahead for potential CERN participation in the project if it happens.



*Close-up of one of the components of the CLIC compact linear collider prototype on which the FLASH technology is based.* *(CERN-PHOTO-202008-108-17)*

The innovations brought about by the CLIC research programme continued to find applications in the medical field. Breakthrough compact high-gradient acceleration technology is being developed in collaboration with the Lausanne University Hospital in Switzerland in the framework of FLASH, a highly efficient radiotherapy technique involving electron beams (see p. 37).

## THE CERN QUANTUM TECHNOLOGY INITIATIVE

The CERN Quantum Technology Initiative (QTI), announced by the CERN Management in June 2020, sees CERN join a rapidly growing global effort to bring about a "second quantum revolution". Though relatively new to the quantum technologies scene, CERN is in the unique position of having, in one place, the diverse set of skills and technologies – including software, computing and data science, theory, sensors, cryogenics, electronics and material science – necessary for such a multidisciplinary endeavour. CERN also has compelling use cases that create ideal conditions to compare classic and quantum approaches to certain applications, and a rich network of academic and industry relations working in unique collaborations such as CERN openlab.

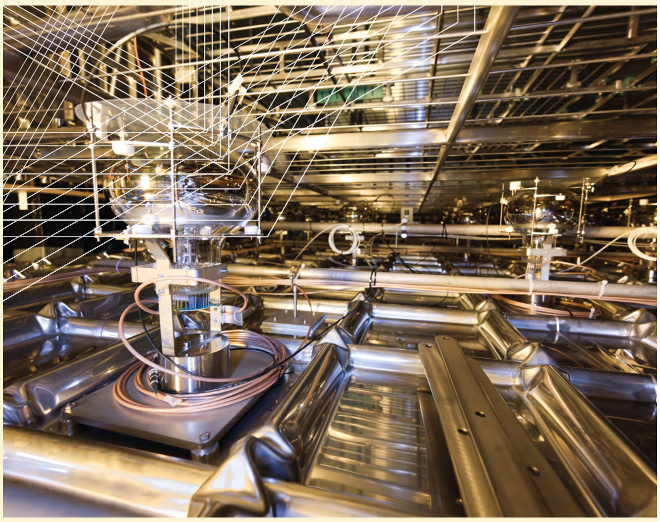
During the next three years, CERN QTI will assess quantum technologies' potential impact on CERN and on high-energy physics, looking at the HL-LHC timescale and beyond. To this end, after establishing governance and operational instruments, the initiative will work to define concrete R&D objectives in the following four areas: quantum computing, quantum sensing and metrology, quantum communication and quantum theory. It will also develop an international education and training programme in collaboration with leading experts, universities and industry, and identify mechanisms for knowledge sharing within the CERN Member States, the high-energy physics community, other scientific research communities and society at large.

## NEUTRINO RESEARCH

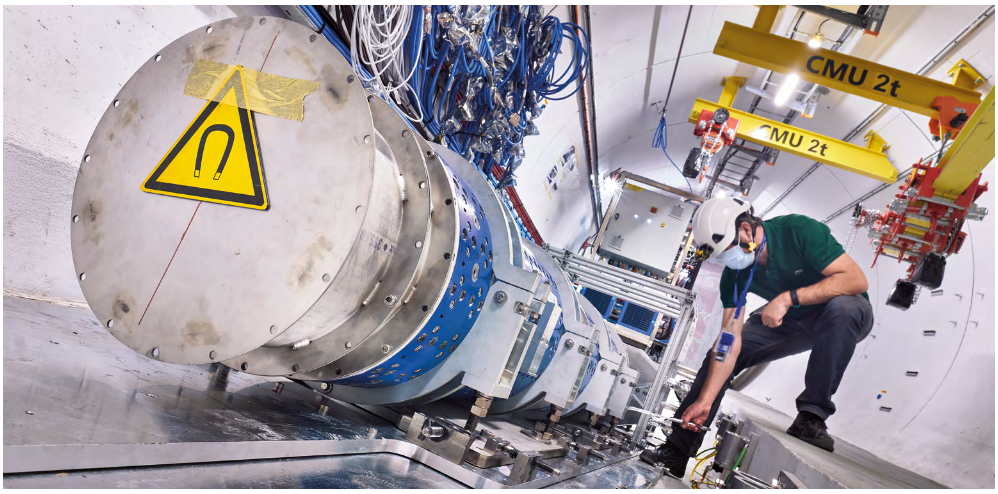
Neutrinos, particles with a very small mass that permeate the universe, could help physicists to elucidate some fundamental questions such as why there is an imbalance between matter and antimatter in the universe. For several years, the physics community has been studying neutrinos with a heightened interest that is reflected in the update of the ESPP, which also deals with research in this area. The ESPP recommends that CERN's neutrino research programme be consolidated through participation in projects based in the United States and Japan and that the Laboratory provide the infrastructure needed for testing and prototyping.

In this framework, CERN is involved in the development of ProtoDUNE, a prototype of the future DUNE (Deep Underground Neutrino Experiment) detector in the United States. In fact, two neutrino detector prototypes are under development: a single-phase detector filled with liquid argon, which will record the signals generated when a neutrino smashes into an argon atom, and a dual-phase version comprising a layer of gaseous argon to amplify the signals of the less energetic particles before they collide with the liquid.

In 2020, after 350 days of continuous operation had proved its robustness, the technology of the first detector was validated for use in the first DUNE cryostat. At the same time, the CERN neutrino group put forward a proposal for a new version of the detector based on the vertical-drift time projection chamber (TPC) concept and new readout units based on a new technology. After the success of two prototypes based on this version, the United States Department of Energy came down in favour of this solution for the experiment's second far detector.



*Inside the ProtoDUNE detector, which was successfully tested in 2020.* *(CERN-PHOTO-201906-156-2)*




*Installation of the magnet of the FASER experiment in the LHC tunnel.*
*(CERN-PHOTO-202011-156-8)*

## PHYSICS BEYOND COLLIDERS

CERN's scientific complex offers numerous research opportunities that do not involve the use of colliders. Launched in 2016, the Physics Beyond Colliders programme is studying these opportunities, bringing together theoretical physicists, experimental physicists and accelerator engineers to exploit the full potential of CERN's scientific infrastructures.

2020 saw good progress on the optimisation of the SPS beamline in the North Area for the high-energy KLEVER and NA62 experiments, which study kaon decays, and on the engineering work for the installation of AMBER, the experiment that will succeed COMPASS. The optical and baseline studies for the NA64++ experiment, which plan to study dark-sector physics, were completed in 2020, along with the definition of the beamline required for MuonE, an experiment that will study certain properties of the muon. The integration of a heavy-ion experiment (NA60++) in the EHN1 North Experimental Area was also studied.

Optimisation of the Beam Dump Facility (BDF) continued, with studies geared towards reducing beam losses. The BDF will mainly produce charmed hadrons for the experiments that specialise in the study of the hidden sector. A prototype of the BDF target, which was tested in 2018, was dismantled using a fully automated system in order to analyse the state of its components following irradiation by the beams.

A gas target was installed inside the LHCb detector to produce collisions between protons from the LHC and gas molecules, paving the way for studies on quantum chromodynamics and the structure of hadrons. The study of the use of crystals to bend proton beams continued in parallel.

High-intensity gamma rays could be produced through the laser excitation of partially ionised atoms accelerated in the LHC. A first experiment designed to prove the principle of the gamma factory project at the SPS was presented to the SPS Committee. Progress was made on the specification of the required components and the development of models and codes.

Considerable progress was made on the installation of the FASER experiment: the civil-engineering work and the preparatory work for the technical infrastructure were completed and the first part of the detector was installed. Located downstream of the ATLAS interaction point, FASER aims to identify long-lived exotic particles and dark matter particles. A technical proposal for the installation of the neutrino detector in the LHC is also being prepared.

With a view to submitting a proposal for the construction of a prototype all-electrostatic storage ring at COSY (Germany), studies continued with efforts to evaluate the research and development needed for precision measurement of the electric dipole moment of the proton.

The magnet for BabyIAXO, a helioscope that could house microwave cavities for axion searches, was designed at CERN.

## AWAKE

The AWAKE (Advanced Wakefield Experiment) project is preparing for a second run due to take place after the Long Shutdown. 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 those of today's accelerators. Measurements of plasma from a new source installed in 2020 and of electron beams were performed during the year, and the detailed design of a new electron source and beamline was finalised. The development of the electron source began in collaboration with the team from CLEAR, the CERN Linear Electron Accelerator for Research.

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Composition as of 31 December 2020

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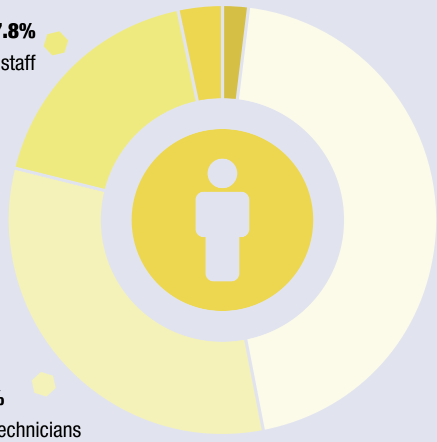
| Worldwide LHC Computing Grid (WLCG) | Ian Bird |

# CERN IN FIGURES

## CERN STAFF

### Total: 2635 people



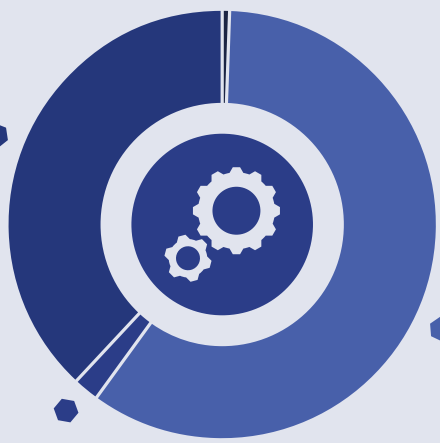

## EVOLUTION OF STAFF MEMBERS

| | |
|---|---|
| 2016 | 2560 |
| 2017 | 2633 |
| 2018 | 2667 |
| 2019 | 2660 |
| 2020 | 2635 |

In addition to staff members, CERN employed 756 fellows (including TTE technicians), trained 555 students and apprentices, and hosted 1132 associates in 2020. CERN's infrastructure and services are used by a large scientific community of 11 399 users (see p. 16).

## CERN EXPENSES

### Total expenses: 1157.4 MCHF




In 2020, 36.8% of CERN's budget was returned to industry through the procurement of supplies and services. CERN strives to ensure a balanced industrial return for its Member States (see p. 38).

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Sixty-sixth 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 2017–2018 is available at:
https://e-publishing.cern.ch/index.php/CERN_Environment_Report
The 2020 Knowledge Transfer annual report is available at:
http://kt.cern/annual-report
The 2020 CERN openlab annual report is available at:
https://openlab.cern/resources/annual-reports
The 2020 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-2020
A glossary of useful terms is available at: https://cern.ch/go/glossary

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Renzo Piano Building Workshop: p. 10 (top right)
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NASA: p. 25
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Brookhaven National Laboratory: p. 48 (bottom)
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