Annual Report
2022

CERN

CONTENTS

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

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

MESSAGE FROM THE PRESIDENT OF THE COUNCIL

CERN has a proven track record of formulating, planning and implementing long-term scientific visions. In my first year as President of the Council, this was severely challenged on two fronts. We were faced with the continuing COVID-19 pandemic and the emergence of war in Europe, both of which had significant financial implications for the Organization. Against this backdrop, we also strove for a consensual scientific vision for CERN's future.

At the beginning of my mandate, CERN's COVID-19 level was red: the most restrictive. At the end of the year, it was green. Thanks to remarkable scientific research in the life sciences, the world was emerging from the worst of the pandemic, and CERN had come back to life.

The Council warmly congratulated the CERN Management and personnel on their handling of the pandemic and the smooth return to the workplace when it was safe to do so. I acknowledge with gratitude the fantastic amount of work carried out through the pandemic, leading to the restart of the accelerator complex in 2022. We all look forward to Run 3 physics resuming in 2023, as well as progress towards the High-Luminosity LHC.

COVID-19 was not the only challenge the world faced in 2022. On 24 February, the Russian Federation, a CERN Observer, invaded Ukraine, an Associate Member State. At an extraordinary meeting of the Council on 8 March, CERN's 23 Member States declared that they "condemn, in the strongest terms, the military invasion of Ukraine by the Russian Federation, and deplore the resulting loss of life and humanitarian impact, as well as the involvement of Belarus in this unlawful use of force against Ukraine." The Council decided that: "CERN will promote initiatives to support Ukrainian collaborators and Ukrainian scientific activity in the field of high energy physics; the Observer status of the Russian Federation is suspended until further notice; and CERN will not engage in new collaborations with the Russian Federation and its institutions until further notice." At its June meeting, the Council declared that it intends to terminate CERN's International Cooperation Agreements with the Russian Federation and the Republic of Belarus at their expiration dates in 2024.

The invasion heralded high energy costs and rising inflation, which introduced uncertainly into budget planning. The Council appreciated efforts made by the Management and staff to mitigate these challenges and will work in 2023 to do its part. This situation is likely to be with us for several years.

Despite this bleak context, there was cause for celebration as we marked the 10th anniversary of the discovery of the Higgs boson, conclusive evidence for the Brout-Englert-Higgs mechanism. The Council also continued to attend to its core business, ensuring that CERN provides the best possible programme in experimental high energy physics. In 2020, following the updated European Strategy for Particle Physics, CERN launched a feasibility study for a Future Circular Collider, recognising that such a machine presents significant technological, geological, environmental and economic challenges. The Council appreciates CERN's leadership in studying a range of technologies for the long term. It is rewarding to note the progress made at CERN on muon-collider and proton-driven plasma wakefield techniques, to cite two examples.

Finally, it was a pleasure to welcome two new Vice-Presidents of the Council in 2022, Kostas Fountas and Eric Laenen. I would like to thank the outgoing Vice President, Jochen Schieck, the outgoing Chair of the Audit Committee and the Finance Committees, Umberto Dosselli, and the outgoing Chair of the Scientific Policy Committee, Leonid Rivkin, for their outstanding commitment and dedication. I am certain that the Council will benefit in 2023 from the experience gained in 2022 while facing highly challenging issues and reaching consensus in the best interests of the Organization.

Eliezer Rabinovici

E. Rabinovici

MESSAGE FROM THE DIRECTOR-GENERAL

2022 was another great year for CERN's scientific programme and other activities of the Organization, despite major global challenges.

On 24 February 2022, the world was shocked by the news that the Russian Federation had invaded Ukraine. The CERN community was quick to act, sending 820 000 Swiss francs, half raised by the personnel and half from the CERN budget, to help the Red Cross's humanitarian work in Ukraine. Among other supporting actions, we implemented a "Science for Ukraine" initiative, offering early-career positions for Ukrainians impacted by the war. Many individuals from the CERN community offered support and help to Ukrainian refugees.

The economic crisis following the COVID-19 pandemic, exacerbated by the war in Ukraine, made 2022 a challenging year. As a mark of social responsibility, and to make savings, several measures were put in place to reduce the Laboratory's electricity consumption. These included an early start to the year-end technical stop in 2022, and a 20% reduction of accelerator operation in 2023. Various additional measures were implemented to save energy across the CERN sites.

On a more positive note, 2022 also saw the world emerge from the pandemic, and the Laboratory returned quickly to its former vibrant self. This was particularly true when summer arrived. Over two wonderful days in July, we celebrated the 10th anniversary of the discovery of the Higgs boson and the start of the LHC's Run 3. The anniversary was marked by publications from the ATLAS and CMS experiments in a special issue of the journal *Nature*, summarising the great progress made in ten years of Higgs boson research at CERN. This was not the only scientific highlight of the year, as many beautiful physics results were produced in all areas of CERN's scientific programme.

Run 3 comes after three years of intense work on the accelerator complex and the experiments during long shutdown 2 (LS2), which was carried out with amazing efficiency against the backdrop of COVID-19. It is strong testimony to all involved that Run 3 got off to a great start, with the LHC operating at the unprecedented energy of 13.6 TeV and providing an impressive intensity ramp-up. The experiments were quick to make excellent use of the new data, and the Worldwide LHC Computing Grid took it all in its stride, operating with excellent availability and reliability. The CERN research programme is much more than the LHC, and it was rewarding to note the successful restart of experiments and facilities across the whole accelerator chain: ISOLDE, n_TOF, the East Area, the AD and ELENA, the Neutrino Platform and the fixed-target programme in the North Area. Preparation for the High-Luminosity LHC (HL-LHC) also made significant progress in 2022, with the completion of the civil-engineering work and crucial advancement in the understanding of the new-generation niobium–tin (Nb_3Sn) superconducting magnets that will provide the final beam focus.

Among other 2022 highlights was the progress of the Future Circular Collider (FCC) Feasibility Study. Such a facility would have unrivalled research potential to succeed the LHC and take particle physics to the end of the century. It is, however, extremely challenging on many fronts. The Feasibility Study aims to demonstrate whether the FCC can be built affordably and with full respect for the environment.

CERN demonstrated its credentials in this respect by applying for the ISO 50001 energy-management certification. A huge amount of work was undertaken to establish the requisite structures and documentation. These culminated in reviews and audits at the end of the year.

In September, CERN approved a comprehensive Open Science Policy that aims to make all CERN research accessible, inclusive and transparent, both for other researchers and for wider society.

None of these achievements would have been possible without the commitment of the Laboratory's personnel, and the unwavering support of our Member and Associate Member States and beyond. I thank them all for enabling the activities you will discover in this report.

Fabiola Gianotti

Fabiola Gianotti

2022 IN PICTURES

From the tenth anniversary of the Higgs boson's discovery to the start of the LHC's third physics run at world-record collision energy, it has been a significant year of achievements for CERN. Milestones have been reached by CERN's accelerators and experiments and thanks to knowledge transfer and other aspects of daily life at the Organization. Enjoy a visual journey through some key moments of 2022.

5 JANUARY

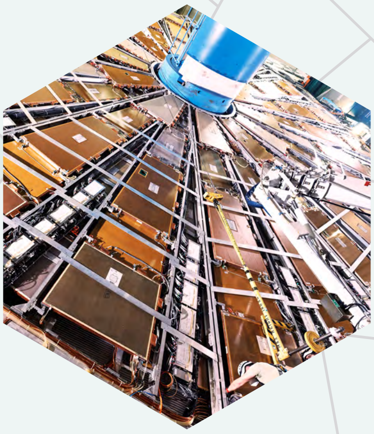
The BASE experiment makes the most precise comparison yet between protons and antiprotons, establishing that their electric charge-to-mass ratios are identical to within an uncertainty of 16 parts per trillion.

CERN-PHOTO-202203-053-17)

12 JANUARY

Arts at CERN awards the Collide artistic residency – split between CERN in Geneva and the city of Barcelona – to Dorota Gawęda and Eglė Kulbokaitė.

(OPEN-PHO-LIFE-2022-005-2)



24 JANUARY

Using the full Run 2 data, the ATLAS experiment delivers the most precise measurement of luminosity at the LHC. Precise knowledge of luminosity is essential for all data analysis at the experiment.

(CERN-PHOTO-202201-006-18)

3 MARCH

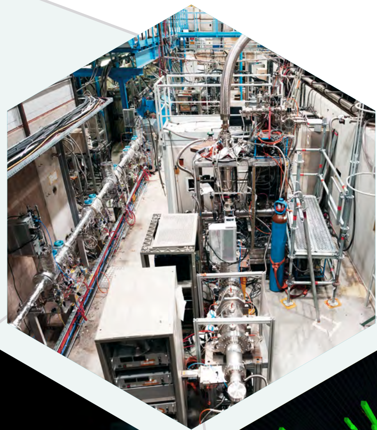
Brazil signs an agreement to become an Associate Member State of CERN, the first country in Latin America to do so.

(CERN-PHOTO-202203-036-6)

8 MARCH

CERN launches CIPEA, its Innovation Programme on Environmental Applications. The programme encourages experts at CERN to harness their technologies and know-how for a more sustainable future.

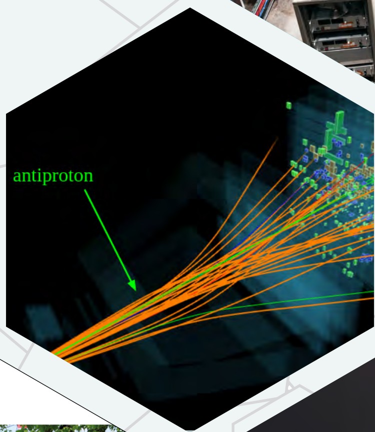
(KTTGROUP-PHO-MISC-2022-002-23)



16 MARCH

ASACUSA sees surprising behaviour of hybrid matter–antimatter atoms in superfluid helium, paving the way for the use of matter–antimatter hybrids beyond particle physics.

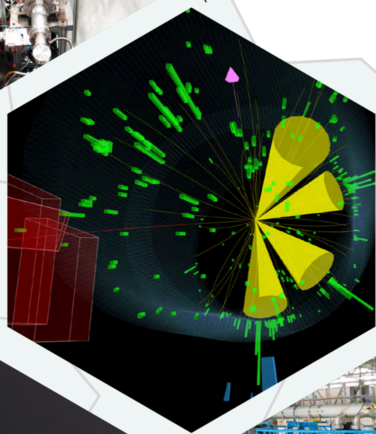
(CERN-PHOTO-202202-025-5)



7 APRIL

The LHCb collaboration presents an analysis of particle collisions at the LHC that may help determine whether antimatter seen in space originates from dark matter.

(LHCb-PHO-EXP-2022-001-1)



19 APRIL

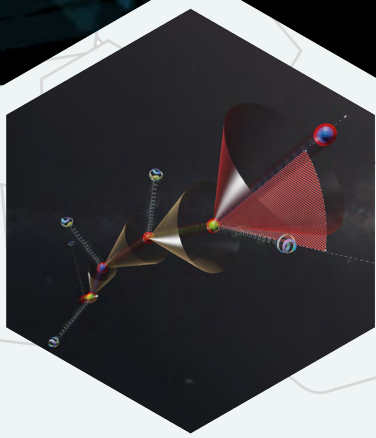
The CMS experiment performs the most accurate measurement to date of the mass of the top quark.

(CMS-PHO-EVENTS-2022-009-1)

22 APRIL

Construction of CERN’s new data centre in Prévessin begins. This new, energy-efficient facility will be completed by the end of 2023.

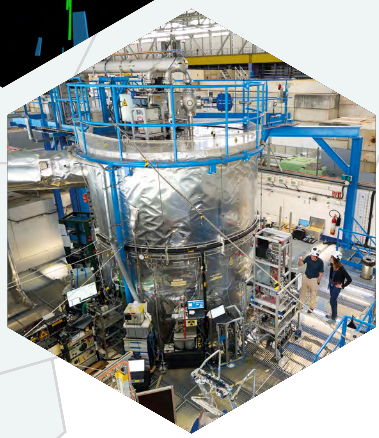
(CERN-PHOTO-202204-070-22)



18 MAY

The ALICE collaboration makes the first direct observation of the dead-cone effect, a fundamental feature of the strong force that binds the nucleus of atoms.

(CERN-GRAPHICS-2022-015-7)



18 MAY

The CLOUD experiment discovers a new way in which aerosols rapidly form and grow at high altitude. The discovery will improve the reliability of global climate models.

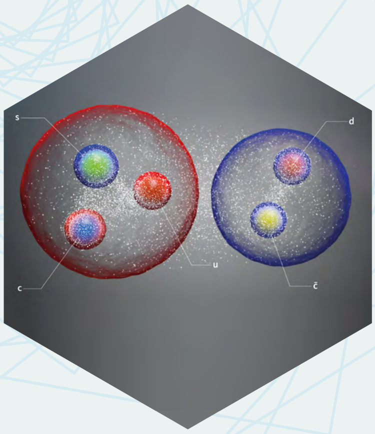
(CERN-PHOTO-202204-064-2)

29 JUNE

Three teams of high-school students from Egypt, France and Spain win the CERN Beamline for Schools competition. The third winning team, from France, was at DESY.

4 JULY

The ATLAS and CMS experiments release results of the most comprehensive studies of the properties of the Higgs boson, 10 years since they discovered it.
(CERN-PHOTO-202201-006-6
CERN-PHOTO-202108-102-7)



4 JULY

CERN celebrates the tenth anniversary of the discovery of the Higgs boson.
(CERN-PHOTO-202207-120-68)

5 JULY

The LHCb collaboration discovers three new exotic particles: a new kind of pentaquark and the first-ever pair of tetraquarks.
(CERN-GRAPHICS-2022-027-6)

5 JULY

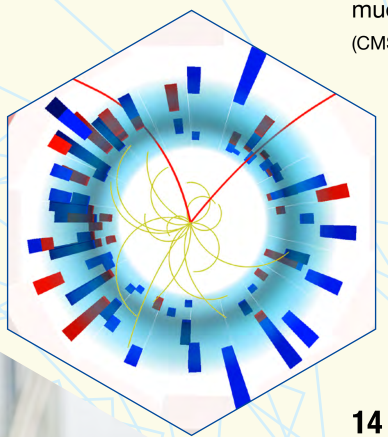
After a successful restart, the LHC begins its third run for physics (#Run3), recording high-energy proton collisions at the unprecedented energy of 13.6 TeV.

(CERN-PHOTO-202207-121-124)

11 JULY

Using Run 2 data, the CMS collaboration precisely measures the rare decay of the B-meson to a muon–antimuon pair.

(CMS-PHO-EVENTS-2022-031-1)



14 JULY

The first CERN-driven satellite, CELESTA, is successfully launched by the European Space Agency to monitor radiation in space.

(CERN-PHOTO-202101-002-3)

18 SEPTEMBER

After 30 years of telling CERN's story, the Microcosm closes its doors for the last time in preparation for CERN Science Gateway, a new education and outreach facility.

(CERN-PHOTO-201603-050-1)

20 SEPTEMBER

CERN and Solvay, a Belgian science company, launch their three-year education programme, with the aim of fostering interest in STEM across the world.

(OPEN-PHO-MISC-2022-008-22)

26 SEPTEMBER

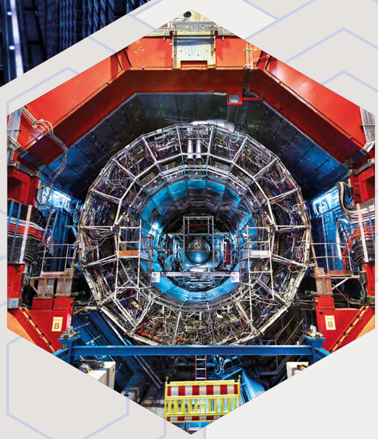
LHCf completes its first data-taking period of LHC Run 3, coinciding with the machine's record fill time of 57 hours.
(CERN-PHOTO-202209-161-2)

3 OCTOBER

CERN approves its new Open Science Policy, combining several existing open science initiatives to make all CERN research fully accessible, inclusive, democratic and transparent, for other researchers and the wider society.
(OPEN-PHO-LIFE-2021-017-13)

1–4 NOVEMBER

The first Quantum Technologies for High Energy Physics (QT4HEP) event is held at CERN, an international conference where experts discuss how quantum technologies can benefit particle physics and other research fields.
(CERN-PHOTO-202211-178-85)



9 NOVEMBER

The ALICE collaboration takes stock of its first 10 years of studying quantum chromodynamics – one of the pillars of the Standard Model that describes how quarks and gluons interact.
(CERN-PHOTO-202008-104-64)

17–18 NOVEMBER

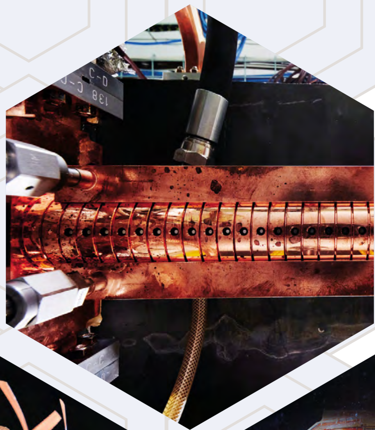
The second edition of the Sparks! forum takes place at CERN, bringing together experts to discuss how future technology can be used for health.
(OPEN-PHO-MISC-2022-018-443)

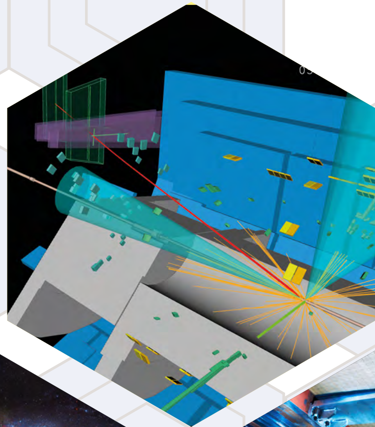
25 NOVEMBER

CERN partners with CHUV and THERYQ to develop a revolutionary device for cancer therapy based on linear collider technology.
(CERN-PHOTO-202008-108-2)

30 NOVEMBER

The ATLAS collaboration measures the interaction strength of two processes: top-quark pair production and Z-boson production. This provides valuable insight into the strong and electroweak interactions.
(ATLAS-PHOTO-2022-061-1)





1 DECEMBER

CERN and Airbus sign a collaboration agreement to assess the use of superconducting technologies for future low-emission aeroplanes.
(CERN-PHOTO-202211-195-7)

12 DECEMBER

The ALICE collaboration uses data from the LHC to estimate how transparent the Milky Way is to antimatter.
(ALICE-PHO-GEN-2022-011-3)

20 DECEMBER

The LHCb collaboration presents high-precision measurements of rare B-meson decays that agree with the Standard Model, superseding previous results that had indicated departures from the theory.
(CERN-PHOTO-202204-063-1)

A LABORATORY FOR THE WORLD

The Laboratory has emerged invigorated from 2022 – a year that was marked by an upsurge in the number of scientists coming to CERN and in ideas and innovation, fostered by a favourable health situation and the launch of the third run of the LHC. The efforts of the 17 000-member-strong CERN community were once again focused on the present, as many major projects were implemented during the year, as well as looking to the future, as the Laboratory continued to develop its plans for the coming decades. On closer inspection, this vast community is made up of 2700 staff members carrying out CERN's mission and 12 000 users affiliated with institutes in 82 countries. Many of these users have been able to take advantage of the LHC's restart to pursue the research conducted by the scientific collaborations based at CERN.

(CERN-PHOTO-202304-106-55)

BREAKDOWN OF CERN USERS ACCORDING TO THE COUNTRY OF THEIR HOME INSTITUTE, AS OF 31 DECEMBER 2022

NUMBER OF USERS: 11 860

MEMBER STATES (7147)

Austria 85 – **Belgium** 129 – **Bulgaria** 43 – **Czech Republic** 244 – **Denmark** 49 – **Finland** 90 – **France** 844 – **Germany** 1225 – **Greece** 119 **Hungary** 73 – **Israel** 64 – **Italy** 1527 – **Netherlands** 169 – **Norway** 79 – **Poland** 305 – **Portugal** 100 – **Romania** 109 – **Serbia** 33 – **Slovakia** 70 **Spain** 383 – **Sweden** 103 – **Switzerland** 406 – **United Kingdom** 898

ASSOCIATE MEMBER STATES IN THE PRE-STAGE TO MEMBERSHIP (69)

Cyprus 15 – **Estonia** 30 – **Slovenia** 24

ASSOCIATE MEMBER STATES (382)

Croatia 38 – **India** 132 – **Latvia** 16 – **Lithuania** 14 – **Pakistan** 35 – **Türkiye** 122 – **Ukraine** 25

OBSERVERS (2991)

Japan 216 – **Russian Federation** 873 (the Observer status of the Russian Federation has been suspended in accordance with the Resolution adopted by the CERN Council on 8 March 2022) – **United States of America** 1902

OTHER COUNTRIES (1271)

Algeria 2 – **Argentina** 13 – **Armenia** 8 – **Australia** 21 – **Azerbaijan** 2 – **Bahrain** 4 – **Belarus** 18 – **Brazil** 122 – **Canada** 199 – **Chile** 34 **Colombia** 21 – **Costa Rica** 2 – **Cuba** 3 – **Ecuador** 4 – **Egypt** 20 – **Georgia** 32 – **Hong Kong** 15 – **Iceland** 3 – **Indonesia** 5 – **Iran** 11 – **Ireland** 5 **Jordan** 5 – **Kuwait** 4 – **Lebanon** 13 – **Madagascar** 1 – **Malaysia** 4 – **Malta** 1 – **Mexico** 49 – **Montenegro** 4 – **Morocco** 19 – **New Zealand** 5 **Nigeria** 1 – **Oman** 1 – **Palestine** 1 – **People's Republic of China** 333 – **Peru** 2 – **Philippines** 1 – **Republic of Korea** 147 – **Singapore** 2 **South Africa** 52 – **Sri Lanka** 10 – **Taiwan** 45 – **Thailand** 17 – **Tunisia** 2 – **United Arab Emirates** 7 – **Vietnam** 1

As a key player in European and international scientific diplomacy, CERN was impacted by the difficult international context in 2022. Nevertheless, thanks to its spirit of openness and the support of its Member and Associate Member States, the Laboratory succeeded in forging new partnerships, both in Europe and beyond. CERN signed an agreement with Brazil in March 2022, which, once the accession process has been completed and the agreement comes into effect, will grant this major South American country the status of Associate Member State. The terrible war in Ukraine dominated everyone's minds during the year, at CERN and elsewhere. The Organization strongly condemned the military invasion of Ukraine by the Russian Federation and its ally Belarus. The CERN Council, over the course of several sessions held between March and June 2022, adopted a series of measures in response to this aggression, which goes against the values upheld by the Laboratory. The measures included suspending the Observer status of the Russian Federation and the Joint Institute for Nuclear Research (JINR) and declaring the intention to terminate the international cooperation agreements with the Russian Federation and Belarus when they expire in 2024. The Council also decided to review CERN's future cooperation with JINR well before January 2025, when their current international cooperation agreement is due to expire. At the same time, the Laboratory reaffirmed its support for the people of Ukraine by raising funds and offering training and employment opportunities to Ukrainian nationals.

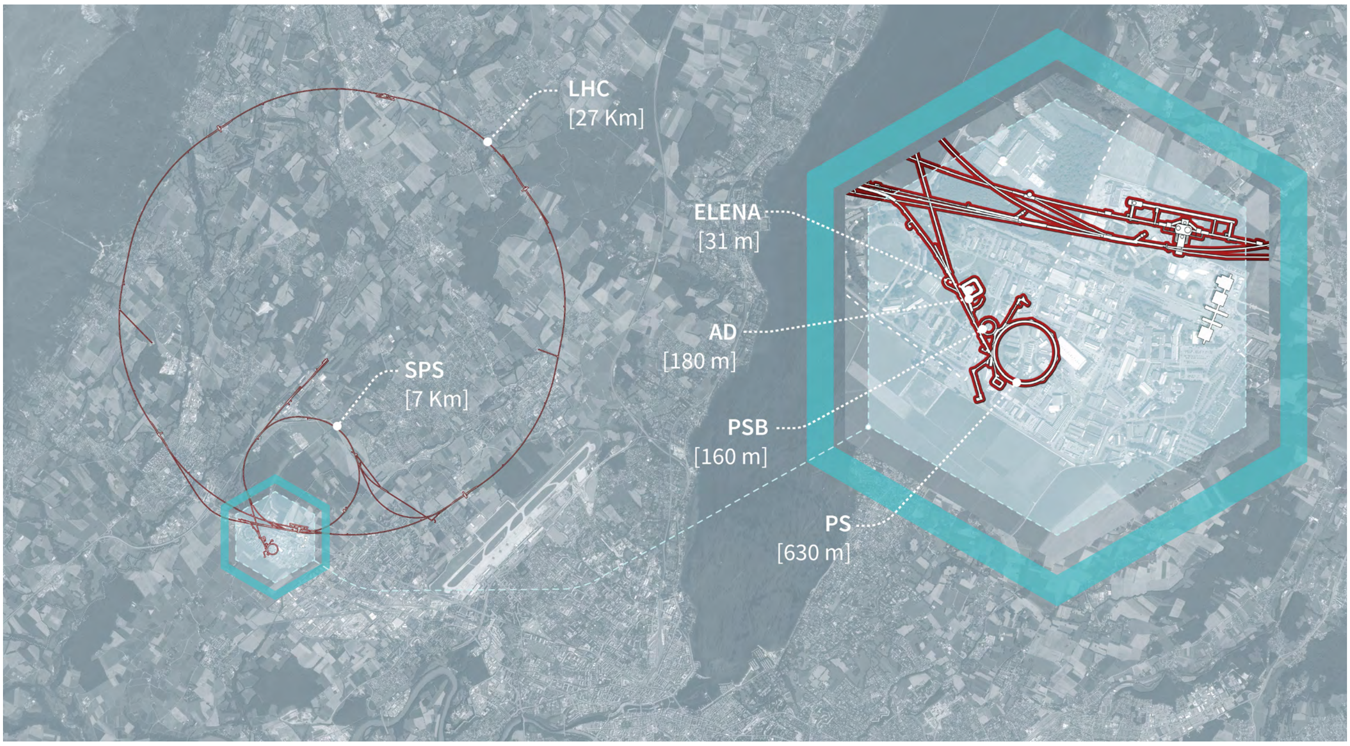
The thousands of CERN alumni scattered around the world are some of the Organization's best ambassadors. This community outside CERN's walls is brought together by the CERN Alumni programme, which celebrated its fifth anniversary on 8 June 2022. This network has gone from strength to strength over the last five years: it had 8500 members in December 2022, some of whom have organised themselves into regional groups spread across three different continents. In 2022, new groups sprung up in Belgium, the San Francisco Bay Area and the United Arab Emirates. This extended family came together in 2021 for the online *CERN Alumni Second Collisions* event, for which the Office of Alumni Relations received a Circle of Excellence gold medal in 2022 from the Council for the Advancement and Support of Education (CASE). The jury highlighted the originality of the event, which gave participants the opportunity to explore a virtually recreated CERN site. In parallel, the Office of Alumni Relations continued to organise on-site events to facilitate the career transition of future CERN alumni. 2022 saw the organisation of, in particular, 14 "Virtual Company Showrooms" to put soon-to-be alumni in contact with potential future employers, two "Moving out of Academia" events addressing the career transition challenges for researchers, and a first "Soon-to-be alumni" networking event for current and future alumni.

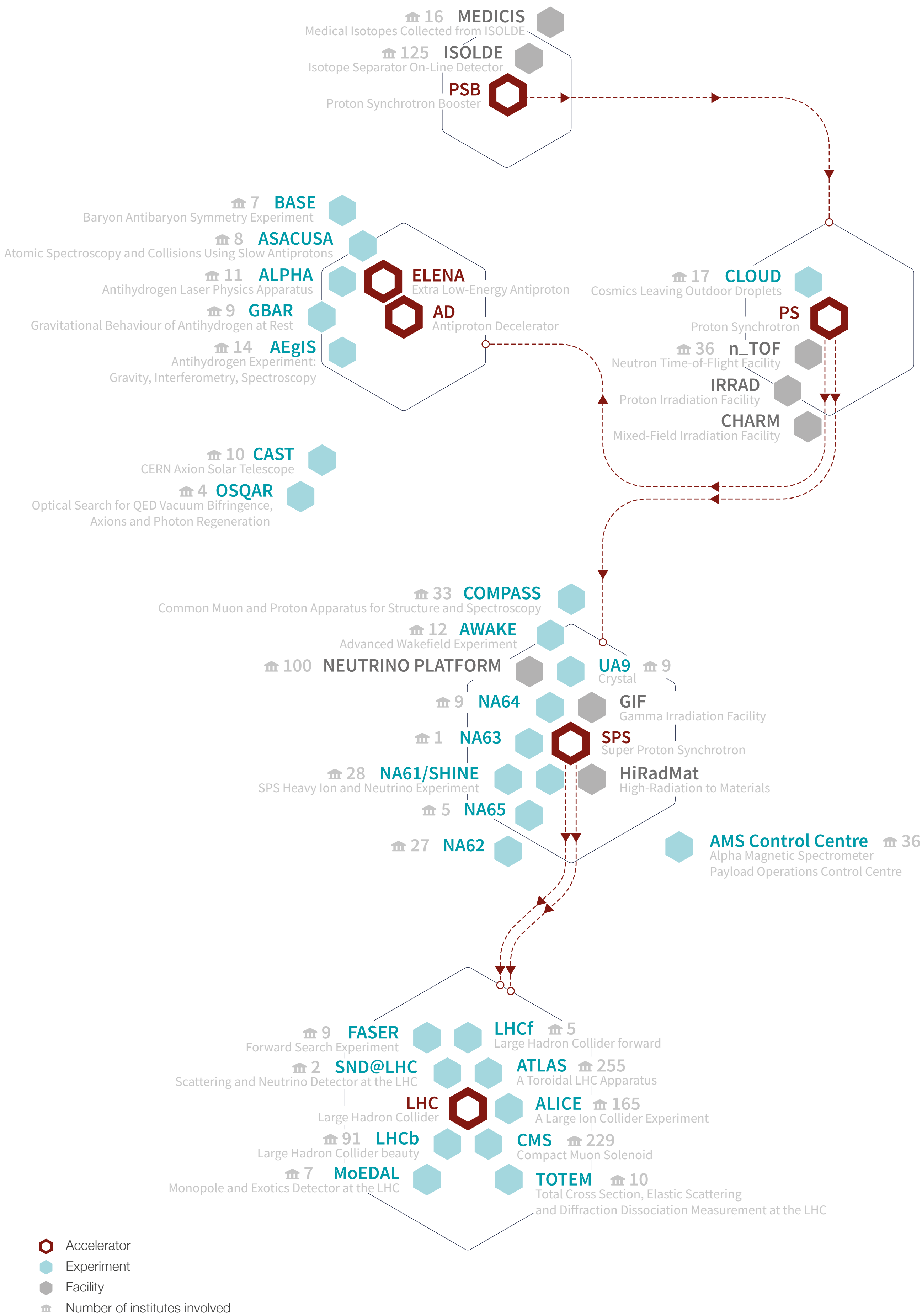
EXPLORING THE NATURE OF THE UNIVERSE

CERN investigates the fundamental structure of the Universe by operating a unique network of accelerators that collide particle beams head on or direct them onto fixed targets. The results of these collisions are recorded by state-of-the-art particle detectors and analysed by thousands of scientists at CERN and across the world.

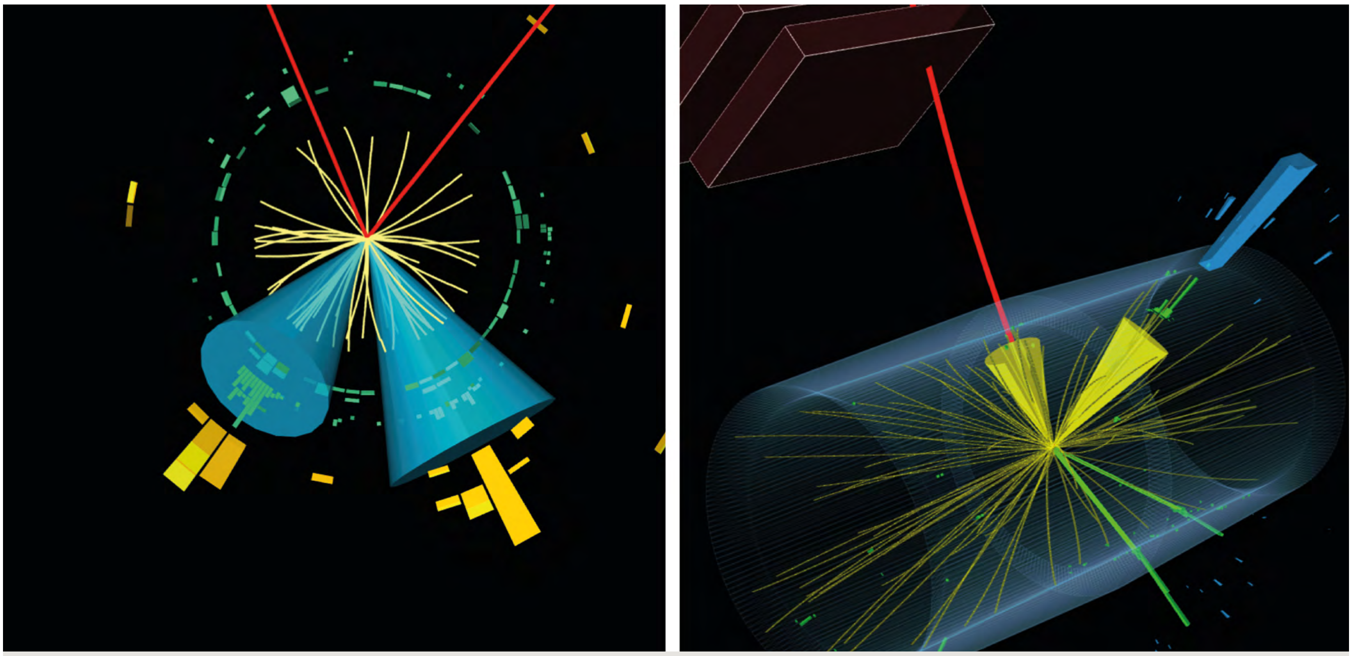
CERN'S ACCELERATOR COMPLEX AND THE EXPERIMENTS THAT IT FEEDS

The Large Hadron Collider (LHC) is CERN's flagship machine, colliding beams of protons and other particles at the highest energies ever achieved. The products of these collisions are recorded by the ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL and TOTEM experiments, and since 2022 also by the newcomers FASER and SND@LHC. The year 2022 was marked by the successful restart of the LHC on 22 April, after a multi-year hiatus for maintenance, consolidation and upgrade work. This was followed on 5 July by the start of the machine's Run 3, at a record collision energy of 13.6 TeV. Other highlights of the year included the 10th anniversary of the discovery of the Higgs boson and the publication by the ATLAS and CMS collaborations on the anniversary day of two papers detailing all that we've learned about this unique particle so far. Throughout the year, these milestones were complemented by a wealth of new knowledge about the building blocks of the Universe, which was gained by analyses of data from Run 1 and Run 2 of the LHC and from experiments at other accelerators at the Laboratory. The last quarter of the year saw ATLAS and CMS deliver the very first physics results based on Run 3 data, and on 18 November the LHC broke another record with lead nuclei colliding at an unprecedented energy of 5.36 TeV per nucleon–nucleon collision in a pilot run ahead of the next full-scale lead–nuclei run, planned for 2023.





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



Candidate events for a Higgs boson produced in association with a Z boson, as recorded by ATLAS (left) and CMS (right). The Higgs boson decays into a pair of jets (cones) originating from charm quarks, and the Z boson decays into muons (red lines on the left) or electrons (green lines on the right). (CERN-HOMEWEB-PHO-2022-035-1)

HAPPY BIRTHDAY, HIGGS BOSON

The date of 4 July 2022 marked exactly 10 years since the ATLAS and CMS collaborations announced the discovery of the Higgs boson. The finding was a landmark in the history of science and won François Englert and Peter Higgs the Nobel Prize in Physics for the prediction they had made decades earlier, together with the late Robert Brout, of the Higgs field. This fundamental field pervades the Universe, manifests itself as the Higgs boson and gives mass to elementary particles.

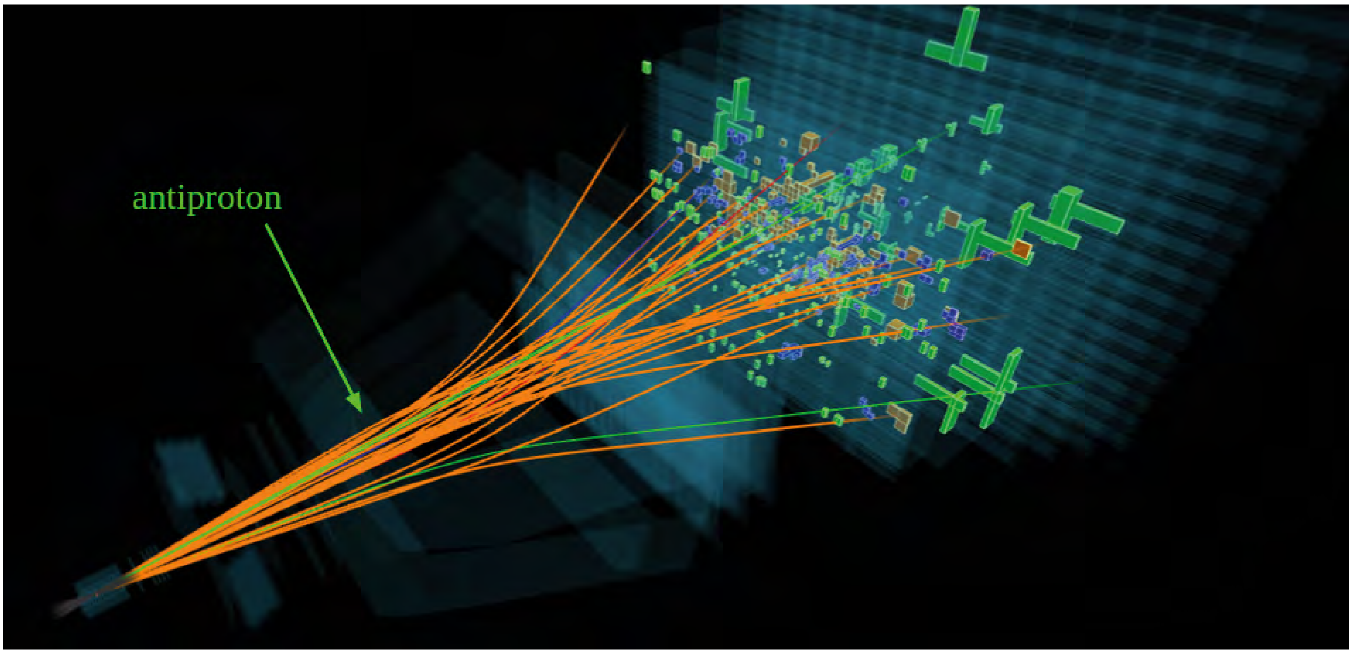
To celebrate the anniversary, CERN hosted a special scientific symposium on 4 July that not only reviewed a decade of discoveries related to the Higgs boson but also considered future prospects. That day, ATLAS and CMS also released two independent papers on the results of their most comprehensive investigations of the Higgs boson to date, detailing everything we've learned about this particle so far.

A good indicator of how far the collaborations have come is how precisely they have measured the basic properties of the Higgs boson. The particle's mass is now known to a precision of around 0.1%, and its lifetime has been measured to be around 10^{-22} seconds.

Another good indicator is the progress made in measuring the interactions with other particles, which are based on studies of how the Higgs boson is produced and decays into other particles. For example, the strengths of the Higgs boson's interaction with other bosons are now measured to a precision of 6–8%, and the strengths of interactions with the third generation of fermions (the tau lepton and the top and bottom quarks) are now measured to a precision of 7–11%.

In addition, evidence has been seen for the decay of the Higgs boson into muons, and first limits have been set on its decay to charm quarks, both of which are second-generation fermions. Evidence has also been seen for rare Higgs boson decays, and stringent bounds have been placed on the Higgs boson's interaction with itself and also on unknown phenomena beyond the Standard Model, such as Higgs boson decays into invisible particles that may make up dark matter.

Taken together with other results, including those from searches for asymmetry between matter and antimatter in the interaction between the Higgs boson and other particles, these achievements indicate that the Higgs boson is increasingly becoming a powerful means to search for new phenomena that, if found, could help to shed light on some of the biggest mysteries of physics.



A proton–proton collision event recorded by the LHCb detector, showing the track followed by an antiproton formed in the collision. (LHCb-PHO-EXP-2022-001-1)

TESTING THE STANDARD MODEL AND ITS EXTENSIONS

The LHC collaborations continue to carry out tests of the Standard Model and its extensions.

In 2022, LHCb unveiled two new kinds of exotic hadrons. One is the first pentaquark found to contain a strange quark, and the other is a doubly electrically charged tetraquark, which was spotted together with its neutral counterpart. The two new tetraquarks represent the first time a pair of tetraquarks has been observed. The findings add three new members to the growing list of new hadrons found at the LHC and will help physicists to better understand how quarks bind together into these composite particles.

LHCb also presented a new analysis of rare B-meson decays that provides one of the highest-precision tests yet of a key feature of the Standard Model known as lepton flavour universality. A previous LHCb analysis had hinted that these mesons decay into muons at a lower rate than they do into electrons, indicating an intriguing departure from the Standard Model prediction that electrons and muons should be produced equally often. The results of the new, improved and wider-reaching analysis are in line with the Standard Model expectation, causing the previous intriguing departure to melt away.

LHCb also obtained new results from studies of matter–antimatter asymmetry in charged B mesons that decay into a combination of π and K mesons. The results, which include the largest matter–antimatter asymmetry ever observed, provide important clues about the Standard Model's mechanism of matter–antimatter asymmetry generation, which is not fully understood.

THE YEAR 2022 SAW ATLAS AND CMS DELIVER THE FIRST PHYSICS RESULTS BASED ON FRESH RUN 3 DATA, AT THE NEW COLLISION ENERGY OF 13.6 TEV.

Using data from proton–helium collisions, obtained by injecting helium gas into the point where the two LHC proton beams would normally collide, LHCb measured the ratio of the rate of antiprotons produced in the decays of particles called antihyperons to that of antiprotons produced right where the collisions took place. The results show that, at the collision energy scale of the measurement, the antiprotons produced via antihyperon decays contribute much more to the total antiproton production rate than predicted by most models of antiproton production in proton–nucleus collisions. The results will improve the predictions of the models, an improvement that may in turn help to determine whether any antimatter seen by experiments in space originates from dark matter.

In further tests of the Standard Model and its extensions, ATLAS conducted several searches for new, long-lived particles, including a search for heavy charged long-lived particles leaving large energy deposits in the ATLAS detector. The data agree with the Standard Model expectation except for a small excess of events in one high-energy and high-mass region. ATLAS also observed the rare production of a single top quark in association with a photon through the electroweak interaction, as well as of a W and a Z boson simultaneously polarised longitudinally. These observations, the first for these processes, provide new opportunities to look for new physics. ATLAS also released the most precise luminosity measurement to date at the LHC, based on its data covering the entire Run 2 of the LHC. Describing the total number of proton–proton interactions in a given dataset, luminosity allows physicists to evaluate the probability of interesting proton–proton collision events occurring, as well as to predict the rates of similar-looking background processes.

Meanwhile, CMS obtained the most precise measurement yet of the mass of the top quark: 171.77 ± 0.38 GeV, using new analysis methods and improved procedures to consistently and simultaneously deal with uncertainties in the measurement. Precise knowledge of the top-quark mass is of paramount importance in testing the internal consistency of the Standard Model. In another precision record, CMS measured the rate of the rare decay of the B_s meson into a muon–antimuon pair as 3.8 ± 0.4 parts in a billion, very close to the Standard Model prediction. CMS also made the first observation of a process in which two oppositely charged W bosons are produced and then scatter off each other, opening a new way to test the Standard Model. The collaboration also set new bounds on the seesaw model of neutrino mass, including the first direct bounds for a heavy “Majorana neutrino” that has a mass larger than 2 TeV and up to 25 TeV.

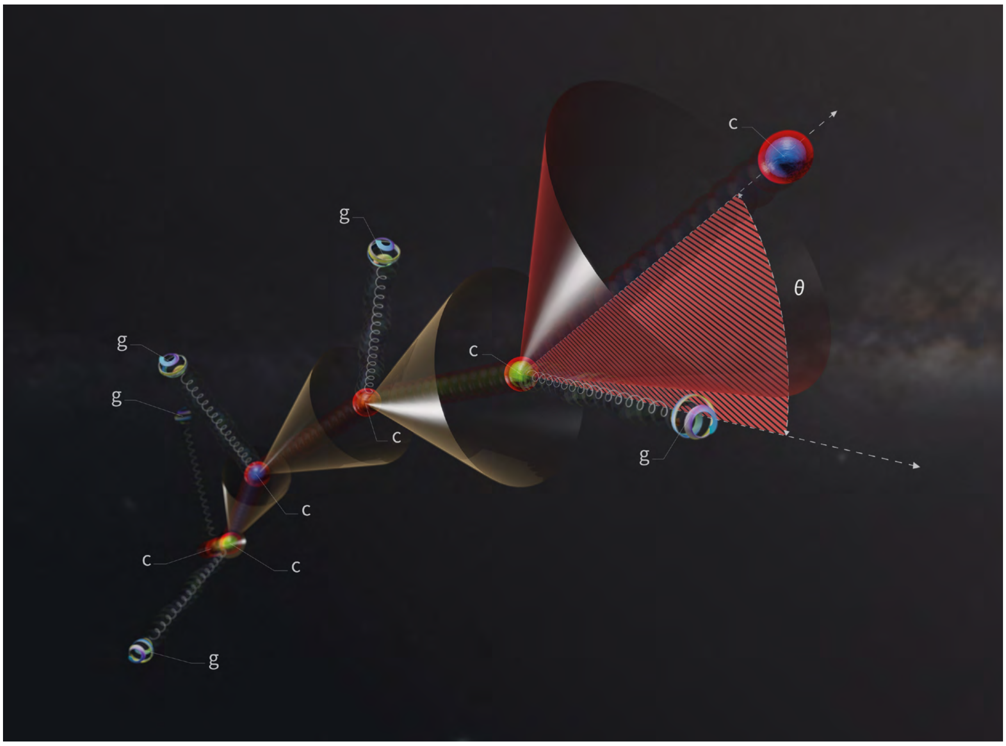
The year 2022 also saw ATLAS and CMS deliver the first results obtained using Run 3 data, at the new collision energy of 13.6 TeV. Just a few weeks into Run 3, CMS presented a measurement of the production rate of pairs of top quarks using the newly collected data. ATLAS also released its first Run 3 measurement of this process, as well as of the production of a Z boson. These early measurements helped the collaborations to validate the functionality of their detectors and software.

For the smaller LHC experiments, highlights of the year included the successful start of physics data taking for the newcomers FASER and SND@LHC, which were designed to study neutrino interactions and look for new, weakly interacting particles. Another highlight was the start of the installation of a new subdetector of MoEDAL, called MAPP, which will expand MoEDAL’s physics scope to include searches for minicharged particles and long-lived particles, in addition to the experiment’s current portfolio of searches for exotic phenomena. MoEDAL also published an analysis of Run 1 data that placed the best limits to date on highly electrically charged objects.

ALICE ANALYSIS

The LHC also collides nuclei to explore quantum chromodynamics (QCD), the theory of the strong interaction, under the most extreme temperature and density conditions on Earth. These heavy-ion collisions create quark–gluon plasma (QGP), a state of matter that is thought to have existed in the early Universe. In 2022, ALICE, the LHC’s heavy-ion specialist, took stock of its first decade of QCD studies in a review paper. These studies led to results that included a suite of observables that reveal a complex evolution of the near-perfect QGP liquid that emerges in high-temperature QCD, the observation of surprising QGP-like signatures in rare proton–proton and proton–lead collisions and measurements of hadron interactions that have implications for nuclear physics and astrophysics.

Heavy quarks can be used to determine the QGP density through the energy they lose in interactions with the QGP constituents. A prediction of QCD is that quarks with a larger



A charm quark (c) in a parton shower loses energy by emitting gluons (g). The shower displays a dead cone of suppressed radiation around the quark for angles (θ) smaller than the ratio of the quark’s mass and energy. The energy decreases at each stage of the shower.
(CERN-GRAPHICS-2022-015-6)

mass lose less energy than their lighter counterparts because of the dead-cone effect, which prevents the emission of gluons in a cone around the quark's direction of flight. In 2022, ALICE confirmed this expected role of quark mass in quark interactions with QGP using measurements of particles that contain charm quarks or (heavier) beauty quarks. In addition, in a study that applied a state-of-the-art analysis technique to a large sample of proton–proton collisions, the experiment made the first direct observation of the dead-cone effect. The technique may offer a way to measure quark masses.

ALICE also showed how different bound states of a charm quark and its antimatter counterpart, produced in lead–lead collisions, are suppressed to varying degrees by QGP. It also showed that this hierarchical suppression is counterbalanced by the recombination of charm quarks and antiquarks in the QGP. The results open new avenues for studying the strong interaction in the extreme conditions of QGP.

ALICE also released the most precise measurements to date of two properties of hypertriton – a nucleus that contains an unstable particle called Lambda in addition to protons and neutrons. The measurements offer new insights into the particle interactions that may take place at the hearts of neutron stars.

By carrying out the first measurement of antihelium-3 absorption in matter and feeding the result into existing models, ALICE also demonstrated that antihelium-3 nuclei can travel a long distance in the Milky Way without being absorbed. This finding will help space- and balloon-based searches for antimatter that may have originated from dark matter.

THEORY DEPARTMENT

In 2022, CERN's Theoretical Physics department conducted cutting-edge research, supported the Laboratory's activities and served the international theoretical physics community. This research, which led to the submission of 391 papers to the arXiv preprint server, spanned many areas, from string theory and quantum field theory to collider physics, cosmology and astroparticle physics.

Notable investigations and results include state-of-the-art calculations of Standard Model particle processes; a study demonstrating that a class of new-physics models involving long-lived particles with particularly high momentum could explain a small excess of events recently reported by ATLAS; a novel search for high-frequency gravitational waves using dark-matter detectors called axion haloscopes; a comprehensive study of the scientific potential of gravitational-wave observations with the planned Laser Interferometer Space Antenna (LISA); a study showing how criteria known as swampland conjectures, which characterise theories that might not be compatible with a consistent theory of quantum gravity, could reveal information about the energy scales of nature; and an analysis of mathematical quantities called "scattering amplitudes" in gravitational theories.

The department made fundamental contributions to all working groups on the physics of the LHC, the High-Luminosity LHC (page 44) and the proposed projects CLIC (Compact Linear Collider), FCC (Future Circular Collider) and a possible muon collider. The department also played a leading role in research concerning the Neutrino Platform (page 48) and the Physics Beyond Colliders programme (page 49) and participated in the CERN Quantum Technology Initiative (page 31).

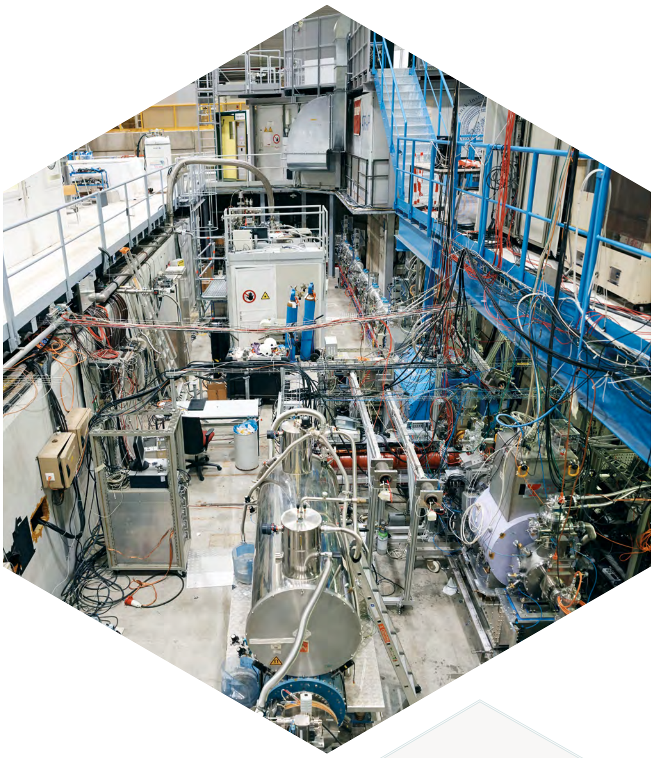
A total of 385 external scientists were hosted by the department, and three Theory Institutes were held, one of which was dedicated to discussing eco-friendly practices for scientific events and business travel. A rich programme of virtual scientific activities was also organised.

ANTIMATTER ARENA

CERN's Antimatter Factory provides low-energy antiprotons to experiments that allow the properties and behaviour of antimatter to be studied and compared with those of normal matter. These comparisons test a fundamental symmetry of the Standard Model called charge-parity-time invariance and a fundamental principle of general relativity known as the weak equivalence principle.

In 2022, low-energy antiprotons from the new ELENA ring, which slows down antiprotons even further than the facility's Antiproton Decelerator, were routinely and stably delivered to the ALPHA, AEgIS, ASACUSA, BASE and GBAR experiments in the first extended run with the new decelerator, resulting in AEgIS trapping over 50% of the antiprotons. The year also saw a new experiment, PUMA, being connected to the ring.

THE CHARGE-TO-MASS RATIO IS NOW THE MOST PRECISELY MEASURED PROPERTY OF THE ANTIPROTON.



The ASACUSA experiment at CERN's Antimatter Factory.
(CERN-PHOTO-202202-025-4)

Both PUMA and a variant of BASE called BASE-STEP, which is being developed, aim to transport antimatter to other facilities for nuclear-physics and antimatter studies, respectively.

Physics highlights in 2022 included BASE's high-precision measurements of the so-called cyclotron frequency of protons and antiprotons. These measurements resulted in the most precise comparison yet between the charge-to-mass ratios of protons and antiprotons, which were found to be equal to within 16 parts per trillion. The result is four times more precise than the previous best comparison between these ratios, and the charge-to-mass ratio is now the most precisely measured property of the antiproton. In addition, using the same cyclotron-frequency measurements, BASE tested whether or not protons and antiprotons behave in the same way under the influence of gravity. Because BASE is placed on the surface of the Earth, its proton and antiproton cyclotron-frequency measurements were made in the gravitational field on the Earth's surface. Any difference between the gravitational interaction of protons and antiprotons would result in different proton and antiproton cyclotron frequencies. Sampling the varying gravitational field of the Earth as the planet orbits around the Sun, the BASE scientists found that any difference between the two is less than 3%.

Another 2022 highlight was ASACUSA's finding that a helium atom containing an antiproton in place of an electron has a surprising response to laser light when immersed in liquid or superfluid helium. The experiment found a narrowing of the antiproton spectral lines of this hybrid helium atom in liquid helium and an abrupt further narrowing when the temperature of the liquid helium was decreased to values below the temperature at which the liquid becomes a superfluid, flowing without any resistance. This response to light is starkly different to that of the same hybrid atom in high-density gaseous helium, as well as to that of many normal atoms in liquids or superfluids. The narrowing of the lines in superfluid helium suggests that hybrid helium atoms could be used to study this form of matter and potentially other condensed-matter phases.

The year also saw ALPHA's vertical version, ALPHA-g, designed to carry out a direct measurement of the effect of gravity on antimatter, begin operation. The ALPHA team also took delivery of and began operating a caesium fountain clock, which provides a primary time standard on the CERN site. The clock will serve as the frequency reference for spectroscopic measurements on antihydrogen in 2023.

THE ISOLDE SPHERE

CERN's nuclear-physics facility, ISOLDE, directs a 1.4-GeV proton beam from the PS Booster (page 22) to a target station in order to produce beams of radioactive isotopes for a wide range of studies. The year 2022 saw ISOLDE reach a milestone of 30 years of world-class investigations since the facility's relocation from the Synchrocyclotron to the PS Booster in 1992. Over these three decades, the facility has consistently reinvented itself in order to push the frontiers of science with radioactive beams.

ISOLDE's radioactive beams can be re-accelerated to energies of close to 10 MeV per nucleon using the HIE-ISOLDE linear accelerator. In 2022, ISOLDE delivered radioactive beams to 45 experiments, 10 of which received re-accelerated beams.

Physics highlights from 2022 include the observation of the light emitted in the transition between the first excited state and the ground state of the thorium-229 nucleus. This so-called radiative decay of the first excited state, which is known as an isomer and takes a relatively long time to decay, is a key ingredient in developing a thorium-229 nuclear clock. Such a clock could have a precision better than that of today's most precise atomic clocks and could serve as a sensitive tool with which to search for phenomena beyond the Standard Model, such as ultralight dark matter and variations of fundamental constants over time.

Another highlight was a study that reversed common understanding of the physics of nuclei. Evidence suggests that, despite the complexity of nuclei, for those with a number of nucleons close to particular "magic" numbers, corresponding to full nuclear shells, nuclear properties are governed by a single unpaired nucleon. However, ISOLDE measurements of the magnetic-dipole moment of neutron-rich indium nuclei, which describes how much the nuclei behave like a bar magnet, showed that the moment undergoes a surprisingly abrupt change at magic neutron number 82. The results indicate that the single-particle picture dominates only for the nucleus with magic neutron number 82.

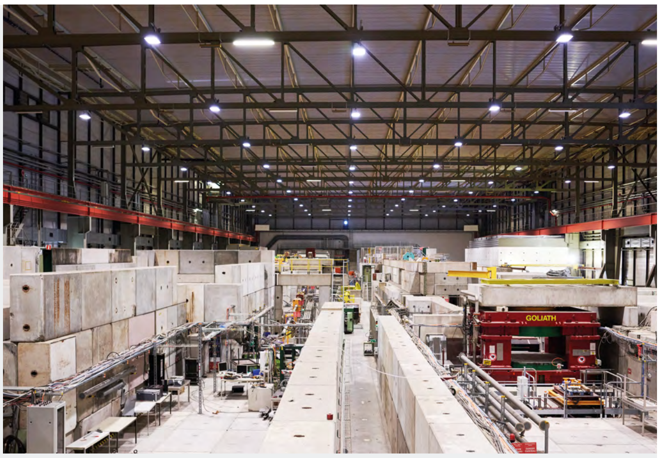
ISOLDE researchers also delivered the results of a new study that is pertinent for the lithium problem in nuclear astrophysics. This decades-old problem describes a pronounced difference between the observed amount of lithium-7 nuclei and that predicted by “Big Bang nucleosynthesis” models of the way that light nuclei were made in the early Universe. Such primordial lithium-7 nuclei originated from the decay of beryllium-7 nuclei. The new ISOLDE study investigated a possible beryllium-7 destruction channel using a re-accelerated beryllium-7 beam, providing new data to help to shed light on the problem.

Artist’s impression of a nuclear clock.

THE OBSERVATION AT ISOLDE OF A LONG-SOUGHT DECAY OF THE THORIUM-229 NUCLEUS IS A KEY STEP TOWARDS A CLOCK THAT COULD OUTCLASS TODAY’S MOST PRECISE ATOMIC CLOCKS.

FIXED-TARGET EXPERIMENTS AND BEYOND

Significant advances were also made in 2022 by other CERN-based experiments, many of which are fed by particle beams from the PS Booster and the PS and SPS accelerators (page 22). These advances include a new study from the CLOUD experiment showing that aerosol particles can form and grow in the Earth’s upper troposphere in an unexpected way. The new mechanism may represent a major source of cloud and ice seed particles in areas of the upper troposphere where ammonia is efficiently transported vertically, such as over the Asian monsoon regions.

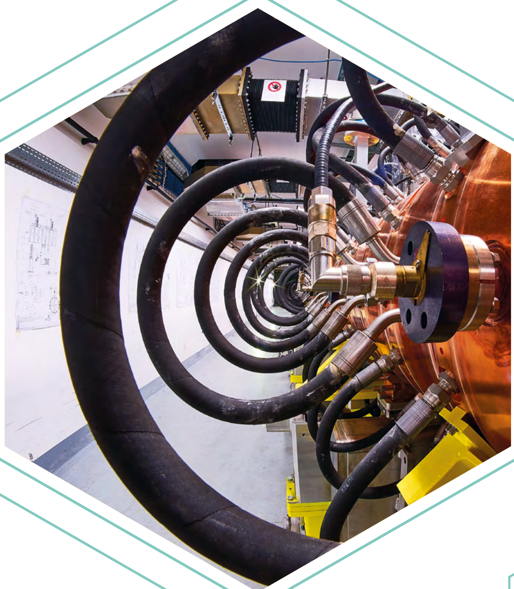


CERN’s North Area. *(CERN-PHOTO-202104-058-22)*

The year also saw the publication of a paper on the design and implementation of an irradiation station at the n_TOF facility that allows radiation damage studies to be performed in irradiation conditions close to the ones encountered during the operation of accelerators. Another highlight was the result of a search for axions from the Milky Way’s dark-matter “halo” using the CAPP axion haloscope at the CAST experiment, which has now been completed. The CAPP data narrowed down the theoretical space in which to look for these hypothetical particles. Other notable results include the NA62 experiment’s new competitive limits on the existence of lepton number violation in charged kaon decays, a process that, if found, would point to neutrinos being Majorana particles – particles that are their own antiparticles. The NA64 experiment also set new bounds on theoretical bosons, including bosons that could explain the difference between the measured and the predicted value of the muon’s magnetic moment.

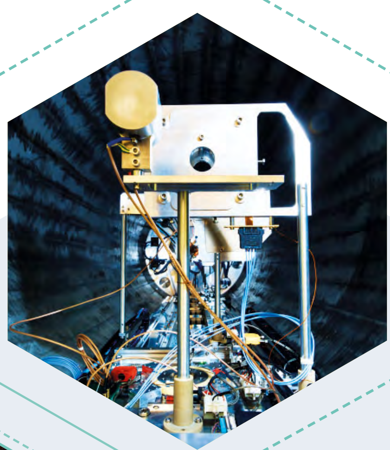
DISCOVERY MACHINES

In 2022, CERN's accelerator complex began its third run. On 5 July, after more than three years of upgrade and maintenance work during the second long shutdown (LS2), the first collisions took place in the Large Hadron Collider (LHC) experiments at a record energy of 13.6 TeV. This new data acquisition period will expand the LHC's already diverse physics programme. The performance of the entire accelerator complex was extremely encouraging this year. The fact that these decades-old machines (the Proton Synchrotron turned 63 this year!) and their associated facilities continue to produce physics at the limit of their capacities is a striking demonstration of the commitment and ingenuity of all the teams involved. It is also down to the successful execution of the strategy put in place to upgrade the accelerators to ensure that they operate extremely efficiently and reliably.



LINEAR ACCELERATOR 4 (LINAC 4)

February 2022: the first beams of the year circulate in Linac 4, at the nominal energy of 160 MeV.
(CERN-PHOTO-201704-093-10)



ISOLDE

March 2022: physics resumes in the ISOLDE target area. HIE-ISOLDE's new solenoidal spectrometer produces excellent results.
(CERN-PHOTO-202202-016-41)

PS BOOSTER (PSB)

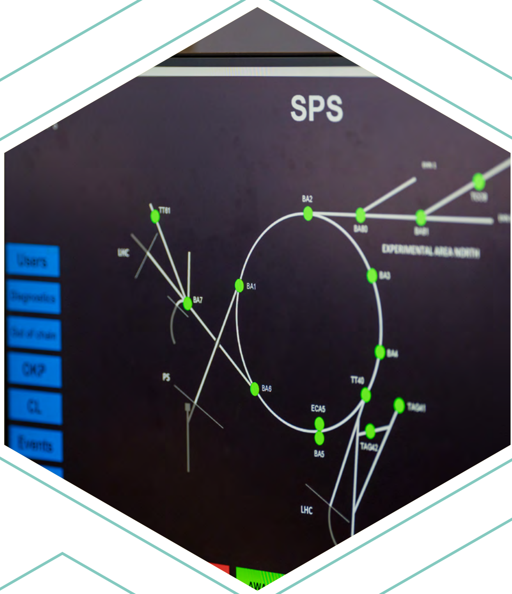
February 2022: the Booster receives its first beam of the year, from Linac 4. (CERN-PHOTO-201908-211-4)

SUPER PROTON SYNCHROTRON (SPS)

March 2022: the first beam is injected into the SPS from the PS.
(CERN-PHOTO-202207-121-146)

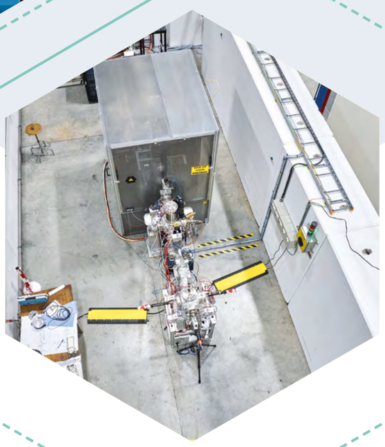
LARGE HADRON COLLIDER (LHC)

April 2022: the first beams of the year circulate in the LHC at an injection energy of 450 GeV.
July 2022: The LHC experiments record the first collisions at a record energy of 13.6 TeV.
(CERN-PHOTO-202207-121-41)



PROTON SYNCHROTRON (PS)

February 2022: the PS accelerates its first beam of the year.



ANTIPROTON DECELERATOR (AD) AND ELENA

April 2022: physics resumes at the AD/ELENA complex, which includes two new experiments, PUMA and BASE-STEP.
(CERN-PHOTO-202212-214-16)

SUCCESS FOR THE INJECTOR COMPLEX

In early spring, the injector complex was switched on again following a relatively short but effective year-end technical stop (YETS) over the winter of 2021/2022. On 14 February, H^- ions were again accelerated to 160 MeV in **Linear Accelerator 4 (Linac 4)**, CERN's newest accelerator, which forms the first link in the proton accelerator chain. Four days later, slightly ahead of schedule, the **Proton Synchrotron Booster (PSB)** began operation, accelerating its first proton beam.

This year, all the experiments and facilities supplied by the **Proton Synchrotron (PS)** received operational beams, the objectives having been comfortably achieved. Beams were also delivered to the Large Hadron Collider (LHC).

A further significant increase in beam brightness, in other words particle concentration, was achieved in the PS, and progress was made in the reproducibility and quality of the beams supplying the LHC at the target intensity of 2.6×10^{11} protons per bunch. As a result, the machine reached the beam parameters required for the High-Luminosity LHC (HL-LHC). The PS also injected lead ion beams into the Super Proton Synchrotron (SPS) and light-ion extraction tests were carried out.

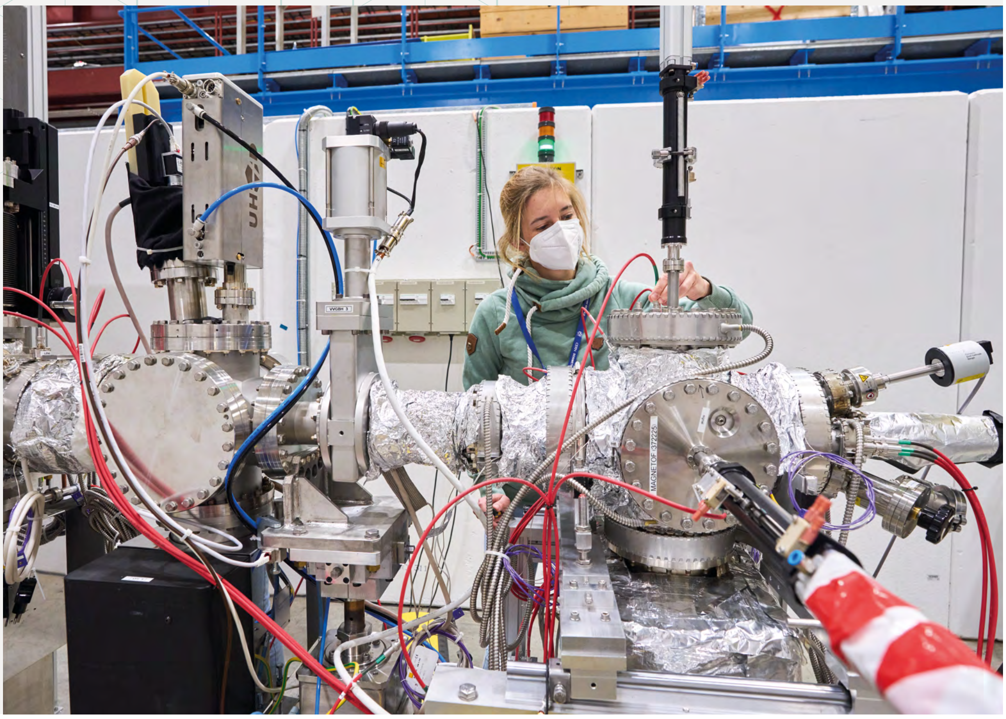
Despite this success, the PS team had to deal with a series of non-conformities. All were ultimately resolved or mitigated, although longer-term solutions are required in certain cases to guarantee the machine's operational availability, particularly in the new HL-LHC operation regime, which demands superior equipment performance.

RESTART OF PHYSICS AT THE ANTIMATTER FACTORY

With the progressive recommissioning of the PS and the SPS at the beginning of the year, physics was able to resume at the antimatter factory at the end of April. The **Antiproton Decelerator (AD)**, which produces low-energy antiprotons for the study of antimatter and to "create" anti-atoms, sends antiprotons to **ELENA** (Extra Low-Energy Antiprotons), CERN's new deceleration ring, at an energy of 5.3 MeV. ELENA then decelerates the antiprotons to 0.1 MeV, enabling the experiments to trap nearly 100 times more antiprotons than previously.

This year, ELENA successfully delivered antiprotons to all the antimatter factory experiments – ALPHA, AEgIS, ASACUSA, BASE and GBAR – and to two new experiments, PUMA and BASE-STEP, designed to transport antiprotons to other facilities at CERN and elsewhere.

The first components of the antiProton Unstable Matter Annihilation (PUMA) experiment were connected to ELENA this year. The PUMA trap is designed to feed antiprotons from the antimatter factory into ISOLDE for the study of proton and neutron distribution in the nuclei of certain unstable isotopes.
(CERN-PHOTO-202212-214-8)



The new kicker magnet was installed in the SPS in December.
(CERN-PHOTO-202212-225-8)

In the **Super Proton Synchrotron (SPS)**, the ramping up of the beam intensity with trains of 48 and 72 bunches per beam continued, with up to 1.8 x 10^{11} protons per bunch being reliably achieved. A further increase to the target intensity of 2.3 x 10^{11} protons per bunch is planned for late 2024.

The performance of the SPS's new acceleration system, which is based on radiofrequency (RF) transistor power amplifiers and has been in operation since November 2020, was improved. In short-pulse tests, it reached a peak power of 2 MW. Nonetheless, the failure rate of the amplifiers was higher than expected, and analyses are being carried out to determine the causes.

The supply of beams to the LHC, made up of a maximum of 288 high-intensity proton bunches at 25-nanosecond intervals, was extremely reliable in the different filling modes requested by the LHC operators. In addition, the SPS comfortably met the LHC's requirements in terms of higher intensity, reaching 1.5 x 10^{11} protons per bunch in November, which exceeded the previous intensity record by 25%.

On 3 November, circulation of lead nuclei in the SPS began. Lead nuclei comprise 208 nucleons (protons and neutrons) and are used to study quark–gluon plasma, a state of matter in which quarks and gluons are not confined within nucleons but can move freely and interact over a much larger volume. In the test, lead nuclei were accelerated in the SPS and successfully delivered to the LHC two weeks later with a maximum intensity of 1.9 x 10^8 ions per bunch – better than the objective set for the HL-LHC. In a pilot run in the LHC, lead nuclei were then accelerated to a record energy of 5.36 TeV per nucleon–nucleon collision, enabling the LHC experiments (ALICE, ATLAS, CMS and LHCb) to record a few lead–lead collisions over two days. This is a key step in the preparation of the physics campaign with lead–lead collisions, scheduled to take place from 2023 onwards during Runs 3 and 4 of the LHC. However, due to the early start of the 2022/2023 year-end technical stop (YETS) as part of energy-saving measures (see box on page 28), the planned tests of the 14 different modes of injecting lead nuclei into the SPS were not carried out.

During the YETS, a new kicker magnet was installed in the accelerator in December. The old kicker magnet had been heating up significantly during injection, limiting the beam intensity at times. To prevent this issue, a new kicker magnet design was developed.

NEW INJECTION METHOD FOR LEAD IONS

The CERN ion injector complex underwent a series of upgrades in preparation for a doubling of the total intensity of the lead-ion beams for the HL-LHC. In the SPS, teams began using a technique known as momentum slip-stacking, which involves injecting two batches of four lead-ion bunches separated by 100 nanoseconds to produce a single batch of eight lead-ion bunches separated by 50 nanoseconds. This will allow the total number of bunches injected into the LHC to increase from 648 in Run 2 to 1248 in Run 3 and subsequent runs. Once all the upgrades have been completed, the LHC will produce ten times more heavy-ion collisions than in past runs.

As well as being a key link in the LHC accelerator chain, the SPS supplies beams to the fixed-target experiments in the **North Area** and to the AWAKE experiment and the HiRadMat facility; beam availability exceeded the objectives in 2022. For the North Area, on the other hand, beam availability was 10% below the target due to a series of separate equipment failures that required long interventions in the activated areas. Despite this, the SPS provided the North Area with a record 2.3 x 10^{19} protons and improved beam injection quality. And although operation with lead ions did not take place for the LHC – with the exception of the two-day pilot run – lead ions were successfully sent to the North Area for two weeks of physics (instead of four as initially planned).

NUCLEAR PHYSICS CONTINUES UNABATED

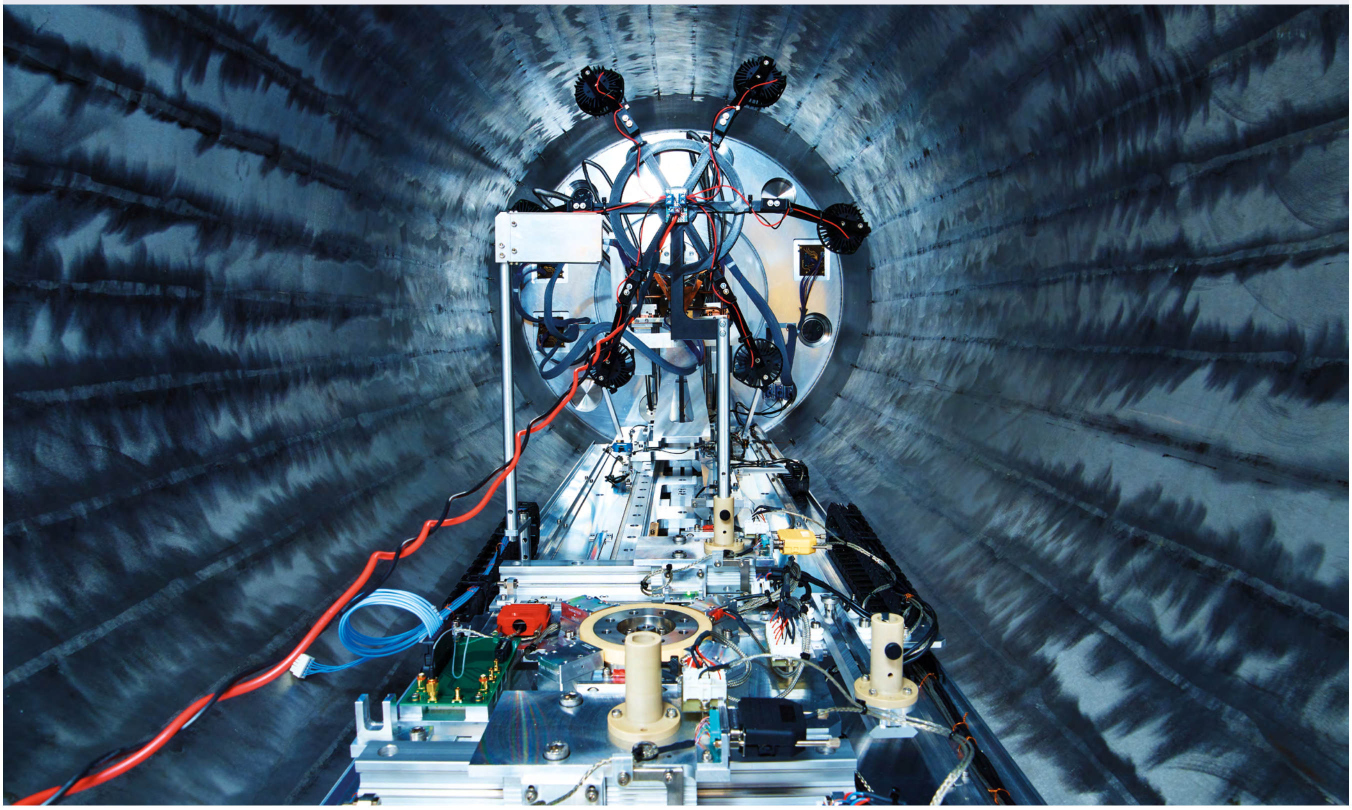
The acquisition of physics data by the experiments at ISOLDE, HIE-ISOLDE and n_TOF restarted this year.

The beams provided by the PS Booster that collide with the Isotope Mass Separator On-Line facility (**ISOLDE**) targets produce rare radioactive isotopes of various elements of the periodic table, some of which are then selected using a combination of lasers and electrical and magnetic fields to produce radioactive beams.

These beams, which are either used at low energies or reaccelerated by the HIE-ISOLDE (High Intensity and Energy Isotope Mass Separator On-Line) linear accelerator, are steered towards several facilities for experiments that cover a wide range of disciplines, from the study of nuclear structure and decay to astrophysics, condensed matter physics and life sciences.

Between March and November, 45 experiments were supplied with radioactive beams, 10 of which used reaccelerated beams. In addition, six HIE-ISOLDE experiments obtained excellent results with the new solenoidal spectrometer commissioned in 2021, which is designed to study the special properties of exotic nuclei.

The "nano-lab", a unique facility designed to develop innovative materials for the ISOLDE targets, was commissioned this year following receipt of the final components.



The new HIE-ISOLDE solenoidal spectrometer. *(CERN-PHOTO-202202-016-24)*

START OF RUN 3

A risk analysis carried out during the superconducting dipole magnet training campaign in 2021 led to the decision to start Run 3 of the **Large Hadron Collider (LHC)** at a target energy of 6.8 TeV instead of the 7 TeV initially planned – 0.3 TeV higher than the beam energy during Run 2 (6.5 TeV).

By the end of 2021, seven of the eight sectors of the LHC had been trained at this energy. Training of the last sector (sector 2–3) took place at the beginning of the year. This sector had had to be restored to ambient temperature at the end of 2021 to allow a magnet interconnection module to be replaced.

On 22 April, following a campaign of some 8000 tests on the power supply to all of the magnet circuits, the first proton beams of the year circulated around the 27 kilometres of the LHC ring at an injection energy of 450 GeV, marking the start of four years of physics data acquisition.
In the weeks that followed, the LHC specialists worked around the clock to progressively recommission the machine and safely increase the energy and intensity of the beams – this included a lengthy electron cloud scrubbing campaign – in order to provide all four of the LHC's large experiments with collisions at a record energy of 13.6 TeV.

And then, on 5 July, a round of applause broke out in the CERN Control Centre when all the subsystems of the LHC experiments had been started and had begun to record high-energy collisions at 13.6 TeV. A new physics season had begun! The event, broadcast live on various platforms, rounded off three days of celebrations marking the 10th anniversary of the discovery of the Higgs boson (page 16).

After more than three years of upgrade and maintenance work during the second long shutdown (LS2), Run 3 of the LHC started at the beginning of the summer. The LHC will run for nearly four years at an energy of 13.6 TeV, giving the experiments unprecedented precision and potential for discoveries. Higher collision rates, a higher collision energy, upgraded read-out and data-selection systems, new detection systems and a new IT infrastructure: all these factors bode well for a promising physics season and will further broaden the scope of the LHC's already very diverse physics programme.

The ATLAS and CMS detectors are expected to record more collisions during Run 3 of the LHC than during the two previous runs combined. The LHCb experiment has been fully upgraded and is predicted to increase its data acquisition by a factor of 10, while the objective of the ALICE team is to achieve a significant 50-fold increase in the number of collisions recorded.

The establishment of the first stable beams was followed by a period of commissioning alternating with the ramping-up of beam intensity. Progressively, the team carefully increased the number of bunches per beam, resulting in validation by the LHC Machine Protection Panel after a set time and a certain number of fills with a given configuration. This year, over a period of just five and a half weeks, the LHC progressed in steps of 72, 315, 603, 987, 1227, 1551, 1935, 2173 and finally 2413 bunches per beam, with the first fill at 1227 bunches made on 29 July, a few days ahead of schedule. Everything went well despite a few inevitable complications, and, on 12 August, 2440 bunches per beam were achieved.

ON 5 JULY, A ROUND OF APPLAUSE BROKE OUT IN THE CERN CONTROL CENTRE WHEN ALL THE SUBSYSTEMS OF THE LHC EXPERIMENTS HAD BEEN STARTED AND HAD BEGUN TO RECORD HIGH-ENERGY COLLISIONS AT 13.6 TEV.

This year, the LHC's cryogenic system achieved an availability of more than 99%, the highest since the start-up of the accelerator, with an energy-saving mode implemented during periods when full power was not required. This resulted in additional energy savings of around 19 GWh.

Nonetheless, 2022 remained a commissioning year for the LHC. The teams had to deal with issues arising from the upgrade work carried out during LS2 and with limitations of beam intensity due to the thermal load caused by the formation of electron clouds, in particular in sector 7–8. Fortunately, these problems were solved efficiently and alternative beam configurations were tested and then used to overcome these limitations.

Three major changes had to be made to the programme during the year. An issue with the RF cavities resulting in the temporary loss of cryogenic conditions during commissioning resulted in a two-and-a-half-week delay in May. This time was put to good use to complete installation of the new LHCb vertex detector (page 46).

A second, similar issue with the RF cavities led to an unscheduled three-week stop in August-September, following which mitigation measures were put in place. The cycle was shortened by a further two weeks due to the early start of the 2022/2023 YETS. As a result, the four weeks of operation with ions planned for the end of the year was postponed until 2023.

All in all, the machine and beam performance exceeded initial expectations. The integrated luminosity prediction for

2022 was 25 inverse femtobarns (fb^{-1}), based on a beam availability factor of 30%, which matches average values for commissioning years. In fact, the beam availability factor for a large part of the physics run was closer to 50%, despite the two unscheduled stops in May and August–September and the curtailment of the run at the end of the year. Along with the good beam performance, this availability resulted in the delivery of 40 fb^{-1} for both ATLAS and CMS.

The LHC would not have achieved this impressive number of collisions without the considerable flexibility and good performance of the injector complex, which concluded the second year of its third run at the end of November. The injectors reaped the benefits of the LHC Injector Upgrade (LIU) undertaken during LS2.

At 6 a.m. on Monday, 28 November, the LHC Engineer in Charge flipped the switch and the last proton beams of 2022 completed a final circuit of the LHC before being discarded into the dedicated beam dumps. This marked the end of the first year of Run 3 and the start of the year-end technical stop, a mere 21 weeks after the very first collision at 6.8 TeV per beam.

The **inverse femtobarn** is the unit of measurement of integrated luminosity, which is a measure of both the number of collisions and the amount of data collected. At the LHC, one inverse femtobarn corresponds to approximately 100 trillion (10^{14}) proton–proton collisions.

ENERGY-SAVING MEASURES

In line with the Management's strategic objectives, CERN has drawn up a plan to improve the Laboratory's energy management in the long term. However, the current energy crisis now makes the need to save energy more pressing. Measures were implemented for winter 2022/2023 to ensure that CERN plays its part in mitigating the impact of the crisis. The 2022/2023 year-end technical stop (YETS) therefore started on 28 November, two weeks earlier than initially planned.

THE SM18 TEST FACILITY IN THE HL-LHC ERA

The SM18 test facility is preparing to receive the magnets and RF cavities of the HL-LHC, for which a major upgrade campaign has been under way since 2014. In particular, a special test string, known as the HL-LHC IT string, had to be developed to validate the HL-LHC's inner triplets and is currently being installed in the facility. Mounted on a new metallic structure, the inner triplet test string is identical in every way to the inner triplet model that will be installed at Point 5 of the HL-LHC. It will allow the installation procedures and the tests of the individual systems to be developed and validated quickly and will also facilitate the execution of the entire hardware commissioning programme for many of the key technologies of the HL-LHC project. The final stages of installation and interconnection of the test string are planned for the second quarter of 2023. The validation tests will run from 2024 to 2025.

A new metallic structure was built at SM18 to house the HL-LHC's inner triplet test string (HL-LHC IT string).
(CERN-PHOTO-202205-082-2)

The CERN Data Centre in Prévessin. The building's shell has already been constructed. The building consists of three floors, which will be progressively filled with computing equipment over the first ten years of operation. (CERN-PHOTO-202201-010-38)

COMPUTING: ENABLING RESEARCH AND SUPPORTING OUR COMMUNITY

Computing infrastructure, in addition to providing the means to extract understanding from particle collisions, also enables our Laboratory to carry out its daily operations. The hidden IT layers underwent significant expansion and hardening during 2022 to become more robust and future-proof. Power distribution units were replaced in the computer centre, 50% of the campus routers were replaced, 4400 virtual machines were migrated to a new control plane layer, and the heterogeneous architecture was expanded to support GPUs and ARM-based processors. The single-sign-on service was expanded, with new versions covering more apps, and there was major evolution in the container orchestrator OpenShift, the version-control system Gitlab and the web-hosting framework Drupal.

Similarly for front-end services, the migration to the open-source CERNphone solution was expanded and accelerated by developing requested features. A new generation of the CERNBox service was also rolled out and 40 000 DFS (Distributed File Service) home directories were migrated to it. Data privacy was significantly strengthened in both our campus service-management tool, ServiceNow, and our open-source conference-management tool, Indico. Indico received a "Geneva Engage" award for its outstanding contribution to promoting online collaboration. Zenodo grew to serve the open-data needs of even more worldwide research communities, facilitated by grants from the US National Institutes of Health (NIH), the European Commission and the Arcadia Foundation.

As a complement to in-house consolidation, strategic moves to cloud services were enabled by signing a new contract with Microsoft for online mail and collaborative productivity tools, and the migration of 20 000 mailboxes to ExchangeOnline got well under way.

RUN 3 DATA TAKING

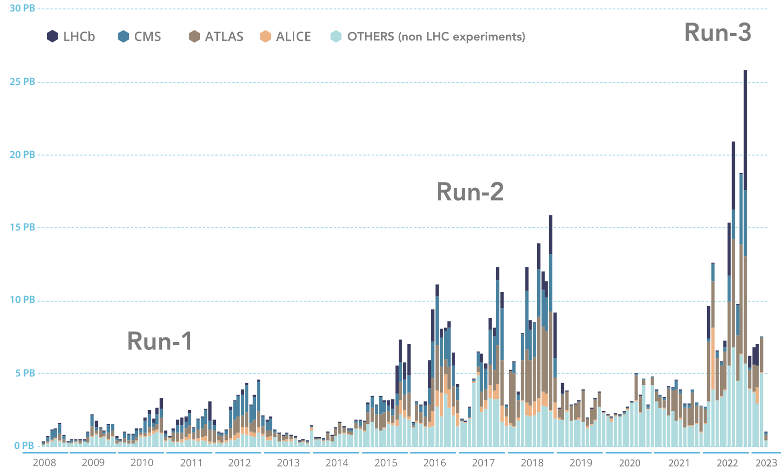
In 2022, the new CERN Tape Archive (CTA) system, commissioned during LS2, was ready to serve the higher demands of Run 3. A new record peak of 26 petabytes (PB) of data was stored in November alone, more than twice the total stored in the entire first year of LHC data taking, 2010. The prompt analysis needs were served by disk at up to 500 GB/s, with a total of 3.79 exabytes (EB) of data delivered by EOS physics. The file transfer service distributed 1 billion files and 1.39 EB.

Similarly, the new LHC logging system, NxCALS, which is based on Hadoop big-data technologies, was successfully used in production for the first time for Run 3.

THE GRID THAT NEVER SLEEPS

The Worldwide LHC Computing Grid (WLCG) successfully met the challenges of the start of LHC Run 3. This global computing network, involving 170 data centres in 42 countries, grew to a record 1.3 million computer cores and 2 EB of storage.

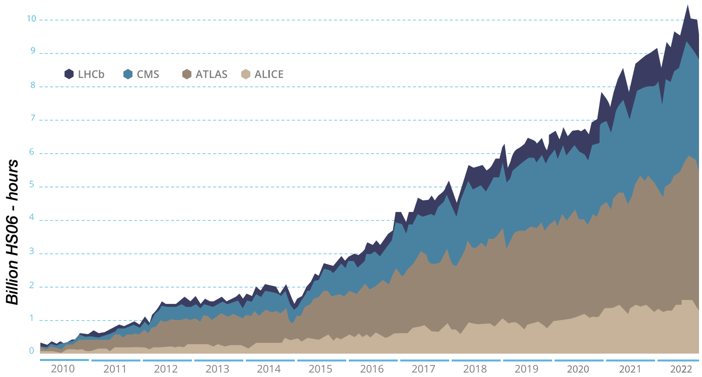
In preparation for Run 3, a series of data challenges were run to test the full data-handling chain, from data acquisition at the LHC experiments to the export of data to Tier-1 sites of the WLCG and archive storage. The WLCG services were thus well prepared to support the data-taking activities of the experiments at ever increasing rates, with global data



The data written in the CERN tape storage per month since 2008.

A record-breaking 26 PB of data was collected and archived in November 2022.

transfer rates reaching an average of about 40 GB/s. The experiments also continued to benefit from large amounts of opportunistic computing resources from WLCG sites and other facilities, which provided at least 40% extra compute capacity above the formal commitments of the WLCG funding agencies.



Evolution of the global core processor time delivered by the WLCG

The global central-processing-unit (CPU) time delivered by the WLCG, expressed in billions of HS06 hours per month. HS06 is the benchmark used for measuring CPU performance in high-energy physics.

CERN DATA CENTRES: CONTINUOUSLY REJUVENATING

The Meyrin Data Centre is at the heart of the WLCG. The work that had begun in 2021 to upgrade and replace hardware continued, to ensure readiness for Run 3. In parallel, work began on the construction of the new CERN data centre in Prévessin. In April, a special “first stone” ceremony was held to mark the beginning of this construction work.

The Prévessin Data Centre (PDC) will be completed by the end of 2023. This new, energy-efficient facility will play a vital role in meeting the computing needs of the HL-LHC, which will require ten times the compute capacity of today when it comes online. It will provide computing resources with a total electrical power requirement of up to 12 megawatts.

Energy efficiency lies at the core of the PDC’s design; CERN’s Procurement Service paid special attention to including sustainable solutions for the new building. The PDC will make use of the latest cooling technologies and will recover heat energy to warm other buildings on site. During the PDC’s first phase of operation, most of the rejected

MAKING A POSITIVE IMPACT

To maximise its positive impact upon society, the IT department works closely with CERN’s Knowledge Transfer group, including through several CERN openlab projects that focus on impact of CERN technologies and expertise upon research fields beyond particle physics, particularly medical applications.

The IT department also continues to host and support UNOSAT, the United Nations Satellite Centre. UNOSAT provides satellite imagery and geospatial information to support the UN’s humanitarian efforts, protecting refugees following natural disasters, disease outbreaks and other crises.

CERN increases the positive impact of its computing technologies through participation in EU-funded projects involving other leading research organisations. An example of such a project that was launched in 2022 is FAIRCORE4EOSC, which will develop new core components for the European Open Science Cloud (EOSC). The project, which brings together 22 partners from 10 countries, will use the CERN-developed tools InvenioRDM and Zenodo as digital repository solutions to provide a FAIR (findable, accessible, interoperable, reusable) infrastructure for research software archiving. CERN is also contributing to EOSC through the ESCAPE (European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures) project.

In September, the ARCHIVER project, which is led by CERN and is investigating options for digital preservation and archiving, received the prestigious Digital Preservation Coalition’s award for collaboration and cooperation.

heat will be recovered; projects for using it are now under consideration.

LOOKING BEYOND RUN 3 TO THE HL-LHC ERA

In January, the IT department published a new three-year strategy, focused on ensuring that it is an enabling partner for stakeholders across the full CERN community. This strategy has helped to pave the way for a successful start of Run 3 and provides a framework for meeting the IT challenges that will be thrown up by Run 4, when the HL-LHC is launched.

CERN participates in several EU projects focused on computing technologies. These play an important role in ensuring that the Organization is ready to meet the computing challenges of the future, as well as helping to ensure that computing technologies developed at CERN make a positive impact on society. These projects address important topics, such as artificial intelligence, “digital twin” simulation technology, the next generation of “exascale” supercomputers and open data.

CERN openlab is another vital mechanism for addressing these challenges. This unique public-private partnership between CERN and leading IT companies supports around 28 R&D projects tackling cutting-edge IT challenges facing the whole Organization. These projects, which are spread across the Laboratory, address challenges related to exascale technologies, AI technologies and quantum computing.

CERN openlab’s quantum computing projects contribute to the broader CERN Quantum Technology Initiative (QTI), which enjoyed great success in 2022.

FOSTERING THE QUANTUM REVOLUTION

The CERN QTI’s research programme is divided into four main areas: quantum computing and algorithms; quantum theory and simulation; quantum sensing, metrology and materials; and quantum communication and networks. Several exciting new projects involving researchers across the Organization were established in 2022 and were carried out in close collaboration with quantum technology experts in both industry and academia. CERN also welcomed two European research institutes – INFN and IIT – as new members of its IBM Quantum Network Hub.

In addition, the CERN QTI organised the International Conference on Quantum Technologies for High-Energy Physics (QT4HEP), at which members of the quantum technologies community from academia and industry discussed recent developments in the field and worked to identify activities within particle physics – and other sciences – that can benefit most from the application of quantum technologies.

The CERN QTI organised many education and training activities, capitalising on its collaboration with industry. It also supported the second-ever World Quantum Day celebration, which included a special scientific symposium.

CERN was also part of a consortium to propose the founding of an Open Quantum Institute, which will work to ensure that emerging quantum technologies are used to tackle key societal challenges. The proposal was made through GESDA, the Geneva Science and Diplomacy Anticipator Foundation, in collaboration with leading research institutes and technology companies.

TRAINING THE IT STARS OF THE FUTURE

Throughout the year, the IT department organised a wide range of education and training activities, including workshops and hands-on training sessions on a variety of computing topics, led by CERN specialists and invited experts.

A rich programme of academic training lectures was made publicly available online. Computing topics included Internet history, computational models for neuroscience and data protection. A particular highlight was a three-lecture series in May on the history of distributed computing, from the web to the grid and beyond. Internet pioneer Vint Cerf and Web inventor Sir Tim Berners-Lee joined and actively participated in these lectures.

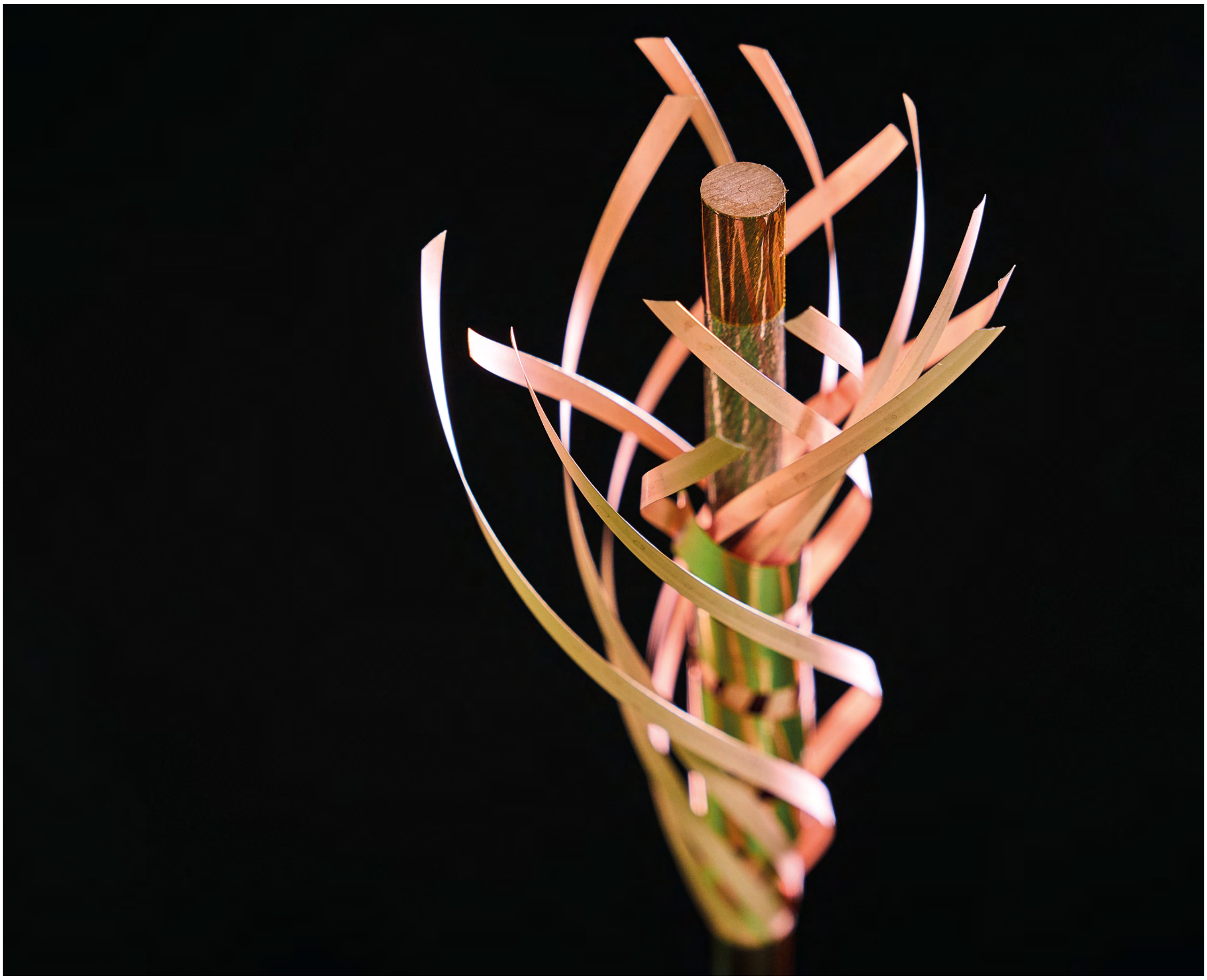
The CERN openlab Summer Student Programme was held on site for the first time since the start of the COVID-19 pandemic. Out of 1770 applications, 32 students from 19 countries were selected to take part in the programme in 2022. As well as working on projects involving cutting-edge computing technologies, the students attended a special series of lectures and visits.

The CERN School of Computing (CSC) also returned to its full curriculum after two years of being impacted by the COVID-19 pandemic. The main CSC took place in Kraków, Poland, and a thematic CSC, which focused on writing efficient scientific software for heterogeneous computing architectures, was held in Corsica, France. In addition, a new, first-of-a-kind security-focused thematic CSC was held in Split, Croatia. These three residential schools were attended by a record 155 students (selected from 320 applications), and offered a combined total of four weeks of lectures, exercises and networking.

PUSHING THE FRONTIERS OF TECHNOLOGY

In its quest to understand the Universe, CERN is continuously developing cutting-edge technologies. These technologies are taken into wider society with the help of our industrial and institutional partners. They have applications spanning the environment, aerospace, healthcare, and quantum and digital technologies.

Such collaboration takes many forms: the procurement of equipment and services, involvement in EU projects and transfer of CERN's knowledge to companies and research institutes. This chapter highlights some examples of how CERN's technology and know-how were paired with the expertise of our partners in 2022 to develop technology for society.



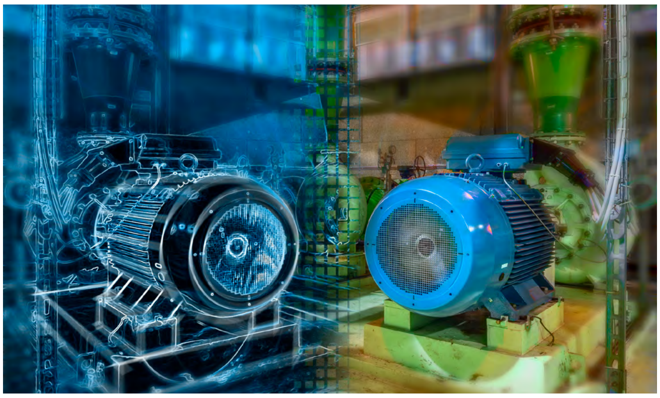
CERN's superconducting power transmission cable, used to assess the feasibility of superconductivity for aircraft. *(CERN-PHOTO-202211-195-7)*

CIPEA CERN Innovation Programme on Environmental Applications

CIPEA – CERN INNOVATION PROGRAMME ON ENVIRONMENTAL APPLICATIONS

In acknowledgement of global environmental challenges, the CIPEA programme was launched to invite the CERN community to develop innovative ideas for environmental applications based on CERN's technologies, know-how and facilities.

The programme started with a kick-off event in March, which was followed by a few months of intense idea generation and the organisation of a CIPEA Innovation day in June. The response from the CERN community was enthusiastic. Of the many proposals presented, eight are currently under development – seven of which are supported by the KT Fund.



Data collected from CERN's cooling and ventilation system will be used to develop simulations to test energy-reduction scenarios. (OPEN-PHO-MISC-2023-007-1)

A PARTNERSHIP BETWEEN ABB AND CERN FOR SUSTAINABILITY AND ENERGY EFFICIENCY

ABB Motion, a company specialising in digitally enabled motor and drive solutions, started collaborating with CERN in 2022 with a view to reducing the energy consumption of cooling and ventilation infrastructures. As well as developing best practices for CERN itself, the outcomes may inspire other laboratories or industrial sites to follow the same path. The condition-monitoring platform, installed in 2022, will collect data from CERN infrastructures; this data will be used to simulate and test energy-reduction scenarios.

A PARTNERSHIP BETWEEN CERN AND AIRBUS ON FUTURE CLEAN AVIATION

In 2022, CERN and Airbus announced the launch of a joint project to evaluate how superconductivity could contribute to the decarbonisation of future aeroplanes. A superconducting demonstrator named SCALE (Superconductors for Aviation with Low Emissions) will be built at CERN. The project will combine CERN's expertise in superconducting technologies with the innovative aircraft design and manufacturing capabilities of Airbus UpNext, a subsidiary of Airbus.

CELESTA: FIRST CERN MICROSATELLITE IN SPACE

In July, CELESTA was launched into space – a result of the collaboration between CERN, the University of Montpellier and the European Space Agency (ESA). CELESTA is a nanosatellite in the form of a cube, weighing just one kilogram and measuring 10 centimetres on each side. Known as the 1U CubeSat nanosatellite, it will study the effects of cosmic radiation on electronics. The satellite's payload is the Space RadMon, a miniaturised and low-power version of the LHC's well-proven radiation monitoring device. A model of the satellite was first tested in CHARM, a unique CERN facility capable of reproducing, to a large extent, the radiation environment of low Earth orbit. Everything went smoothly and, as planned, the mission has collected data that will be analysed soon.

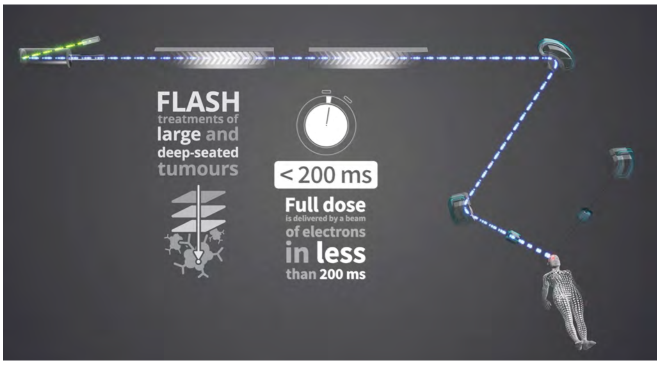
CELESTA was launched using the Vega C rocket from the Guiana Space Centre in French Guiana.

ACCELERATING THE SECOND QUANTUM REVOLUTION WITH CERN TECHNOLOGY

Quantum technologies are set to revolutionise our world. Quantum computing, communications and sensing have the same extreme requirements as high energy physics, such as ultra-high vacuum, precise timing and use of superconducting materials. As part of CERN's Quantum Technology Initiative (page 31), the Knowledge Transfer group promoted the Laboratory's unique technologies at numerous events, including the CERN-UK Quantum Technology Roadshow, with a view to identifying industrial partnership opportunities.

APPLYING MACHINE LEARNING FOR FAST DECISION MAKING IN SELF-DRIVING CARS

CERN and Zenseact, a company owned primarily by Volvo Cars, generated new insights into hardware-optimised machine-learning models to develop autonomous-driving technologies that can greatly enhance the decision-making process for cars. In 2022, the collaboration published its findings, showcasing how CERN's expertise in machine learning, combined with specialised hardware, software and the company's domain knowledge, can influence the future of autonomous driving.



The new FLASH radiotherapy device, based on CERN's accelerator technology.

A PARTNERSHIP BETWEEN CERN, CHUV AND THERYQ FOR A WORLD FIRST IN CANCER RADIOTHERAPY

CERN, the Lausanne University Hospital (CHUV) and an innovative medical technology company, THERYQ (ALCEN Group), signed an agreement for the first ever development of a revolutionary FLASH radiotherapy device that will use very high-energy electron (VHEE) radiation to treat cancers that are resistant to conventional treatments.

The device will include a compact linear accelerator based on CERN technology and will use very high-energy electron beams of 100 to 200 MeV, allowing cancers to be treated up to a depth of 20 cm using the FLASH technique. It has the potential to lower the overall cost of treatment, and its compactness means that it can be used in a hospital setting. It will be based at CHUV and is expected to be operational within two years, with the first clinical trials planned for 2025.

DOING BUSINESS WITH CERN

CERN requires a constant stream of supplies and services in order to construct and operate its accelerators, detectors and computing facilities. Industry in CERN's Member States helps keep the research facilities running, providing everything from simple day-to-day items to highly technical components. For the period 2022–2026, which is marked by the high-luminosity upgrade of the LHC (HL-LHC), CERN plans to spend 2.5 billion Swiss francs on procurement. In doing so, CERN is creating unique opportunities for industry to invest in cutting-edge technologies.


CERN's Director for Finance and Human Resources, Raphaël Bello (second row, fourth from the left), represented CERN at the second edition of the Big Science Business Forum (BSBF) along with ten of its European Big Science counterparts (EMBL, ESA, ESO, ESRF, ESS, European XFEL, FAIR, Fusion For Energy, ILL and SKA Observatory).

The Procurement service, together with CERN's technical departments, started to assess the implementation of measures to reduce the CO_2eq (carbon dioxide equivalent) emissions, both direct and indirect, associated with the purchase of goods and services for the Organization. A supplier sustainability rating platform focusing on suppliers' CO_2eq emissions is being implemented. These activities are being conducted within the scope of the CERN Environmentally Responsible Procurement Policy Project (CERP3).

In 2022, CERN took part in the second edition of the Big Science Business Forum (BSBF), together with EMBL, ESA, ESO, ESRF, ESS, European XFEL, F4E, FAIR, ILL

Signature of contracts with KrioSystem. (OPEN-PHO-TECH-2022-003-2)

and SKAO. The Forum highlighted upcoming procurement opportunities for European companies in fields ranging from superconductivity to civil engineering, helping to promote the acquisition of new knowledge and foster innovation.

The Procurement Service also organised national industry events with the Baltic States, Belgium, Greece, Israel, Norway, Portugal and the United Kingdom. A total of 104 firms participated in these industry events, and around 400 business-to-business meetings bringing their representatives into contact with CERN personnel were organised. These events are important not only for matching industry's capabilities with CERN's projects and needs, but also for addressing the challenge of achieving balanced industrial return across the Member and Associate Member States.

In 2022, CERN signed contracts with the Polish company KrioSystem and the Swiss company Linde-Kryotechnik for the provision of two cryogenic distribution lines and two helium refrigerators, respectively, for the HL-LHC project. These important components will be installed next to the ATLAS and CMS experiments.

Overall, CERN's procurement activities included 24 500 orders of various types, 78 invitations to tender, 151 price enquiries above 50 000 CHF, and the signature of 223 contracts, 101 of which were collaboration agreements. Expenditure on various orders and contracts totalled 477 MCHF (approximately 39% of the CERN budget).

INNOVATING WITH EU PROJECTS

As the leading European particle physics organisation, CERN actively participates as a partner in and/or coordinates projects that are co-financed by the European Union (EU) under its framework programmes for research and innovation. In 2022, CERN was involved in over 58 EU projects (excluding MCSA H2020 Individual Fellowship and Horizon Europe Postdoctoral fellowships) and coordinated 22 such projects, with a total European Commission contribution to CERN amounting to some 45.75 million euros. Six projects with a strong knowledge-transfer component (AIDAinnova, ATTRACT1B, ATTRACT2, I.FAST, PRISMAP and RADNEXT) are coordinated by CERN. Total EU funding for those six projects amounts to some 70 million euros, distributed among the participating institutes and companies.

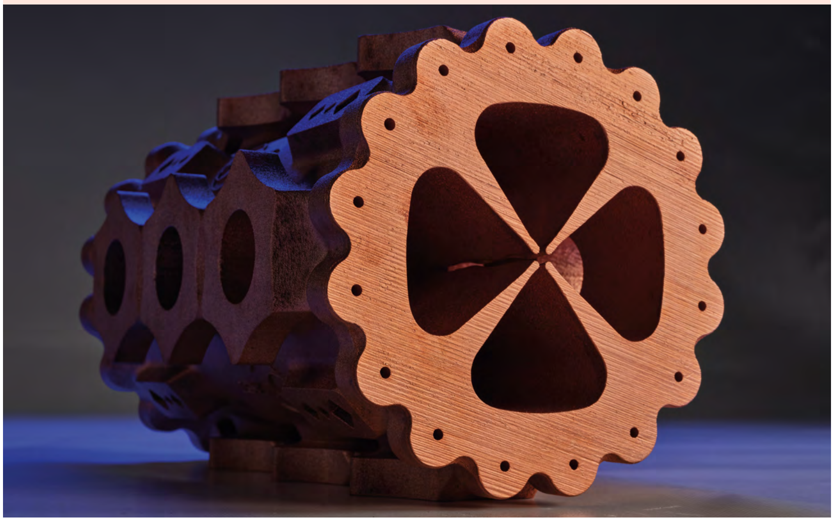
ATTRACT PHASE 2 UNVEILS THE PROJECTS THAT WILL BENEFIT FROM ITS 28 MILLION EURO FUND FOR INNOVATION

The ATTRACT project presented the 18 research and development and innovation projects that will receive funding to move to a pre-market product. Among them is AHEAD, which will build on development work at CERN to offer a new way to manufacture smart pipes for the next generation of cooling systems.

FIRST 3D-PRINTED RFQ OPENS THE DOOR TO THE WIDESPREAD USE OF ACCELERATORS

Particle accelerators play a crucial role in healthcare and industry, and hold the potential for ambitious environment and energy applications. However, their size and manufacturing cost are often obstacles to their widespread use in society. This picture shows the first 3D printing of a radiofrequency quadrupole, a critical accelerator component, which was made possible by the I.FAST project and Trumpf (Germany). Used on a wider scale, this technique could pave the way towards more affordable and versatile particle accelerators.

As part of its goal to put Europe at the forefront of accelerator science and technology, this Horizon 2020 project also invited senior bachelor's and master's students to take part in its summer challenge to find new and innovative environmental applications for particle accelerators. The students, from varying backgrounds, worked in multidisciplinary teams to tackle the challenge, presenting their ideas to experts in relevant fields on the last day.



The radiofrequency quadrupole (RFQ) created from pure copper using a 3D printer. (CERN-PHOTO-202205-094-49)

INSPIRING AND EDUCATING

A key pillar of CERN's mission is to inform and engage citizens of all ages, enthuse them about the wonder of the science and technology underpinning CERN's research and its impact on our daily lives, and inspire students to pursue careers in science and engineering.

In 2022, in-person education, outreach and training activities returned to their pre-COVID-19 pandemic levels, reaching audiences across the Member States, Associate Member States and beyond.

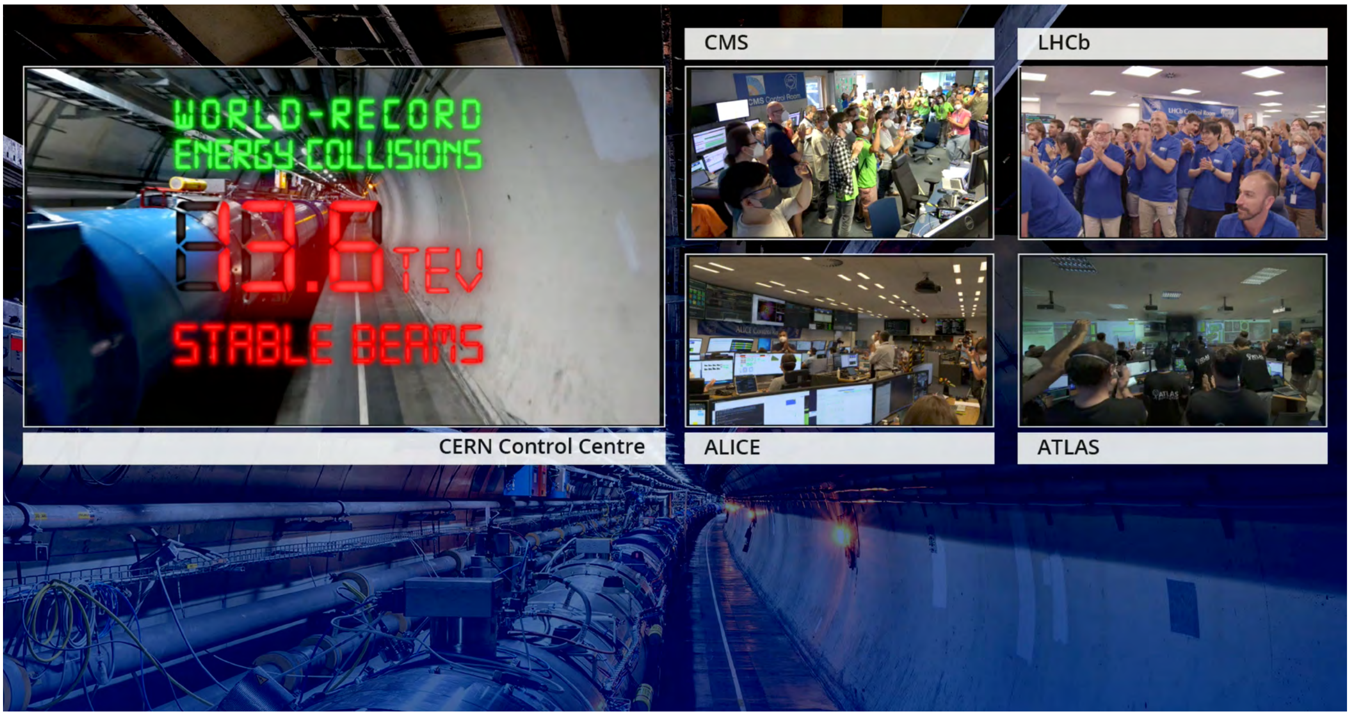
HIGGS10: CELEBRATION, 10 YEARS ON AND PREPARING THE FUTURE

A multi-channel campaign celebrated three key milestones in 2022: the re-start of the LHC, the 10th anniversary of the discovery, at CERN, of the long sought-after Higgs boson, and the start of the third run of data taking for physics at the LHC.

The campaign, which encompassed media relations, digital communications, special issues of the CERN Bulletin and the CERN Courier, an exhibition and in-person events, including a scientific symposium for the Higgs boson discovery anniversary, was developed in close collaboration with partners in CERN's Member States and laboratories worldwide.

The campaign reached a range of audiences, with strong engagement: 8500 clippings across general and specialist media outlets; airing of the satellite feed of the start of Run 3 by TV channels in 25 countries; a seven-fold increase in traffic to the CERN website, with 75% new visitors; 18 000 mentions on social media; 75 000 concurrent viewers of the Run 3 live broadcast, with more than 27 000 comments and questions during the stream. In-person events – both at CERN and in local communities – reached more than 400 people. The scientific symposium was followed in the CERN Auditorium and also online by over 1100 people. The campaign won an European Excellence Award, in the Science and Education category.

The live broadcast of the start of Run 3 of data taking at the LHC had received almost 5 million views from around the world by September 2022.



Artist Ian Purnell produced this image, of physicists assembling GEM detectors for the CMS experiment, during his residency at CERN as one of the Connect winning artists.
(OPEN-PHO-ACCEL-2023-002-36)

ENGAGING AT CERN, LOCALLY AND GLOBALLY

Guided tours for groups started up again, adding to the tours for individual visitors that had resumed the year before. Just over 95 000 people visited CERN in 2022, around 80 000 of whom also visited the on-site exhibitions Microcosm and Universe of Particles, both of which were again fully open to the public. The Globe of Science and Innovation again bustled with activity: a total of 70 public events took place, including 55 science shows. Those who were not able to travel to CERN had the possibility to get to know the Laboratory online: around 5500 people took part in 125 virtual tours for schools and the general public.

Visits by decision-makers are key to maintaining long-term support for CERN's mission. A total of 132 high-level delegations visited CERN in 2022, marking a return to pre-pandemic levels.

CERN's travelling exhibitions visited Ukraine, Switzerland, Germany, Netherlands and France, attracting an estimated total of 150 000 visitors.

Engagement with local communities has always been an important part of the Laboratory's outreach activities. The International Day of Women and Girls in Science was again very successful: around 60 female scientists and engineers from CERN, EPFL, the University of Geneva and, for the first time, the Annecy Particle Physics Laboratory (LAPP), visited more than a hundred classrooms in the local region to talk to some 2700 pupils about their careers as women in science and engineering.

The Arts at CERN programme continued to celebrate a decade of fostering dialogue between art and physics. Twenty artists carried out residencies at CERN. The second call of the four-year Connect residency programme, organised in cooperation with the Swiss Arts Council, Pro Helvetia, was announced. The programme is a collaboration with scientific institutions around the world.

CERN SCIENCE GATEWAY – RAMPING UP TO THE OPENING

All the buildings of CERN's Science Gateway had been erected by the end of 2022, with work continuing inside the buildings, on the installation of solar panels on the roofs and on the landscaping.

The three exhibitions were completed and are ready to be installed in 2023. They include 42 hands-on exhibits, 43 objects, nine full-body experience exhibits, one fully operational proton accelerator, labels and texts in five languages and tactile content and audio descriptions for blind and visually impaired visitors. The five new artworks that will accompany the Exploring the Unknown exhibition were commissioned for production, in collaboration with the Arts at CERN programme.

Fourteen enquiry-based education workshops are being developed, for visitors aged five and upwards, addressing topics related to the science and technology of CERN, the process and nature of science, and careers in science.

Six different science shows designed to introduce scientific topics in a theatre-like style are in preparation. Some were performed in the Globe of Science and Innovation during 2022, as part of the public events programme.

Furniture, internal signage and audiovisual equipment for the auditorium were ordered with a view to equipping it as a prime venue for scientific, public and private events.

Fundraising efforts continued. A total amount of 87 MCHF has been secured, exclusively through external donations. CERN's Science Gateway is expected to welcome its first visitors in autumn 2023.

CERN Director-General, Fabiola Gianotti, with architect Renzo Piano and John Elkann, Chair of Stellantis, inspecting progress in the construction of CERN's Science Gateway, the new flagship project for education and outreach.
(CERN-PHOTO-202208-134-28)

CURATING SERENDIPITY AROUND FUTURE TECHNOLOGY FOR HEALTH

The second edition of Sparks! the serendipity forum at CERN took place in November. Dedicated to the theme of Future Technology for Health, the event again encompassed a discussion forum, with 50 participants (from CERN, academia, industry and policy) and a public event featuring 14 presentations by leading scientists in the field.

In addition, six new episodes of the Sparks! podcast were produced. Participants included a Nobel laureate and other leading voices in the fields of genetics, ethics, health tech, data distribution, artificial intelligence and international collaboration.

All the individual talks given during the public event are available on CERN's YouTube channel.

WORLDWIDE MEDIA INTEREST

During the year, 353 journalists visited CERN on 90 organised media visits, and just over 173 000 press clippings were registered from media outlets across CERN's Member States, Associate Member States and beyond. Media interest in CERN peaked in April, with the re-start of the LHC, and in July, with the Higgs boson discovery anniversary and start of Run 3 physics. The CERN Council's resolutions in response to the military invasion of Ukraine by Russia (page 13) also generated high media interest.

Media visits by journalists from CERN's Member States sustain interest in and support for CERN. An online national media visit provided a tailor-made programme for 17 Finnish journalists from 14 media outlets.

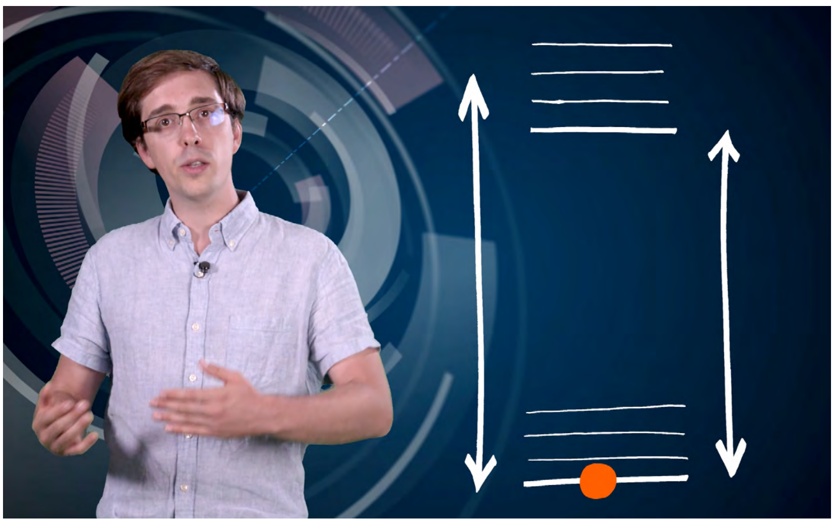
CONSOLIDATING CERN'S DIGITAL PRESENCE

CERN's strong digital presence continued in 2022, with approximately 5 million visitors to the main website (extrapolated data, due to the cookie policy adopted in 2021).

A hundred news stories about the Laboratory's activities were published on CERN's home website for the general public. News of physics results accounted for around 30% of these publications.

CERN's presence on social media generated 134 million views and high levels of engagement, in particular during the Higgs boson discovery anniversary and LHC Run 3 campaign: followers across all CERN channels increased by 230 000.

The CERN Courier magazine continued to reach around 100 000 readers, with just over 300 000 unique visitors to cerncourier.com. As part of the series launched the previous year, the CERN Courier hosted four webinars focusing on LHC technology, which attracted approximately 1000 participants.



The CERN-Solvay education programme aims to trigger and foster interest in science, technology, engineering and mathematics (STEM) and in STEM careers among high-school students.

EMPOWERING TEACHERS AND STUDENTS

CERN's on-site teacher programmes resumed and more than 550 teachers from 50 countries took part in the 24 programmes that were run in the second half of 2022. In parallel, online teacher programmes reached a further 1100 teachers, thus sustaining the crucial relationship with teacher communities across the globe.

S'Cool LAB activities gave 4500 students and teachers the opportunity to experience first hand the cutting-edge research being carried out at CERN. In addition, the S'Cool LAB team continued to organise live and interactive online science shows, with a total of 830 participants in 13 shows.

High-School Student Internship Programmes for Italy and Serbia took place, completing this programme. The Beamline for Schools competition returned to CERN, after two years at DESY in Germany. Two teams, from Spain and Egypt, conducted their winning proposals at CERN, with a third team from France at DESY. Once again, participation in this competition broke records, with proposals from 304 teams representing 71 countries.

CERN and the Belgian science company Solvay launched a three-year programme combining online and on-site learning, as part of the Science Gateway education portfolio. Short videos featuring simple hands-on experiments to be done at home or in the classroom, and longer videos discussing wider scientific topics connected to CERN's research were launched on CERN's social media channels and on a dedicated website. The online course videos reached 6500 unique viewers on CERN's YouTube channel.

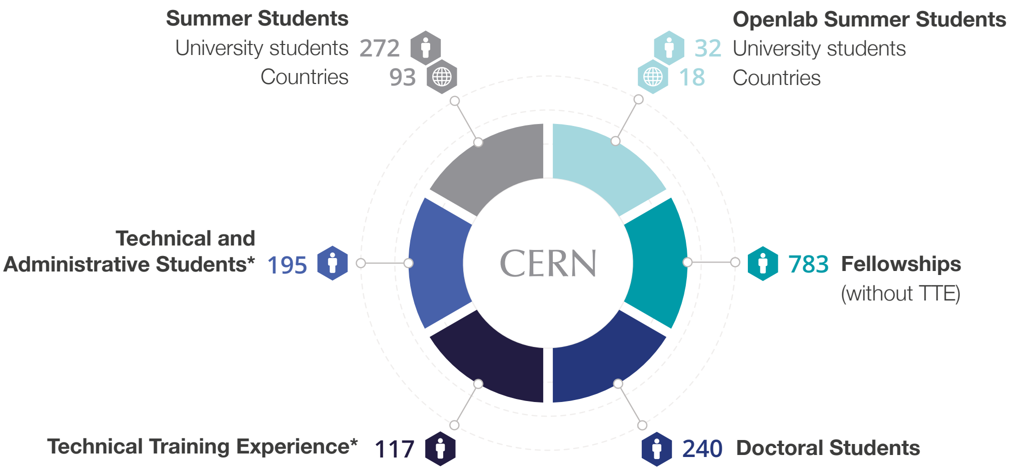
TRAINING YOUNG RESEARCHERS

CERN offers a unique learning environment for students and young professionals, providing them with excellent technical skills and international experience and making them highly qualified for careers in industry, business and academia in CERN's Member and Associate Member States. In 2022, some 900 fellows and more than 450 doctoral, technical and administrative students, 70 trainees and 220 short-term interns all took part in a large range of opportunities to work and learn. A dedicated initiative called Science for Ukraine was launched in March 2022, and five Ukrainian nationals joined CERN as students and fellows on earmarked positions.

Moreover, CERN welcomed more than 300 summer students from over 90 countries to its sites; around 30 of them, from 19 countries, attended the Openlab Summer Student Programme. Ukrainian summer students who were unable to come to CERN benefited from a comprehensive online version of this key programme.

PARTICIPATION IN THE BEAMLINE FOR SCHOOLS COMPETITION BROKE RECORDS, WITH PROPOSALS FROM 304 TEAMS REPRESENTING 71 COUNTRIES.

Training programmes at CERN



* as of 31.12.2022

CERN offers a wide range of scientific and technical training opportunities in an international setting. As well as working on cutting-edge scientific and technological projects, students attend a special series of lectures and visits.

A SAFE AND SUSTAINABLE RESEARCH ENVIRONMENT

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

ENVIRONMENTALLY RESPONSIBLE RESEARCH

During the year, CERN conducted a communication campaign dedicated to highlighting its various efforts to protect the environment and raise awareness about environmental issues. The campaign featured a series of articles, infographics and events.

A two-day “CERN and the Environment” workshop organised by the CERN Environmental Protection Steering Board (CEPS) was held in October and featured presentations and discussions spanning various topics, including energy, research on environmentally friendly coolants and detector gases, water, the local environment, mobility, travel and food.

EFFECTIVE ENERGY MANAGEMENT: ISO 50001

As part of CERN’s commitment to managing energy responsibly, the Organization sought ISO 50001 certification. ISO 50001 is the international standard that specifies the requirement for systems and processes to continuously improve energy performance. It requires the setting-up and subsequent monitoring and enhancement of an energy management system. CERN published its first Energy Policy in October 2022. The Policy’s key objectives are to keep the amount of energy required for CERN’s activities to a minimum, improve energy efficiency and recover waste energy. In addition, in the light of the worldwide energy crisis, CERN has developed operational responses to specific energy shortage scenarios, including reduced accelerator operation schedules and extended year-end technical stops, as well as various energy-saving measures for the campus.

Announcement poster for the CERN and environment workshop, 12–13 October 2022.

TRAINING FOR SAFETY

The relaxation of COVID-19 related measures meant that an increasing number of safety courses could resume in the classroom format in 2022. This was notably the case for the two programmes of the first-aid training scheme, which aims to train several hundred emergency first responders each year as well as advanced first aiders (SST*).

114 000 e-learning safety courses followed.
1040 classroom safety courses delivered to
4990 people.
4600 service desk tickets answered.

* SST: Sauveteur secouriste du travail (workplace first-aider)

OPTIMISING CERN'S HSE OPERATIONAL RESPONSE

May 2022 saw the official launch of the HSE Operational Response (HOR) project, which will run until 2025. Its objective is to design a clear and effective framework for the services of the Occupational Health and Safety and Environmental Protection (HSE) unit, including comprehensive means of communication with internal and external stakeholders. It will be implemented through thorough mapping of the HOR, enhanced definition of the respective roles of HSE members and stakeholders, the adjustment and broad communication of operational processes and better integrated deliverables (document types, information system). The project covers many different aspects: safety risks and emergency situations identification; medical and personal assistance; emergency response to protect environment and organizational assets; safety inspections and safety reviews.

MANAGEMENT OF COVID-19

2022 was a pivotal year in the management of COVID-19. CERN moved from its most severe COVID-19 level (red) at the beginning of the year to a substantial easing of measures (green level) in the spring. Measures were adapted as the health situation and the regulatory context evolved. The management of positive cases was successfully automated in the summer, allowing the Medical Service to focus on the most serious cases.

HOW THE AUTOPSY OF A LHC BEAM DUMP CORE IS HELPING TO PREPARE FOR LS3 AND BEYOND

The LHC beam dump core autopsy, a multidisciplinary project undertaken during LS2 and completed in 2022, centred on the unprecedented action of dismantling the two LHC beam dumps at Point 6 in preparation for an upgrade for Run 3.

The specific radiation protection challenges of the project were considerable, owing to high residual doses, contamination risks and uncertainties around the state of the inner material. The corresponding infrastructure had to be designed and developed using in-house expertise and involved several sections of CERN's radiation protection group. These sections contributed to the planning of all stages of the operation, from state-of-the-art simulations to predict the dose rate and activation levels to defining a dedicated worksite and the necessary protection measures for the people working there.

This long and complex process allowed teams to gather crucial information that is needed to design future generations of beam dumps for the HL-LHC era and to optimise dismantling procedures for LS3 and beyond.

THE REVIEW OF THE "FAIR SHARE" PRINCIPLE FOR RADIOACTIVE WASTE

The possibility to eliminate radioactive waste is critical for the Organization. A tripartite agreement on radiation safety and radiation protection signed with the Host States in 2010 allows CERN to eliminate radioactive waste in both countries using the most technically and economically advantageous pathways. However, the agreement requires an equitable distribution of the waste between the two countries, known as the "fair share principle". The implementation of this principle was laid down in a decision taken in 2012 that reflected CERN's limited experience of radioactive waste elimination at that time. In 2022, the decision was replaced by a new one reflecting the experience gained and lessons learnt in the previous ten years. It will allow CERN to eliminate its most radioactive waste to the future deep geological repository in Switzerland while using the full capacity of the French pathways for low- and medium- level radioactive waste.

This revised decision also facilitates the monitoring of the "fair share principle" by introducing three indicators that allow the share of eliminated waste to be measured and compared, namely: the volume eliminated, the radiotoxicity of the waste and the elimination costs.

Radioactive Waste Treatment Centre (RWTC) containment enclosure. (CERN-PHOTO-202104-045-12)

BUILDING THE FUTURE

In 2022, all eyes were on the LHC. The collider delighted physicists at CERN and all over the world by producing new physics data for the first time in several years, under optimum conditions. Behind the scenes, part of the CERN community was hard at work building the Laboratory's future and the future of particle physics from the 2020s to the end of the 21st century.

The surface buildings at Point 1 of the HL-LHC, one of two new CERN sites that were completed in 2022. Two identical buildings have been constructed at Point 5, next to the CMS experiment. (CERN-PHOTO-202210-166-12)

The HL-LHC site at Point 5, with buildings designed to limit the site's environmental impact. *(OPEN-PHO-ACCEL-2022-029-2)*

TWO MAIN FUTURE DEVELOPMENTS

LHC operation, the High-Luminosity LHC (HL-LHC), the feasibility study for a Future Circular Collider, research programmes studying neutrinos, antimatter and heavy ions – the list goes on... The vast number of projects under way at CERN can sometimes seem surprising, overwhelming even. But none of these has come about by chance. All of CERN's major projects are governed by a landmark document that lays the foundations for the future of particle physics in Europe: the European Strategy for Particle Physics. This document, the latest update of which was adopted following a comprehensive process of scientific deliberations ending in 2020, sketches out CERN's medium- to long-term future. The construction and operation of the HL-LHC by 2029 is the first step. This fundamental upgrade of the LHC, designed to produce a ten-fold increase in the number of collisions occurring in the collider, involves upgrading not only the machine's components but also a number of the four large detectors' systems. In 2022, the project passed several important milestones, chiefly in engineering and civil engineering. Looking beyond the HL-LHC, the European Strategy for Particle Physics recommends investigating the possibility of building a future circular accelerator on a significantly larger scale than the LHC. This accelerator, construction of which could begin as early as the 2030s, would initially be used as an electron–positron collider serving as a "Higgs factory". In 2022, work continued on the technical and financial feasibility study for this future accelerator, providing more details of the location where the machine would be built.

Although CERN's research and development efforts in 2022 were focused on these two main areas of future research, as laid down by the European Strategy, the Laboratory maintained its role as a particle physics catalyst by lending its support to particle physics experiments and facilities outside Europe and continuing to develop cutting-edge accelerator, detector and information technologies.

In 2015, CERN released its first Masterplan for urban planning, giving a glimpse of potential developments across its two main sites, Meyrin in Switzerland and Prévessin in France, during the period until 2030. As this date is getting nearer, the document was revised to include a look forward for another decade, namely to 2040 and the end of the LHC. This 2040 Masterplan was published in December 2021, and integrates all satellite sites and CERN's unfenced land, taking into account possible developments that will be necessary whatever shape the post-LHC era at CERN may take.

The Masterplan is intended to inform and inspire a reasoned and meaningful dialogue about the management and updating of the CERN site. It is an overarching report that embodies CERN's development priorities, translating the scientific goals set out in the 2020 update of the European Strategy for Particles Physics into an urban planning process that integrates major themes such as the environment, mobility, urbanism, territory and landscape.

The Masterplan outlines CERN's overall strategy and will be used in a variety of practical ways, such as to improve delivery of CERN's environmental objectives, to connect spatial and infrastructure planning with investment decisions, to plan better services for the Organization and its scientific community, and prepare for the future taking into account the needs of the Laboratory along with those of our neighbours.

THE HIGH-LUMINOSITY LHC

2022 was a pivotal year for the High-Luminosity LHC (HL-LHC) project, which aims to increase the LHC's integrated luminosity so that in 12 years of operation it will produce 10 times more collisions than the total produced by the end of 2025. Milestones reached during the year include the validation of technology vital to the functioning of the future accelerator's components, the series production of new equipment and, to crown it all, the completion of the civil-engineering work.

Completion of the civil-engineering work

This work was completed on schedule with the delivery of the final service buildings in September 2022. CERN now boasts two new sites that will accommodate the state-of-the-art equipment required to operate the future machine: Point 1, close to the site of the ATLAS experiment; and Point 5, next to the CMS experiment. Each site features an underground structure comprising an 80-metre-deep shaft, a service cavern and several tunnels that will house equipment such as power converters and radiofrequency equipment. The underground infrastructures are now connected to the surface buildings, which were built between January and September 2022. These surface buildings will house the cycle compressors, cryogenic cooling systems and other services required to operate the future accelerator.

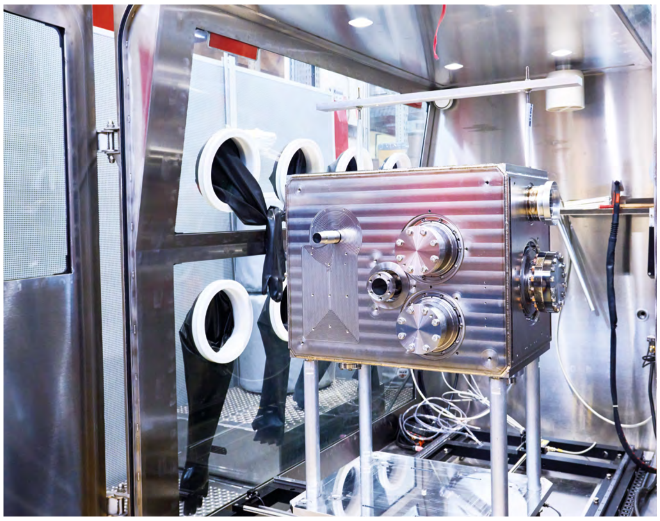
Magnet developments

The superconducting magnets are the keystone of the project. Several types are being designed, prototyped and produced for the HL-LHC simultaneously, each of them playing a vital role in the carefully coordinated arrangement of magnets in the accelerator. The most important magnets in the programme are the powerful niobium–tin quadrupole magnets known as triplets, which are designed to focus the beams circulating in the HL-LHC before they are made to cross in the ATLAS and CMS experiments. In 2022, during a test carried out at CERN, a prototype of the long version of this magnet (7.2 metres) reached nominal current with an operational margin corresponding to a coil peak field of 11.5 T at 1.9 K. This was the first time a magnet of this length had achieved the operating conditions required for use in the HL-LHC. In this respect, the results are very encouraging. A partially re-designed second series magnet will nevertheless be tested in 2023 with a view to reducing the coil limitations observed at 4.5 K, limitations that do not however compromise the magnet's effectiveness in the HL-LHC. Meanwhile, production of the shorter 4.2-metre version of the triplets continued in the USA. Eleven magnets have now been produced and tested by the Accelerator Upgrade Project (AUP) team working with CERN for the HL-LHC. One of these magnets underwent an endurance test, completed in spring, which confirmed the viability of niobium-tin technology in accelerators. The magnet remained intact after a series of five thermal cycles, during which it was subjected to temperature variations of 300 °C and to 50 quenches. In addition to the triplets, all of the new types of magnets developed for the HL-LHC have been validated by prototypes, and series production by the industrial partners of the institutions concerned has begun. These include the D1 beam separation dipoles being constructed and tested at the KEK laboratory in Japan and their D2 counterparts being built at the INFN in Italy and tested at CERN, plus the orbit correction magnets tested at CERN. The series production of the orbit correction magnets began in Spain in 2022 under the responsibility of CIEMAT.

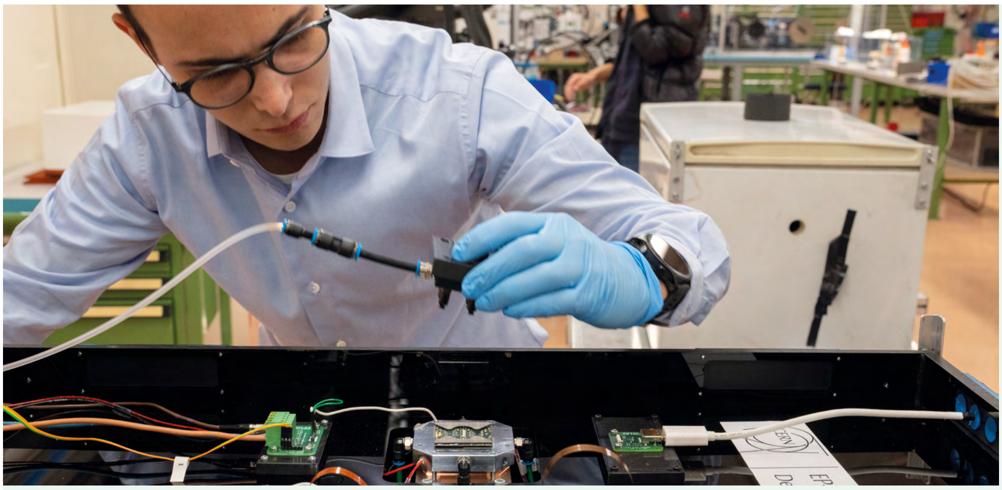
The crab cavities

Another pillar of the HL-LHC programme, the development of the crab cavities, continued in 2022. It is in these cavities that the bunches of particles will be precisely tilted to bring the two colliding bunches into exactly the same location, thereby increasing the luminosity at the collision point by the maximum possible. Two types of crab cavity are being developed: a radiofrequency dipole (RFD) crab cavity and

MQXFBP3, a 7.2-metre-long niobium-tin magnet, reached nominal current for the first time at a temperature of 1.9 K in autumn 2022.
(CERN-HOMEWEB-PHO-2023-013-1)



A double-quarter wave (DQW) crab cavity embedded in its helium vessel. The cavity will be tested and connected to its "twin" before installation in the first DQW cryomodule.
(CERN-PHOTO-202302-056-3)



Construction of the future inner tracking system for the ATLAS detector in October 2022. *(CERN-PHOTO-202210-174-50)*

a double-quarter wave (DQW) crab cavity. Both types were validated by CERN and its industrial partners in 2022. Delivery of the first RFD crab cavity cryomodules is scheduled for summer 2023.

Lastly, excellent progress was made in installing the inner triplet test string (HL-LHC IT string). Over the next few years, this new metal structure, due to be interconnected in the SM18 test facility during 2023, will test no fewer than 50 cryo-assemblies and superconducting transfer lines for the HL-LHC.

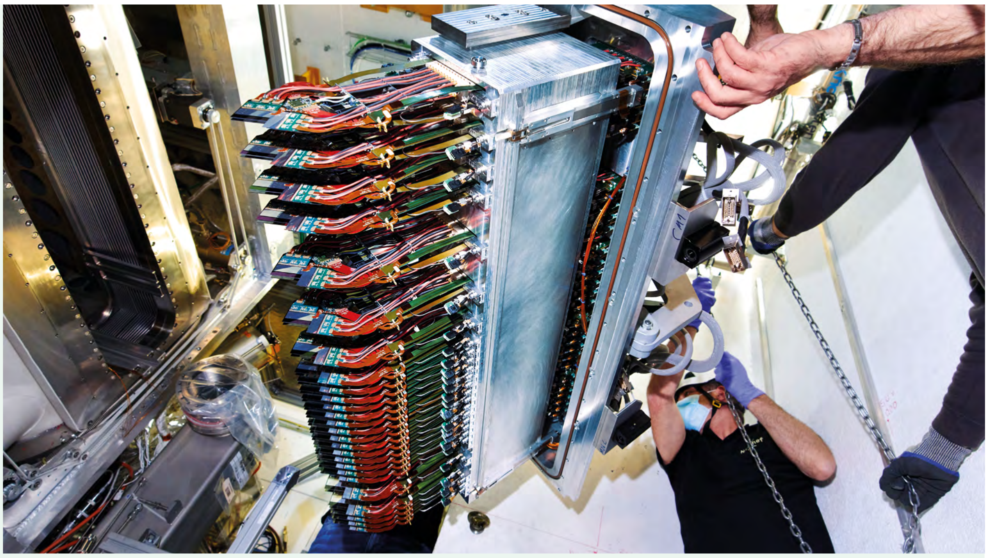
THE LHC EXPERIMENTS

ALICE

As all the systems in the ALICE detector were installed before the end of 2021, the experiment was able to start using the LHC beam as soon as the first test collisions were recorded in the spring of 2022. No major incidents occurred during the start-up and calibration of ALICE. All of the detector's sub-systems were tested with proton beams. The collaboration was able to begin analysis of the proton collisions generated during Run 3, but ALICE's core research programme studying lead-ion collisions will not begin until 2023. This is due to the postponement of the physics campaign of lead–lead collisions in view of the energy crisis. At the same time, the collaboration continued the research and development work required to enable the detector's systems to record luminosity. Significant progress was made with the ITS3, the detector's future inner tracking system. The system's prototype sensors passed the radiation tests, validating their design. The same outcome was achieved for FoCal, a small-angle high-granularity electromagnetic calorimeter. The prototype sensors were validated following a testing campaign in the PS and the SPS. Lastly, the collaboration noted the positive opinion expressed by the LHC Experiments Committee regarding ALICE 3, the completely refurbished detector that the collaboration plans for the fifth and subsequent runs. Following this opinion, the collaboration started looking into the configuration of the new detector and began research on the components, including a new time-of-flight system.

ATLAS

All of the systems of the ATLAS detector were in place by the beginning of 2022, enabling the collaboration to make use of the first collisions of the year in the LHC. The detector was thus able to harvest data from even the April beam splash events (collisions between the proton beam and the beam dumps), which allowed the collaboration to calibrate and commission new components of the detector, including the electronic trigger system for the calorimeters, the new readout systems (including the FELIX system and the ROD software) and more significantly the two new small wheels, major sub-detectors that enable ATLAS to make a finer muon selection. On another note, research and development for the second phase of detector improvement projects proceeded satisfactorily. This is the major upgrade programme to convert ATLAS into a high-luminosity detector. The trigger systems upgrade project made good progress (with validation of the first models of circuit boards), as did the data acquisition project with the completion of the prototype memory card specifications. The prototype was in production by the end of 2022. Inside the detector, the inner tracking system will be completely redesigned. The projects to develop the pixels for this sub-detector, along with the sensors and modules, had all entered a pre-production phase by the end of 2022. The future ATLAS detector will also feature a high-granularity timing detector (HGTD), the ASIC readout chips of which were designed in 2022. The project to develop a second-generation liquid argon (LAr) calorimeter reached an important milestone in 2022. The first components (the electronic trigger system and some of the processors), installed in the LAr calorimeter currently operating, were shown to be both effective and resilient. There was success in the tile calorimeter project too, with 11 of the 12 batches of mini mechanical drawers being produced before the end of 2022. Lastly, the muon system upgrade made progress with construction of the new sMDT (small monitored drift tubes), the addition of new resistive plate chambers and the upgrade of the detector's electronics system.



Installation of the LHCb VELO detector completed the 2022 LHC sub-detector installation programme.
(CERN-PHOTO-202205-078-13)

CMS

The first phase of upgrades to prepare the CMS experiment for high luminosity, namely the improvements to the sub-detectors carried out before and during the second long shutdown, was completed in early 2022 with the installation and commissioning of the last detector components. Over a particularly intense commissioning period, all of the sub-systems were tested and calibrated: the tracker, electromagnetic calorimeter (ECAL), hadron calorimeter (HCAL), muon system, the BRIL (beam radiation, instrumentation and luminosity) sub-detectors, and trigger system. All of the detector's systems were thus able to harvest data ahead of – and again during – the first year of the current run (Run 3). The early stage of this run also provided an opportunity to stress test some of the systems of the Phase 2 upgrade of CMS, most of which will be implemented during the third long shutdown (LS3). The first gas electron multiplier (GEM) chambers built for the Phase 2 upgrade were tested with the LHC beams in 2022 and were shown to be effective. The other Phase 2 upgrade projects made significant progress in 2022. The low-density sensors of the future high-granularity calorimeter (HGCAL) entered the pre-production phase, prototyping of several types of ASIC readout chips progressed, and five module assembly centres were approved for the production of pre-series modules. Production of the sensors and ASIC chips for the future outer tracker continued and several metal structures for the sub-detector reached the pre-production phase. Meanwhile, the ECAL teams reached agreement on an ASIC chip model, and a "supermodule" for the barrel calorimeter upgrade, featuring completely new electronics, demonstrated its validity during a test. Lastly, the programme to define the specifications of the 3D sensors for the inner tracking system made progress and prototypes of the computational mechanics components were designed. Production is due to begin in 2023.

LHCb

The upgrade schedule for the LHCb detector differs considerably from that of the LHC's other large experiments. Most of the major modifications required to prepare LHCb for high luminosity were carried out during the second long shutdown and were therefore completed by 2022. The fact that the vast majority of the detector's sub-systems had to be built and installed, coupled with COVID-19-induced delays, resulted in the installation work being completed somewhat behind schedule. The second half of the VELO (vertex locator) sub-detector, a key component of LHCb's arsenal, was installed in May 2022, completing the installation programme for the year. The VELO was aligned and "closed" in October 2022, demonstrating that it was in full working order. The last piece of the puzzle, the UT (upstream tracker) detector, will be installed in LHCb in 2023. While the installation work was going on, the experiment's different sub-detectors were commissioned over a period of several months, as was the new two-level trigger system, which features a combination of conventional central processing units (CPUs) and graphics processing units (GPUs). Following this upgrade, LHCb is now able to record collisions 10 times faster than previously. Although the detector has already been almost completely refurbished, additional upgrades are being prepared for the upcoming operation phases. The LHCb Upgrade II Framework Technical Design Report, which sets out the experiment's future objectives, was approved by the LHC Experiments Committee at the beginning of 2022. This sent an encouraging signal, giving additional impetus to the research and development work being carried out to improve the experiment's sub-detectors.

Officials from the French regions of Ain and Haute-Savoie visiting CERN in September 2022 to learn more about the feasibility study for the FCC project. (CERN-PHOTO-202209-151-6)

THE FUTURE CIRCULAR COLLIDER (FCC)

What kind of collider?

The 2020 update of the European Strategy for Particle Physics gave the green light for a study of the feasibility of a Future Circular Collider (FCC), which continued throughout 2022. The study is due to report its conclusions in 2025. The FCC would initially be used as an electron–positron collider to precisely describe the properties of the Higgs boson and also those of the W and Z bosons and the top quark. The accelerator would then be converted into a hadron collider reaching unprecedented energies. The data harvested in the new energy regions explored by a collider of this kind could shine a light on some of the mysteries of particle physics. The task of the FCC feasibility study is to analyse all the factors that might influence the accelerator's construction as well as the machine's potential impact on both the scientific landscape and the region. In 2022, the feasibility study made significant progress with respect to the schedule and the placement of the future collider.

A new tunnel...

The placement of the FCC has been changed slightly compared to the initial proposal put forward in 2021. The updated proposal, which takes into account all of the region's cartographic and geological data, describes a ring 90.7 km in circumference positioned so as to limit as far as possible any potential hazards. Fruitful discussions with the governments of the Host States and the local and regional authorities have helped this aspect of the project to take shape. 2022 also provided some interesting answers to the crucial question of how to re-use the materials produced when excavating a tunnel of this size. The projects selected by the Mining the Future competition organised by CERN have come up with several possible solutions ranging from using the excavated materials to make bricks to turning them into topsoil. Successfully re-using the excavated materials will boost the FCC's sustainability credentials as part of the circular economy.

… for a new machine

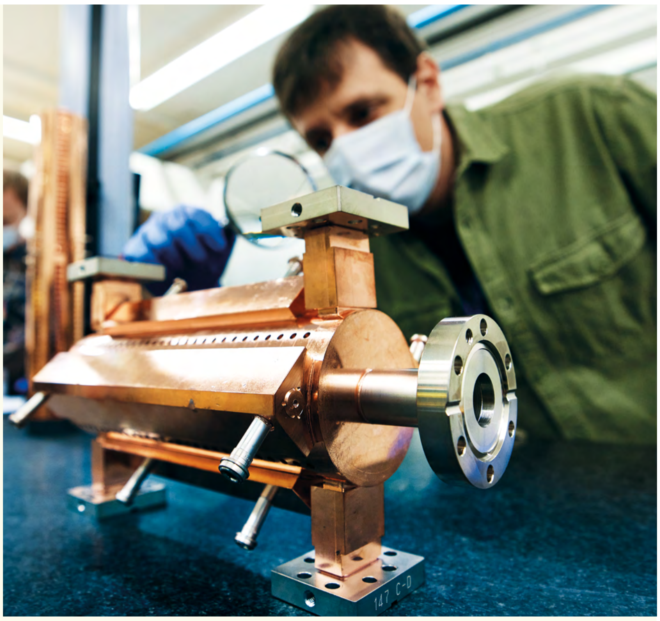
The success of the FCC will depend above all on the development of better and more cost-effective and energy-efficient accelerator technologies. To this end, the projects for the future electron–positron collider's optical systems have been adapted to the new placement model and an initial injector configuration has been developed. Meanwhile, the engineers working on the FCC study are proceeding with the design work for the future radiofrequency cavities, the accelerator's short sections and the beam dumps. And a new accelerator will of course require new detectors. A number of case studies have resulted in several prototype detector projects based on the LHC's detectors and also on the detector projects for linear accelerators.

The new horizons of physics

In 2022, a large number of studies, conferences and workshops helped the physics case of the FCC to progress and take shape. In addition to providing physicists with unrivalled precision in measuring the characteristics of the Higgs boson, it became apparent that the electron–positron collider would produce tau leptons and B mesons (particles that could potentially reveal flaws in the Standard Model) in unprecedented quantities. These studies and events – including the 2022 FCC Week in Paris – have helped bring together the physics community around a consolidated project, the advantages of which are becoming ever more apparent.

LINEAR COLLIDERS

Research and development in the key technologies for linear accelerators continued in 2022 to keep the electron–positron linear collider project CLIC in the wings as an alternative to the FCC. These technologies, being developed to reach very high acceleration gradients over limited distances, are already finding medical applications (page 34). X-band technology, which lies at the heart of the project, was used in accelerating structures in 2022 and the design work on X- and L-band klystrons (devices that provide power to accelerating cavities) made progress, with the first prototypes producing very promising results. Meanwhile, CERN, in coordination with its European partners, redefined its contributions to the ILC, an international linear collider project, in response to the release by the International Committee for Future Accelerators (ICFA) of its programme of work for the future collider covering the period 2023–2026.



A prototype of the CLIC accelerator on which FLASH radiotherapy technology is based. (CERN-PHOTO-202202-013-8)

NEUTRINO RESEARCH

CERN is contributing to research on the elusive neutrino, a particle shrouded in mystery, by participating in major projects in the USA and Japan. Its most important contribution in this field is ProtoDUNE, a prototype of the future DUNE (Deep Underground Neutrino Experiment) due to be built at the Long-Baseline Neutrino Facility (LBNF) in the USA. This installation comprises two prototype liquid argon neutrino detectors, a single-phase version and a dual-phase version with a layer of gaseous argon. In 2022, a new chapter of the preparations began

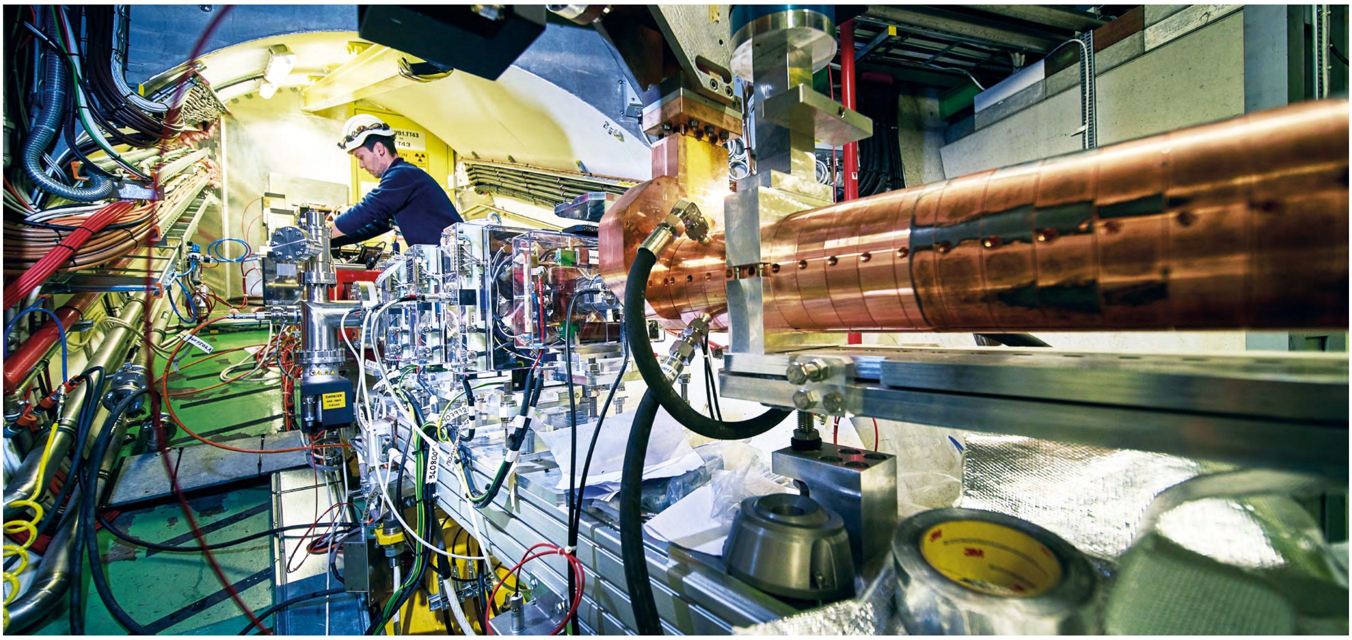
The ProtoDUNE single phase detector. (CERN-PHOTO-202108-105-1) with the start of the validation process for the final detector models. This will be followed by the start of the series production. Over the year, a new cryostat was instrumented and equipped with a vertical drift time projection chamber (TPC), the validity of which was demonstrated in 2021. CERN has also undertaken to deliver two cryostats to the LBNF. The first contracts were awarded in early 2022. Meanwhile, construction was completed of the Micromegas detectors and gas systems developed at CERN for the T2K experiment taking place at the KEK laboratory in Japan. Some initial equipment, including the super fine-grained detector (SuperFGD), has already been shipped to Japan.

PHYSICS BEYOND COLLIDERS

The Physics Beyond Colliders (PBC) programme, which has been under way since 2016, looks at ways of making use of CERN's installations for physics research projects that complement the goals of the main experiments in CERN's colliders programme. The North Area, CERN's largest experimentation area, is particularly well suited to these types of installations, which include numerous fixed-target experiments. In 2022, the PBC programme supported studies for new experiments in the North Area. Three projects – HIKE, SHADOWS and the BDF/SHiP installation – were presented to the SPS Committee in November 2022. A continuation of the NA62 experiment research programme, HIKE plans to study extremely rare kaon decays. SHADOWS and SHiP are designed to look for feebly interacting particles and hypothetical dark matter candidates and to study the physics of neutrinos. Studies have also continued in preparation for the installation of the Forward Physics Facility, which plans to accommodate a series of experiments that would look for weakly interacting particles downstream of an LHC interaction point. The design of the technical infrastructure has made progress and initial analyses of the muon flows generated by the collisions have been carried out to investigate radioprotection issues. In addition, a new international collaboration supported by the PBC programme was being formed at the end of 2022 to demonstrate the principle of crystal-assisted extraction of the secondary halo in the LHC. The experiment's layout and the specifications of the main components were finalised during the year. Lastly, an innovative arrangement of accelerator radiofrequency systems with barrier buckets, tested in 2022, combined with the new multi-turn extraction (MTE) system that has been operational for several years, led to a considerable reduction in losses during extraction from the PS of the beams used in the SPS fixed-target experiments.

AWAKE

The first phase of the second run of the AWAKE experiment concluded successfully in 2022. This experiment is studying the use of proton beams to generate plasma wakefields in a plasma cell. These plasma wakefields accelerate electron beams at acceleration gradients hundreds of times higher than in today's accelerators. This phase successfully "kick started", for the first time, the self-modulation of an entire bunch of protons, a technique that makes it possible to control and stabilise the plasma waves. Completing this crucial stage was an essential prerequisite for the success of the technology underpinning AWAKE. Lastly, the experiment's new plasma source was designed in 2022 and entered production by the end of the year. The installation of the plasma source in 2023 will constitute the next milestone for the experiment.



The AWAKE experiment at CERN. *(CERN-PHOTO-201711-284-12)*

CERN COUNCIL

Composition as of 31 December 2022

President of the Council: Professor E. Rabinovici (Israel)
Vice-Presidents: Professor K. Fountas (Greece), Professor E. Laenen (Netherlands)

MEMBER STATES

Austria
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Professor D. Ryckbosch

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Professor D. Tonev

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H.E. Mr D. Zlatanović

Slovakia
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Ms. I. Figueroa Rojas

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Professor K. Jon-And

Switzerland
Professor F. Canelli
Dr G. Haefliger

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Dr S. Haque
Professor M. Thomson

ASSOCIATE MEMBER STATES IN THE PRE-STAGE TO MEMBERSHIP

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Professor P. Razis

Estonia
Dr K. Otto
Dr M. Kadastik

Slovenia
Professor D. Zavrtanik
Dr M. Slavinec

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Professor A. Mohanty

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Dr D. Stepanovs

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Mr G. Jaškas

Pakistan
H.E. Mr K. Hashmi
Dr R.A. Raza Anwar

Türkiye
Professor A. Baliçki
Ms B. Yüksel

Ukraine
Professor B. Grinyov
Dr A. Zagorodniy

OBSERVERS

European Union, Japan, JINR*, Russian Federation**, UNESCO, United States of America

* status suspended as from 25 March 2022
**status suspended as from 8 March 2022

COMMITTEES OF THE COUNCIL

SCIENTIFIC POLICY COMMITTEE

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(Switzerland)

Members
Professor H. Aihara
Professor C. Biscari
Professor K. Blaum
Professor R. Cousins
Professor N. Glover
Professor B. Heinemann
Professor P. Hernandez
Professor G. Isidori
Professor M. Lindroos
Professor F. Maltoni
Professor J. Monroe
Professor H. Montgomery
Professor K. Scholberg
Professor M.-H. Schune
Professor J.P. Wessels
Professor A. Yamamoto

Ex-officio members

Chair of the ISOLDE and Neutron Time-of-Flight Experiments Committee
Professor M. Pfützner

Chair of the SPS and PS Experiments Committee
Professor J. Nash

Chair of the LHC Experiments Committee
Professor F. Simon

Chair of the CERN Machine Advisory Committee
Professor M. Seidel

Chair of the Scientific Advisory Committee for the FCC Feasibility Study
Professor A. Parker

Chair of the European Committee for Future Accelerators
Professor K. Jakobs

Also present

President of the Council
Professor E. Rabinovici
(Israel)

Chair of the Finance Committee
Dr U. Dosselli
(Italy)

Director-General
Dr F. Gianotti

FINANCE COMMITTEE

Chair
Dr U. Dosselli
(Italy)

Members
One or more representatives from each Member or Associate Member State

TREF (TRIPARTITE EMPLOYMENT CONDITIONS FORUM)

Chair
Professor B. Åsman
(Sweden)

Members
One representative from each Member State

AUDIT COMMITTEE

Chair
Dr U. Dosselli
(Italy)

Members
At least one Council delegate, appointed by the Council
At least two external experts, appointed by the Council

INTERNAL ORGANISATION

Director-General	***Fabiola Gianotti***
DG unit services (DG): Translation, Minutes and Council Support, Internal Audit, Legal Service	
Occupational Health & Safety and Environmental Protection unit (HSE)	Benoît Delille
Director for Accelerators and Technology	***Mike Lamont***
Deputy Director for Accelerators and Technology	Malika Meddahi
Beams (BE)	Rhodri Jones
Engineering (EN)	Katy Foraz
Accelerator Systems (SY)	Brennan Goddard
Technology (TE)	José Miguel Jiménez
Director for Finance and Human Resources	***Raphaël Bello***
Finance and Administrative Processes (FAP)	Florian Sonnemann
Human Resources (HR)	James Purvis
Industry, Procurement and Knowledge Transfer (IPT)	Christopher Hartley
Site and Civil Engineering (SCE)	Mar Capeans
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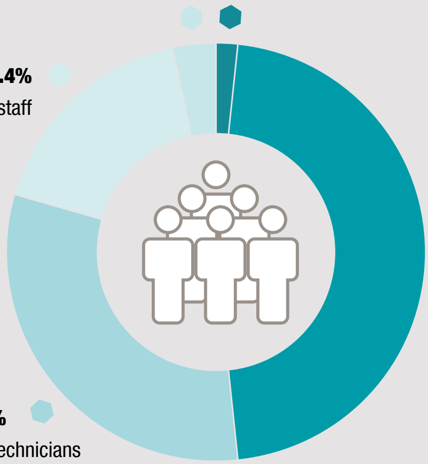
Diplomatic and Stakeholder Relations (IR-DS)	Charlotte Warakaulle
Education, Communications and Outreach (IR-ECO)	Ana Godinho
Director for Research and Computing	***Joachim Mnich***
Deputy Director for Research and Computing	Pippa Wells
Scientific Information Service (RCS-SIS)	
Experimental Physics (EP)	Manfred Krammer
Information Technology (IT)	Enrica Porcari
Theoretical Physics (TH)	Gian Giudice
Project and Study Management	
Advanced Wakefield Experiment (AWAKE)	Edda Gschwendtner
CERN Neutrino Platform	Francesco Lanni
Future Circular Collider (FCC) Feasibility Study	Michael Benedikt
High-Field Magnets R&D Programme (HFM)	Andrzej Siemko
High-Luminosity LHC (HL-LHC)	Oliver Bruning
Linear Collider Studies (CLIC and LCS)	Steinar Stapnes
Muon Colliders	Daniel Schulte
Physics Beyond Colliders (PBC)	Gianluigi Arduini
Science Gateway	Patrick Geeraert
Superconducting RF	Walter Venturini
Worldwide LHC Computing Grid (WLCG)	Simone Campana

CERN IN FIGURES

CERN STAFF

Total: 2658 people



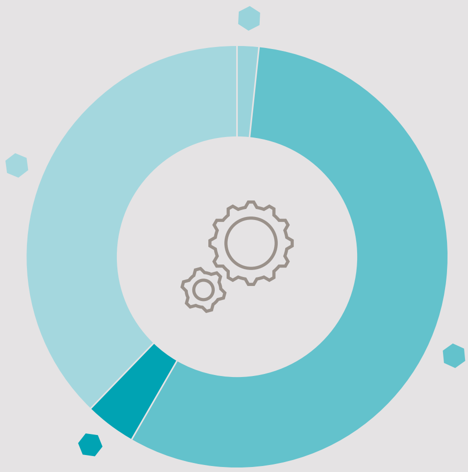
EVOLUTION OF STAFF MEMBERS

2018	2667
2019	2660
2020	2635
2021	2676
2022	2658

In addition to staff members, in 2022 CERN employed 900 fellows (including 117 TTE technicians), trained 1047 students and hosted 976 associates. CERN's infrastructure and service were used by a large scientific community of 11 860 users in 2022.

CERN EXPENSES

Total expenses: 1224.9 MCHF



In 2022, more than 32% 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.

CERN
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Sixty-eighth 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 2021–2022 is available at:
https://e-publishing.cern.ch/index.php/CERN_Environment_Report
The 2022 Knowledge Transfer annual report is available at:
http://kt.cern/annual-report
The 2022 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/search-and-read/online-resources/annual-lists-cern-authored-publications
A glossary of useful terms is available at: https://cern.ch/go/glossary

Images:
From top to bottom: Club de Física Enrico Fermi (Vigo, Spain), Elsewedy Technical Academy (Cairo, Egypt), and École du Sacré-Coeur (Reims, France): p. 8 (top)
Pallanuotovivo/Wikimedia Commons: p. 13 (top)
APS/P. G. Thirolf *et al.*, Ann. Phys. 531, 1800381 (2019): p. 21 (top)
Airbus: p. 33 (middle left)
S. Corvaja, ESA: p. 33 (bottom right)
Big Science for Business Forum: p. 34 (bottom)
Ian Purnell: p. 37 (top left)
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