Annual Report 2023

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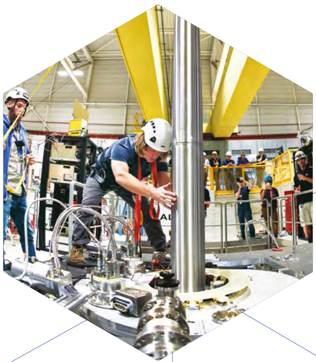
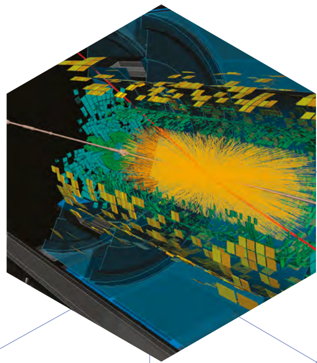
CERN, the European Organization for Nuclear Research, is the world's leading laboratory for particle physics. It provides a unique range of particle-accelerator facilities enabling research at the forefront of human knowledge. Its business is fundamental physics, finding out what the Universe is made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

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





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MESSAGE FROM THE PRESIDENT OF THE COUNCIL

In 2023, the CERN Council saw such a wealth and breadth of achievements that only a small fraction can be highlighted here. What is clear is that the year demonstrated the joint commitment of all Member States to the excellence of the scientific programme at CERN and to the Organization's long-term future.

The strong head and side winds that began with the emergence of COVID-19 and continued with the war in Europe and the ensuing inflation and rise in energy costs had significant financial implications for the Organization. These were largely mitigated thanks to an impressive joint effort by the Council, Management and Staff. The Council agreed to add to the present annual financial contributions an extra contribution of 74.8 million Swiss francs, with members also agreeing to share among them Ukraine's annual contribution to CERN. The Management curtailed CERN's programmes and the Staff voluntarily reduced their salary for one year. All efforts were made to minimise the impact of these measures on CERN's scientific programme.

CERN's flagship accelerator, the Large Hadron Collider (LHC), has worked so well to date that we can often forget the narrow margins within which it operates. We were reminded of this during the summer and the Council greatly appreciated the hard work of the CERN teams for their ingenuity in resolving the technical issues of this complex, cutting-edge machine. The Council also witnessed the impressive progress of CERN's High-Luminosity LHC upgrade. Highlights included the successful tests of the magnets using niobium-tin superconductors and that magnet production is now well underway.

The Council also continued the core business, in particular the future scientific programme of CERN. In late 2023, the CERN Management submitted the mid-term Future Circular Collider (FCC) Feasibility Study report and the reports of its Cost Review Panel and Scientific Advisory Committee to the Council's Finance Committee and Scientific Policy Committee, paving the way to presenting them to the Council in early 2024. The detailed reports dealt with an impressive panorama of aspects, from scientific and technological to environmental and sustainability. The latter two strongly relate to the relations with and policies of the host countries and their diverse communities, and the visit of the Presidents of both countries in November also helped to lay the groundwork for CERN's future.

One of the biggest challenges in planning and building future particle physics facilities is maintaining high-quality expertise, enthusiasm and optimism for long periods in the face of what seem like insurmountable hurdles. The decisions to be taken for a facility such as the proposed FCC, which would enter operation in the 2040s and continue for as long as 50 years, pivot on the support and enthusiasm of those who are beginning their careers today. I was therefore pleased to attend a meeting on "Future Colliders for Early-Career Researchers" held at CERN in September and to witness the enthusiasm and engagement of the young people present. Education is an essential pillar of CERN, and the newly inaugurated Science Gateway will now play an important role in inspiring a new generation of scientists.

Finally, it was a pleasure to work together with the two Vice-Presidents of the Council, Konstantinos Fountas and Eric Laenen. I was glad to welcome the new Chair of the Scientific Policy Committee, Hugh Montgomery, and the new Chair of the Finance Committee, Laurent Salzarulo. I would like to thank the outgoing Chair of the Pension Fund Governing Board, Ossi Malmberg, the outgoing Chair of the European Committee for Future Accelerators (ECFA), Karl Jakobs, and the outgoing Chair of TREF (Tripartite Employment Conditions Forum), Barbro Åsman, for their outstanding commitment and dedication. I am certain that the Council will benefit in 2024 from the experience gained in 2023, in facing the challenging issues ahead and reaching consensus in the best interests of the Organization.

Eliezer Rabinovici

E. Rabinovici

MESSAGE FROM THE DIRECTOR-GENERAL

In 2023, the LHC experiments provided a remarkable illustration of the wealth of precision results that particle physics is continuing to harvest. The vast amounts of data that the LHC has been supplying ever since it began operation, the superb performance of the detectors and innovative data analysis techniques enabled the experiments to obtain results that would have been hard to imagine just a few years ago. Examples of these results include measurements of unrivalled precision of the mass of the top quark and of the Higgs boson in several decay channels, determination of the intensity of the strong force at the Z-boson mass scale with an uncertainty of less than 1%, new ultra-precise measurements of the different behaviour of matter and antimatter and the observation of key features of quark–gluon plasma, to name but a few.

In addition to the four large LHC experiments, the diversity of CERN's research is evident in many other results, such as the first observation of neutrinos produced in a particle collider and the measurement of the effects of gravity on antimatter.

In 2023, the LHC was hampered by some technical issues, which resulted in a shorter proton run. The teams involved demonstrated remarkable responsiveness and creativity in getting the accelerator up and running again. The year ended with the first lead-ion run for five years, which allowed ALICE to record 40 times more events than in all previous heavy-ion runs combined.

The life of the Laboratory was also marked by significant progress on key projects for the future. The construction of the High-Luminosity LHC, a major upgrade of the LHC, achieved important milestones that included conclusive tests of the new niobium–tin superconducting final-focus magnets. The upgrades of the LHC detectors also stepped up the pace, entering the production phase. For the longer term, the European Strategy for Particle Physics has recommended the study of the feasibility of a future circular collider, the FCC, which is deemed to be the most scientifically compelling option for CERN's future research. In 2023, the FCC collaboration concluded the first part of the Feasibility Study with a mid-term report covering numerous aspects ranging from the physics goals and the technical characteristics of the collider to geology, territorial planning, civil engineering and the environment. This first phase of the study has shown that there are no major technical obstacles to the realisation of this ambitious project.

CERN's programme is subject to close scrutiny of its budgetary and environmental implications. In 2023, measures were put in place to limit the impact of inflation and high electricity prices on the CERN budget, and I should like to thank the Member and Associate Member States, as well as the staff, for their contributions in this respect. The third Environment Report, published at the end of the year, has allowed us to present the progress made over the previous two years in improving CERN's performance in key areas such as emissions, biodiversity, land use and waste management. The Laboratory was awarded the ISO 50001 certification, illustrating CERN's commitment to responsible energy management and improving energy efficiency.

The end of the year saw the inauguration of the Science Gateway, CERN's new emblematic centre for education, communication and outreach. With its innovative architecture and stimulating educational content, this new facility is proving a resounding success, offering almost 72 000 enthusiastic visitors in under three months the opportunity to discover science and technology through interactive exhibitions, scientific workshops, shows and events for the general public. In November, we were honoured to welcome two distinguished visitors, the Presidents of our Host States, France and Switzerland. Our two guests reiterated their trust in fundamental science and confirmed their support for CERN and its future, including the FCC. This is a very encouraging message for our community and I am deeply grateful to them.

Fabiola Gianotti

Fabiola Gianotti

2023 IN PICTURES

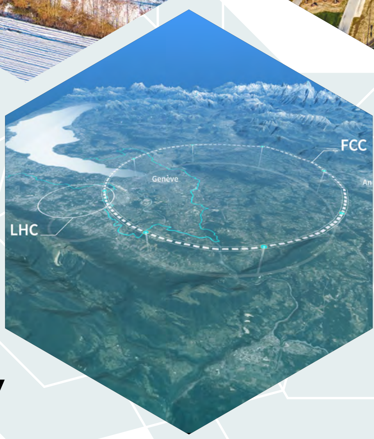
From the inauguration of CERN Science Gateway to the first observation of collider neutrinos and heavy-ion collisions returning to the LHC after five years, the year was memorable in showcasing the Laboratory's commitment to scientific advancement, collaboration, education and outreach. Enjoy a visual journey through some key moments of 2023.

20 JANUARY

CERN celebrates completion of the civil-engineering work for the High-Luminosity LHC, the major upgrade of its flagship collider, the LHC.
(CERN-PHOTO-202301-016-8)

2 FEBRUARY

CERN is awarded ISO 50001 certification for managing energy responsibly. Improving energy performance is part of CERN's commitment to environmentally responsible research.
(CERN-PHOTO-202310-230-9)



21 FEBRUARY

The Feasibility Study for a possible Future Circular Collider (FCC) enters its field phase, involving a major geographical, geological and environmental data-gathering effort.
(CERN-HOMEWEB-PHO-2023-034-3)

24 FEBRUARY

The International Committee of the Red Cross and CERN cooperate on using free and open source technologies for humanitarian action.
(CERN-PHOTO-202212-219-1)

3 MARCH

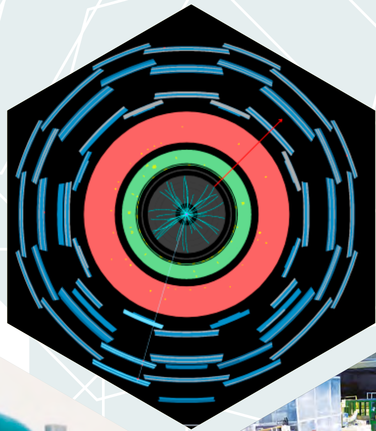
The CMS experiment measures tau-lepton polarisation in Z-boson decays.
(CERN-PHOTO-202108-102-1)

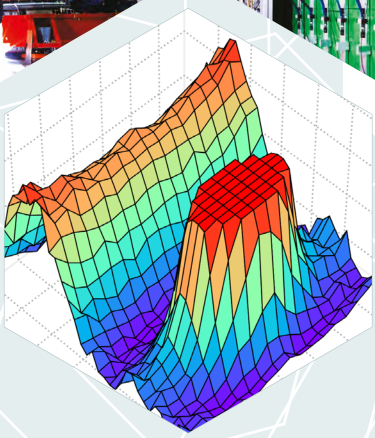
22 MARCH

For the first time in the world, LHC experiments FASER and SND@LHC observe collider neutrinos.
(CERN-PHOTO-202302-065-6
CERN-PHOTO-202312-300-6)

23 MARCH

ATLAS presents an improved measurement of the W boson mass, in line with the Standard Model of particle physics.
(ATLAS-PHOTO-2023-021-1)





31 MARCH

The ALICE experiment sees “the ridge” in the simplest collisions yet, moving a step closer to finding the origin of quark–gluon-plasma-like collective phenomena in small collision systems.
(ALICE-PHO-GEN-2023-009-6)

22 APRIL

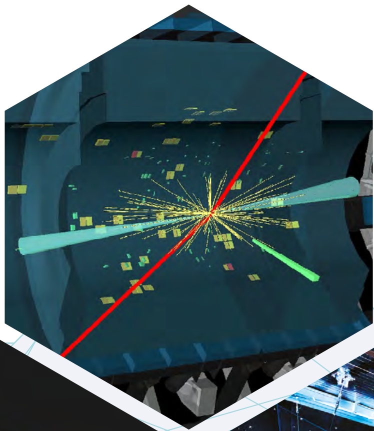
CERN collaborates with SuperNode on new solutions to improve energy transmission and accelerate the transition to renewable energy.
(CERN-PHOTO-202402-042-1)

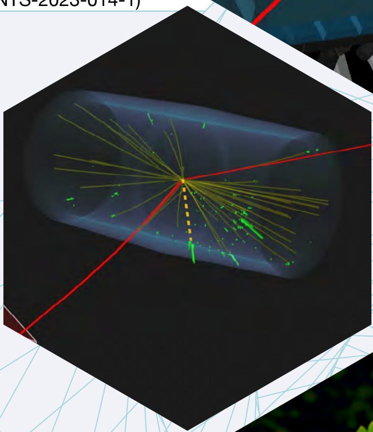
24 MAY

ISOLDE observes a long-sought decay of the thorium-229 nucleus in a solid-state system. This is a key step towards a clock that could outclass today’s most precise atomic clocks.
(CERN-PHOTO-202106-083-1)

26 MAY

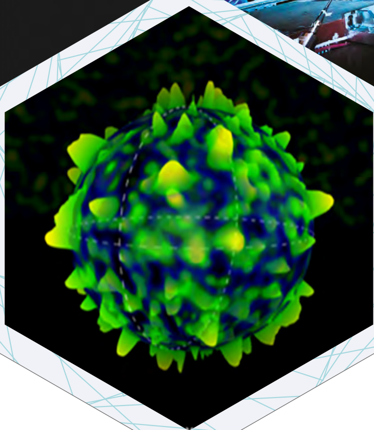
The ATLAS and CMS collaborations join forces to establish the first evidence of the rare decay of the Higgs boson into a Z boson and a photon.
(ATLAS-PHOTO-2023-040-1 CMS-PHO-EVENTS-2023-014-1)





13 JUNE

The LHCb experiment makes the most precise measurement yet of matter–antimatter symmetry in decays of beauty particles.
(CERN-PHOTO-202204-063-2)



21 JUNE

Dutch artist Joan Heemskerk, a pioneer of web-based art, wins CERN's Collide Copenhagen residency award. Her artwork "Prototype" is shown here (on the left).

28 JUNE

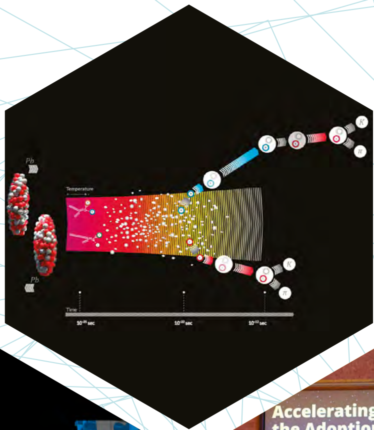
Three teams of secondary-school pupils from the Netherlands, Pakistan and the USA win the 10th edition of the Beamline for Schools competition.

28 JUNE

CERN launches its new programme called CERN Venture Connect to support deep-tech startups.

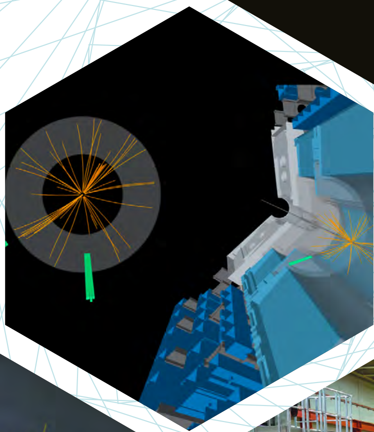
14 JULY

The ALICE experiment sheds light on the dynamics of charm and beauty particles in quark–gluon plasma. It observes that charm is better than beauty at going with the flow.
(ALICE-PHO-GEN-2023-008-1)



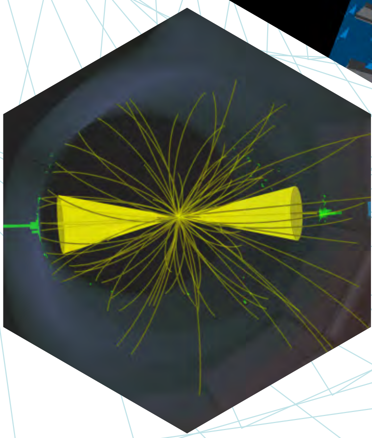
21 JULY

The ATLAS experiment sets a record precision of 0.09% for the mass of the Higgs boson.
(ATLAS-PHOTO-2023-031-3)



28 JULY

With 2023 as the Year of Open Science, CERN, NASA and other scientific institutions join forces to commit to a research future that is open and accessible for all.
(CERN-PHOTO-202307-160-11)



2 AUGUST

The CMS experiment sheds light on hadron formation by demonstrating the evolution from partons to hadrons inside jets produced at the LHC.
(CMS-PHO-EVENTS-2023-021)

21 AUGUST

The NA62 (shown here) and NA64 experiments in CERN's North Area start probing several light dark matter models.
(CERN-PHOTO-202104-059-8)

23 AUGUST

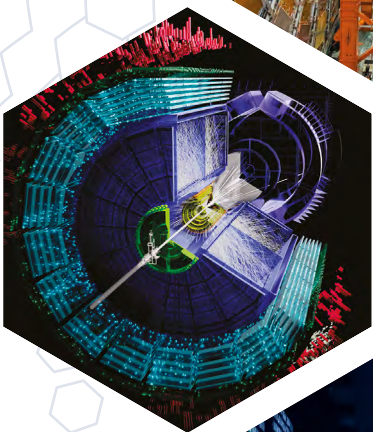
The LHCb experiment observes hypertriton, a key to modelling neutron star cores.
(CERN-PHOTO-201801-025-18)

25 SEPTEMBER

The ATLAS experiment measures the strength of the strong force with record precision.
(ATLAS-PHOTO-2024-002-3)

27 SEPTEMBER

The ALPHA experiment observes the influence of gravity on antimatter.
(CERN-PHOTO-202103-029-3)



28 SEPTEMBER

Inauguration of the CERN Library and Bookshop, after one year of renovations.
(CERN-PHOTO-202309-208-1)

28 SEPTEMBER

The lead-ion run at CERN begins, with the LHC experiments taking data for their heavy-ion physics programmes for five weeks.
(CERN-PHOTO-202309-223-1)

29 SEPTEMBER

CERN reaches the “exa” mark as its data store crosses the remarkable capacity threshold of one exabyte or 1 million terabytes.
(OPEN-PHO-LIFE-2021-017-11)

7 OCTOBER

CERN inaugurates Science Gateway, its new education and outreach centre.
(CERN-PHOTO-202310-241-29)

16 OCTOBER

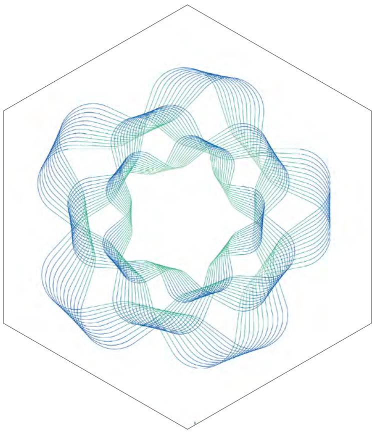
The Open Quantum Institute is launched at the Geneva Science and Diplomacy Anticipator summit. This three-year CERN-based programme seeks to make quantum computing resources and technical expertise widely available.

10 NOVEMBER

The CMS experiment presents its latest search for new exotic long-lived particles and the possibility of “dark photon” production.
(CMS-PHO-EVENTS-2023-027-2)

14 NOVEMBER

The World Food Programme and CERN sign a memorandum of cooperation to promote access to and use of breakthrough IT innovations to fight hunger worldwide.



4 DECEMBER

CERN publishes its Environment Report for 2021–2022, highlighting progress and future developments in ongoing efforts to minimise the Laboratory’s environmental footprint.

16 NOVEMBER

Host State Presidents visit CERN: President of the Swiss Confederation, Alain Berset, and President of the French Republic, Emmanuel Macron.
(CERN-PHOTO-202311-266-21)

A LABORATORY FOR THE WORLD

International collaboration is at the heart of CERN's endeavours. In 2023, a global community of more than 17 000 colleagues coming from across the world participated in the Laboratory's activities with the common goal of pushing the boundaries of knowledge. Throughout the year, which was the first full year of Run 3 of the LHC, both the infrastructure and the data collected at CERN were made accessible to over 12 000 scientific users spanning over 950 institutions across more than 80 countries.

(CERN-PHOTO-202304-106-55)

BREAKDOWN OF CERN USERS ACCORDING TO THE COUNTRY OF THEIR HOME INSTITUTE, AS OF 31 DECEMBER 2023

NUMBER OF USERS: 12 370

MEMBER STATES (7438)

Austria 86 – **Belgium** 129 – **Bulgaria** 46 – **Czech Republic** 252 – **Denmark** 47 – **Finland** 88 – **France** 842 – **Germany** 1296 – **Greece** 112 **Hungary** 80 – **Israel** 74 – **Italy** 1609 – **Netherlands** 167 – **Norway** 77 – **Poland** 322 – **Portugal** 105 – **Romania** 113 – **Serbia** 38 – **Slovakia** 67 **Spain** 413 – **Sweden** 106 – **Switzerland** 419 – **United Kingdom** 950

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

Cyprus 14 – **Estonia** 29 – **Slovenia** 26

ASSOCIATE MEMBER STATES (406)

Croatia 37 – **India** 145 – **Latvia** 21 – **Lithuania** 17 – **Pakistan** 30 – **Türkiye** 129 – **Ukraine** 27

OBSERVERS (3005)

Japan 219 – **Russian Federation** 779 (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** 2007

OTHER COUNTRIES AND TERRITORIES (1452)

Algeria 2 – **Argentina** 16 – **Armenia** 16 – **Australia** 26 – **Azerbaijan** 3 – **Bahrain** 3 – **Belarus** 14 – **Brazil** 135 – **Canada** 206 – **Chile** 45 **Colombia** 24 – **Costa Rica** 3 – **Cuba** 3 – **Ecuador** 4 – **Egypt** 24 – **Georgia** 34 – **Hong Kong** 15 – **Iceland** 3 – **Indonesia** 7 – **Iran** 14 – **Ireland** 4 **Jordan** 3 – **Kazakhstan** 3 – **Kuwait** 2 – **Lebanon** 7 – **Madagascar** 1 – **Malaysia** 4 – **Malta** 1 – **Mexico** 56 – **Montenegro** 3 – **Morocco** 18 **New Zealand** 2 – **Nigeria** 2 – **Oman** 1 – **Palestine** 1 – **People's Republic of China** 414 – **Peru** 3 – **Philippines** 1 – **Republic of Korea** 168 **Saudi Arabia** 6 – **South Africa** 61 – **Sri Lanka** 10 – **Taiwan** 52 – **Thailand** 17 – **Tunisia** 4 – **United Arab Emirates** 10 – **Vietnam** 1

CERN's alumni, spread across the world, are key ambassadors for the Organization. They are brought together by the CERN Alumni Network, which marked its sixth anniversary in June 2023.
The Network has grown significantly since its inception, reaching almost 9500 members at the end of December 2023. Many alumni across the world have organised themselves into regional groups and hold regular meetups. In 2023, new groups were launched in Barcelona and Munich, and the groups in Vienna and Milan–Turin relaunched after a hiatus due to the COVID-19 crisis.

During the course of the year, 138 events worldwide were listed on the alumni website. As well as the Network's sixth anniversary, one of the highlights was a LinkedIn live session from the CERN Neutrino Platform, in collaboration with CERN Talent Acquisition, featuring two alumni who illustrated how a CERN experience can propel one's career forward. Additionally, the Network facilitated career-focused events, such as "Moving out of Academia" sessions, exploring opportunities in sectors such as consulting and software engineering, and a collaborative event with the PSI Career Center entitled "From Research to Industry: Selling your Skills to a Future Employer", offering guidance on job applications. Multiple "virtual company showrooms" were also organised, providing alumni with valuable networking opportunities and insights into job openings in various companies.

President of France, Emmanuel Macron, visited CERN during France's state visit to Switzerland at the invitation of the President of the Swiss Confederation, Alain Berset.
(CERN-PHOTO-202311-266-127)

CERN is committed to strengthening ties and establishing new partnerships with states, institutes and laboratories all over the world. At the end of 2023, CERN had 23 Member States, 3 Associate Member States in the pre-stage to Membership and 7 Associate Member States. In 2023, progress was made towards Brazil becoming an Associate Member State, and Chile and Ireland applied for Associate Membership in September and November 2023, respectively.

Throughout the year, 170 high-level visits took place at CERN. This includes the November visit of the Host State Presidents, Alain Berset and Emmanuel Macron, who reiterated the support of Switzerland and France, respectively, for the Laboratory.

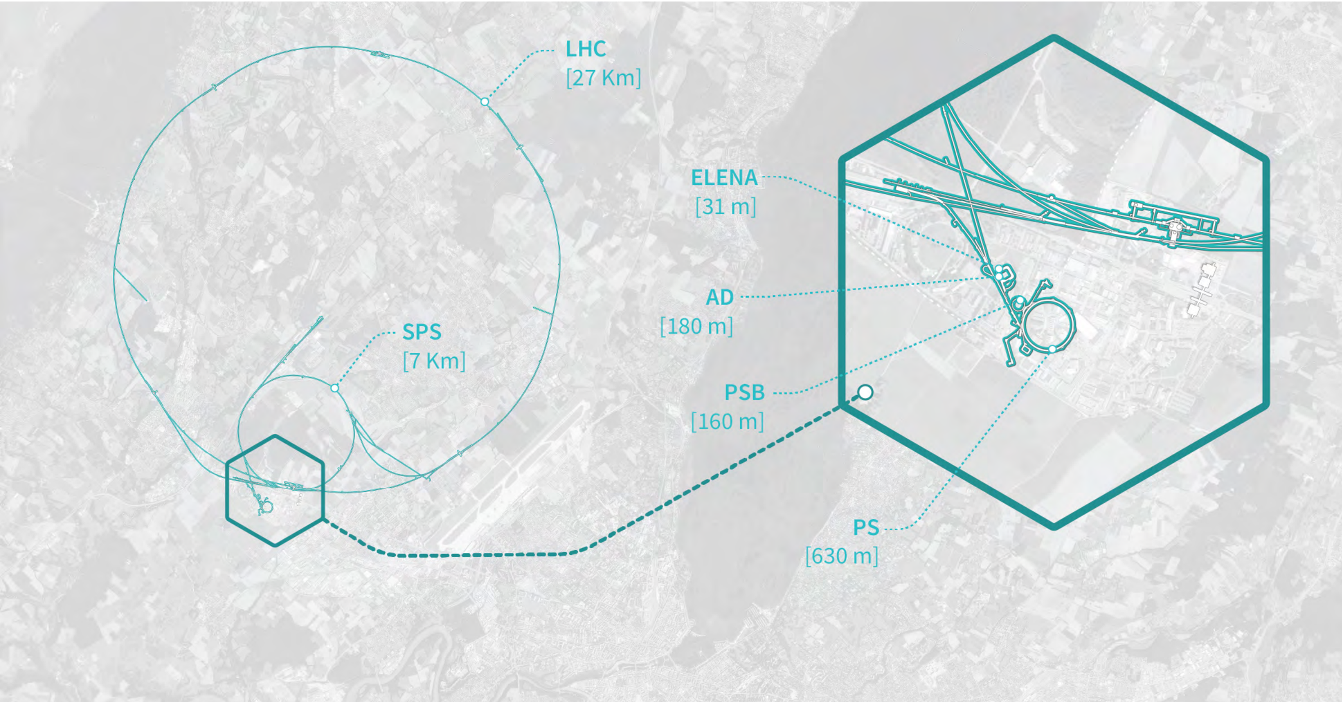
In addition, CERN's capacity-building programmes attracted interest from all over the world, with the Summer Student programme hosting 138 students from 61 countries and a new Doctoral Student programme launching in 2023.

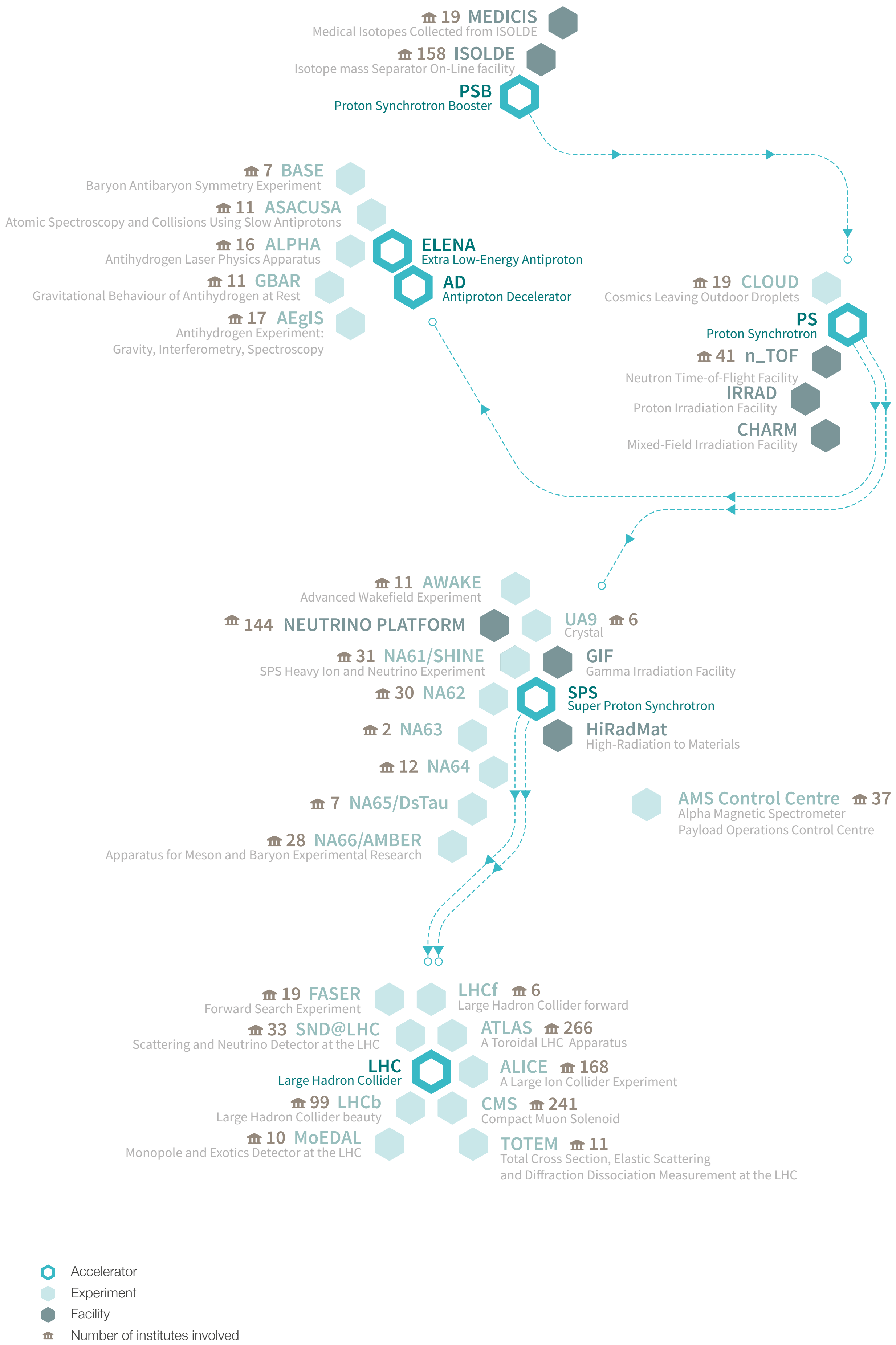
EXPLORING THE NATURE OF THE UNIVERSE

To explore the Universe at the most fundamental level, CERN operates a unique network of accelerators that collide particle beams head on or direct them onto fixed targets. The products of these collisions are recorded by giant detectors and studied by thousands of scientists at CERN and around the globe.

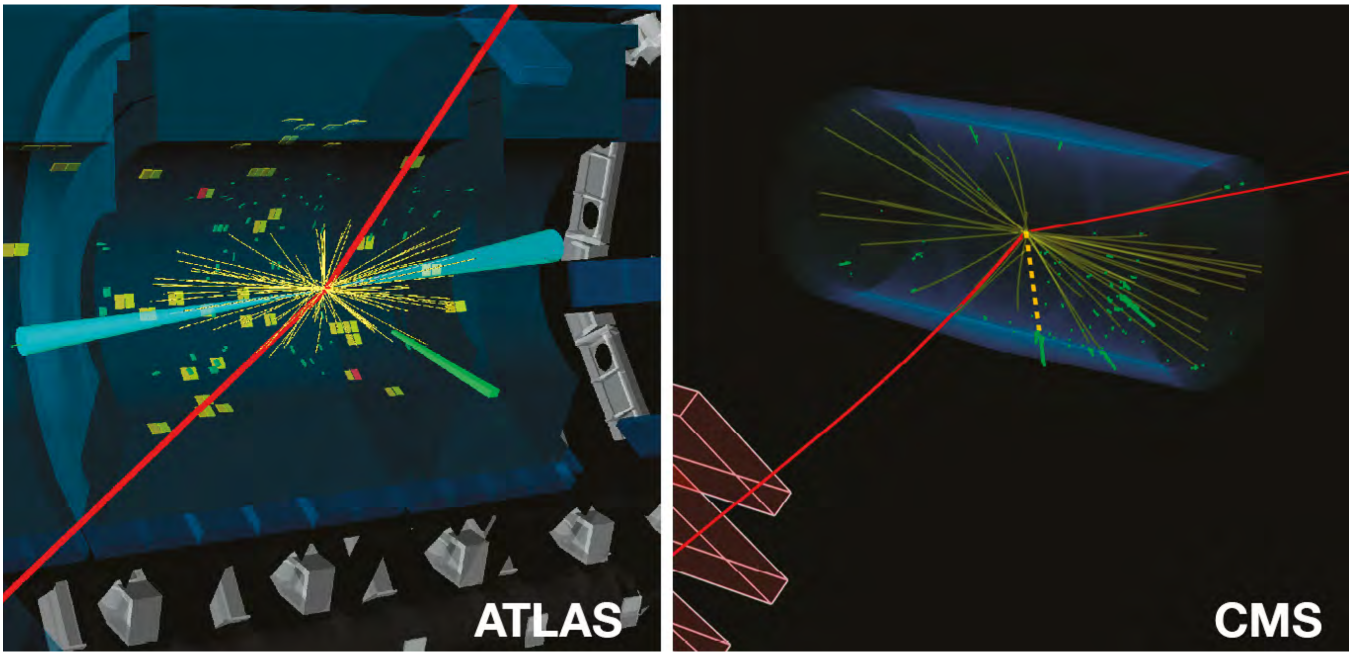
CERN'S ACCELERATOR COMPLEX AND THE EXPERIMENTS THAT IT FEEDS

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 2023 was marked by the second year of Run 3 of the LHC, at an energy of 13.6 TeV, and by the first heavy-ion run in five years, at an energy of 5.36 TeV per nucleon–nucleon collision. Other highlights of the year included the 50th anniversary of the discovery of weak neutral currents and the 40th anniversary of the discovery of the W and Z bosons, which were celebrated with a symposium that covered the past, present and future of this rich seam of physics. Throughout the year, these milestones were complemented by the release of first-class scientific results from experiments at the LHC and other accelerators at the Laboratory. These included the most precise determination of the top-quark mass, obtained by combining previous ATLAS and CMS measurements, the first observation of neutrinos produced at a particle collider by FASER and SND@LHC, and the demonstration by the ALPHA collaboration that, within the precision of their experiment, antihydrogen atoms fall to Earth in the same way as their matter equivalents.





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



Candidate events from ATLAS (left) and CMS (right) for a Higgs boson decaying into a Z boson and a photon, with the Z boson decaying into a pair of muons (red lines). *(ATLAS-PHOTO-2023-040-1 and CMS-PHO-EVENTS-2023-014-2)*

HOMING IN ON THE HIGGS BOSON

The discovery of the Higgs boson at the LHC in 2012 was a landmark in the history of physics, explaining how elementary particles get their mass. Since then, ATLAS and CMS have been diligently investigating this unique particle and seeking to establish the different ways in which it is produced and decays into other particles.

In 2023, ATLAS and CMS joined forces to establish the first evidence of the rare process in which the Higgs boson decays into a Z boson, the electrically neutral carrier of the weak force, and a photon, the carrier of the electromagnetic force. This Higgs boson decay could provide indirect evidence of the existence of particles beyond those predicted by the Standard Model of particle physics. The decay proceeds via an intermediate "loop" of particles that pop in and out of existence and cannot be directly detected. These virtual particles could include new, as yet undiscovered particles that affect the Higgs boson's decay rate.

ATLAS and CMS also released record-precision measurements of the Higgs boson's mass. Precise knowledge of this fundamental parameter is key to accurate theoretical calculations which, in turn, allow physicists to confront their measurements of the Higgs boson's properties with predictions from the Standard Model. The Higgs boson's mass is also a crucial parameter linked to the stability of the Universe's vacuum. ATLAS obtained a Higgs boson mass of 125.11 GeV with an uncertainty of 0.11 GeV by combining a new mass measurement based on an analysis of the particle's decay into two high-energy photons and an earlier mass measurement based on a study of its decay into four leptons. CMS reported a value of 125.08 GeV with an uncertainty of 0.12 GeV using the decay of the particle to four leptons, representing the highest precision to date in a single decay channel.

TESTING THE STANDARD MODEL AND ITS EXTENSIONS

The LHC collaborations continue to carry out tests of the Standard Model and its extensions. The weak force is known to induce a behavioural difference between matter and antimatter – known as charge–parity (CP) symmetry violation – in decays of particles containing quarks. But these differences, or asymmetries, are hard to measure and insufficient to explain the matter–antimatter imbalance seen in the present-day Universe, prompting physicists to both precisely measure the known differences and to look for new ones. In 2023, the LHCb collaboration reported the most precise measurements to date of two key parameters that determine such matter–antimatter asymmetries. One parameter determines the amount of CP violation in decays of neutral beauty mesons and the other determines the amount of CP violation in decays of beauty mesons containing strange quarks. The measurements are in line with the values predicted by the Standard Model and aid researchers in their search for unknown effects.

In a study that surpassed the experiment's design goals, LHCb also detected about 100 of the rare hypertriton and antihypertriton particles in proton–proton collisions at the LHC. The findings strengthen CERN's role as one of the few places in the world where such hypernuclei can be studied in detail, which could offer valuable insight into the particle interactions that take place in the inner cores of neutron stars.

The LHCb team also reported evidence of a new four-quark state, containing a charm quark, a charm antiquark, a down quark and a strange antiquark. The result adds to the more than 20 new exotic hadrons found at the LHC so far, and more generally to the more than 70 new hadrons discovered at the collider. The study of exotic hadrons, which are made up of more than three quarks, offers a powerful way to gain a deeper understanding of quantum chromodynamics, the theory of the strong force that binds quarks into composite particles.

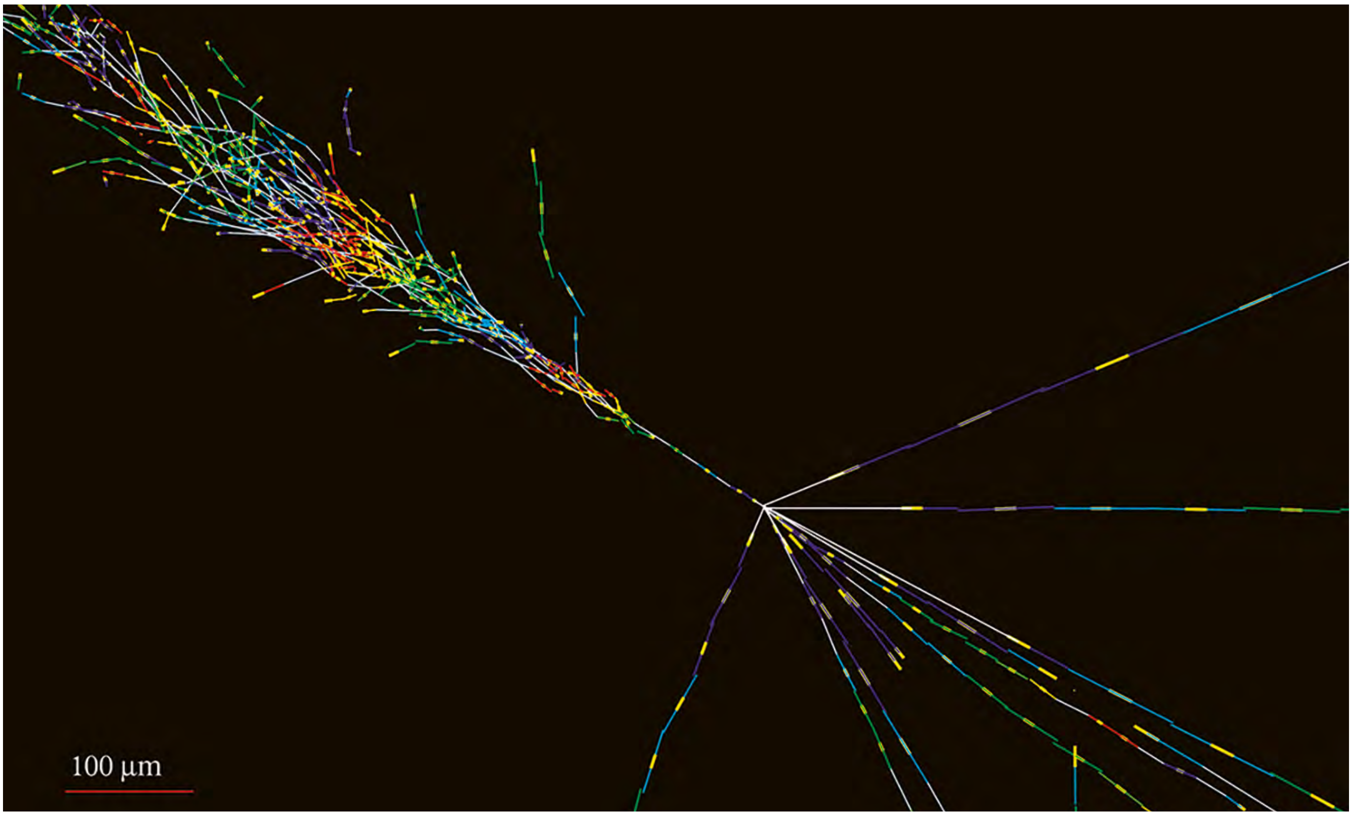
The year 2023 also saw LHCb reveal a measurement of the associated production of J/ψ and ψ(2S) particles in proton–proton collisions at 13 TeV – for the first time at a hadron collider. The result, which was combined with a measurement of J/ψ–J/ψ production, provides important information for improving quantum chromodynamics calculations.

In other tests of the Standard Model and its extensions, ATLAS measured, with a record precision of 0.8%, the strength of the strong force, a key parameter of the Standard Model that had hitherto only been known with percent-level precision; for comparison, the electromagnetic force, which is 15 times weaker than the strong force at the energy probed by the LHC, is known with a precision better than one part in a billion. The result showcases the power of the LHC to push the precision frontier and improve our understanding of nature. In a reanalysis of a sample of 14 million W boson candidates produced in proton–proton collisions, ATLAS also obtained a W mass value of 80360 MeV with an uncertainty of 16 MeV – a result that is in line with the Standard Model and 16% more precise than the previous ATLAS result.

In a comprehensive overview of its searches for weakly interacting supersymmetric particles, which could be a source of the mysterious dark matter in the Universe, ATLAS found that some regions for supersymmetric-particle masses that had previously been viewed favourably, where the dark matter particle has about half the mass of the Z boson or the Higgs boson, are now almost totally ruled out. It also presented examples of “surviving” models that have not yet been probed, which can be used to optimise future searches.

ATLAS also reported the observation of quantum entanglement using collision events that produce a pair of top quarks. Entanglement is an extraordinary feature of quantum mechanics: if two particles are entangled, the state of one particle cannot be described independently from the other. It has been observed in a wide variety of systems, but it has remained largely unexplored at the high energies accessible at hadron colliders. The new observation, which is both the first observation of entanglement between a pair of quarks and the highest-energy measurement of entanglement, opens new ways to test the fundamental properties of quantum mechanics.

Highlights from CMS include the results of the collaboration’s first search for new physics using data from Run 3.



A candidate high-energy electron neutrino charged-current interaction recorded by FASERν, with the electron shower (left of the image) balanced by several charged particle tracks (right).

Specifically, CMS searched for long-lived particles called dark photons in the Higgs boson's decay. Using its improved real-time data-selection algorithm, which was specially refined between Runs 2 and 3 to search for these particles, CMS was able to use the LHC more efficiently, obtaining tight limits on the parameters of the Higgs boson's decay to dark photons using just a third of the amount of data as previous searches.

CMS also reported the observation of the rare decay of the eta meson into four muons. This decay could be sensitive to contributions from new unknown particles and is relevant for calculations of the muon's anomalous magnetic moment, of which the Muon g-2 experiment at Fermilab has made the world's most precise measurement. The observation demonstrates the power of the technique of data scouting, which overcomes the limitation of the maximum amount of data that can be transferred to permanent storage by recording only a fraction of the information.

Another CMS highlight was an analysis of the internal structure (substructure) of sprays, or "jets", of particles, which not only allowed new light to be shed on how quarks and gluons turn into hadrons but also led to a measurement of the strength of the strong force with a precision of 4%. The result represents the most precise measurement of this parameter using jet substructure. Also on the precision front, CMS reported a measurement of the tau-lepton polarisation in the decay of Z bosons to a pair of tau leptons that is nearly as precise as those of single experiments at LEP, the LHC's predecessor. The measurement shows that LHC collision events, although much more complex than those collected at LEP, can provide a precise determination of the tau-lepton polarisation, which is crucial to probe the CP properties of the interaction between the Higgs boson and the tau lepton.

THE YEAR 2023 SAW ATLAS AND CMS TEAM UP TO OBTAIN THE MOST PRECISE DETERMINATION TO DATE OF THE TOP-QUARK MASS.

The year 2023 also saw ATLAS and CMS team up to combine 15 earlier individual measurements to obtain the most precise determination to date of the top-quark mass. The new result, which is based on Run 1 data and has an uncertainty of less than 0.2%, is a good example of the meticulous work that is required to understand LHC data – work that can go on for many years after the data are collected. Also in the top-quark arena, ATLAS and CMS both directly observed the simultaneous production of four top quarks, a rare phenomenon that is notoriously difficult to detect and that could hold a key to physics beyond the Standard Model.

For the smaller LHC experiments, highlights of the year included the first observation of neutrinos produced at a particle collider by FASER and SND@LHC, which entered operation at the start of Run 3 in 2022. FASER reconstructed 153 candidate muon neutrino and antineutrino interactions with a significance of 16 standard deviations, whereas SND@LHC found eight candidate muon neutrino interactions with a significance of 7 standard deviations. The results pave the way for future studies using high-energy collider neutrinos. In a separate analysis, FASER also presented first results from a search for dark photons decaying to an electron–positron pair, yielding new constraints on dark photons.

ALICE ARENA

The LHC also collides atomic nuclei to study 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. One of the key features of QGP formation is a long-range spatial correspondence between the particles that are created in the collisions, which manifests as a ridge-like shape in data plots. In 2023, ALICE, the LHC's heavy-ion specialist, reported the observation of this effect in the simplest collision system yet – "low-multiplicity" proton collisions that create a relatively small number of particles. The observation brings physicists a step closer to finding the origin of QGP-like collective phenomena in small collision systems.

ALICE also released new results based on ultra-peripheral collisions, in which one of the LHC beams may emit a photon of very high energy that strikes the other beam. By studying these photon–nucleus collisions, the collaboration was able to probe the arrangement of gluons inside nuclei, in particular nuclear areas called gluonic hotspots, in which the number of gluons cannot increase any further.

In non-head-on heavy-ion collisions, the overlap region between the ions has an elliptic shape that leaves an imprint on the flow of hadrons. In 2023, ALICE reported a new measurement of such elliptic flow for "non-prompt" D mesons that are not produced promptly after the collisions but later in the decays of B mesons, which contain beauty quarks. The measurement shows that the elliptic flow of the non-prompt D mesons is weaker than that of their prompt counterparts, in agreement with the expectation. The result sheds new light on the thermalisation of beauty quarks in QGP and paves the way for new ALICE measurements based on Run 3 data.

In 2023, ALICE also presented its first results based on data collected with the upgraded detector in 2022, the first year of Run 3. One result is the measurement of the production rates of two different charmonia – bound states of a charm quark

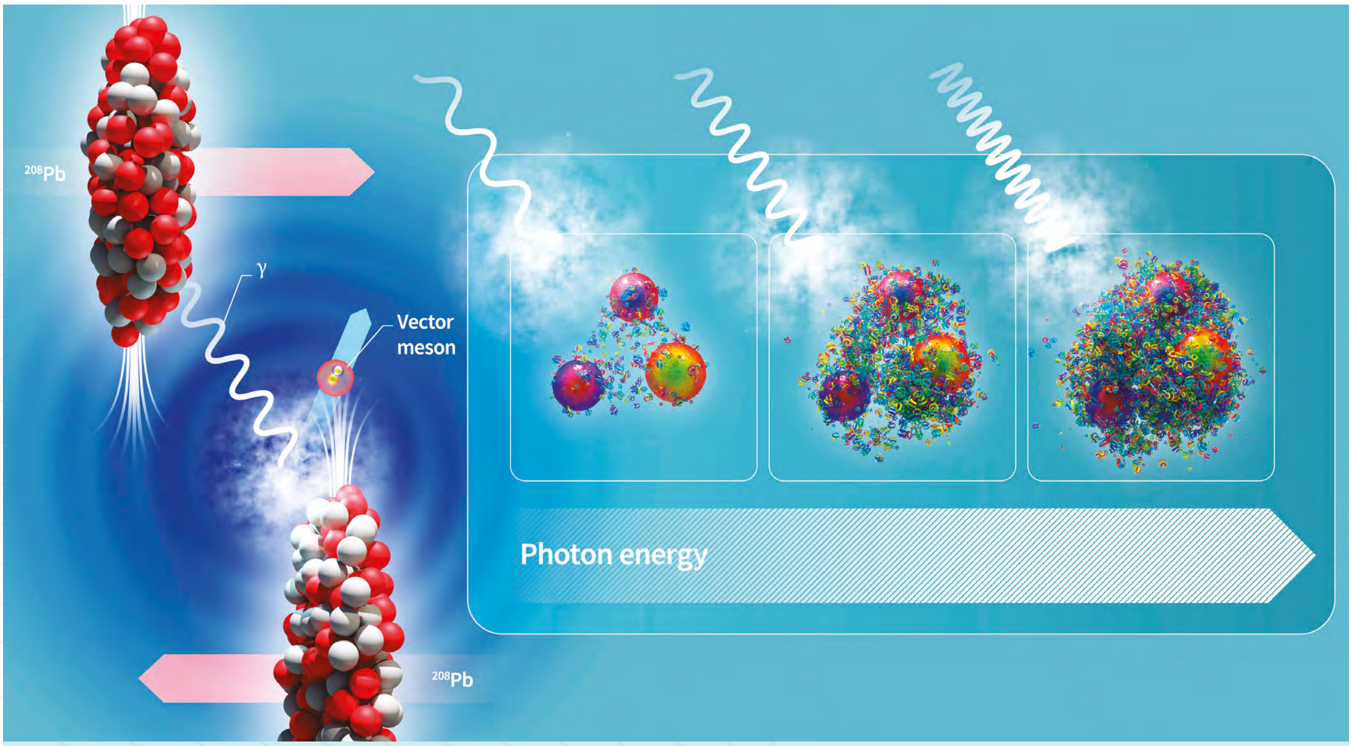


Illustration of an ultra-peripheral collision in which two lead-ion beams at the LHC pass close to each other without colliding. Photons emitted from one beam strike the other, producing electromagnetic interactions. The structure of the gluonic matter in the nucleus gets further exposed when probed by higher-energy photons (see the three boxes).

and its antimatter counterpart – in proton–proton collisions. The results demonstrate ALICE's ability to measure charmonia in both the central and forward regions of the detector and open the way for measurements using data from the heavy-ion run that took place in the last quarter of the year, in which ALICE recorded about 12 billion lead–lead collisions – 40 times more collisions than the total recorded by the experiment in the previous periods of heavy-ion data taking.

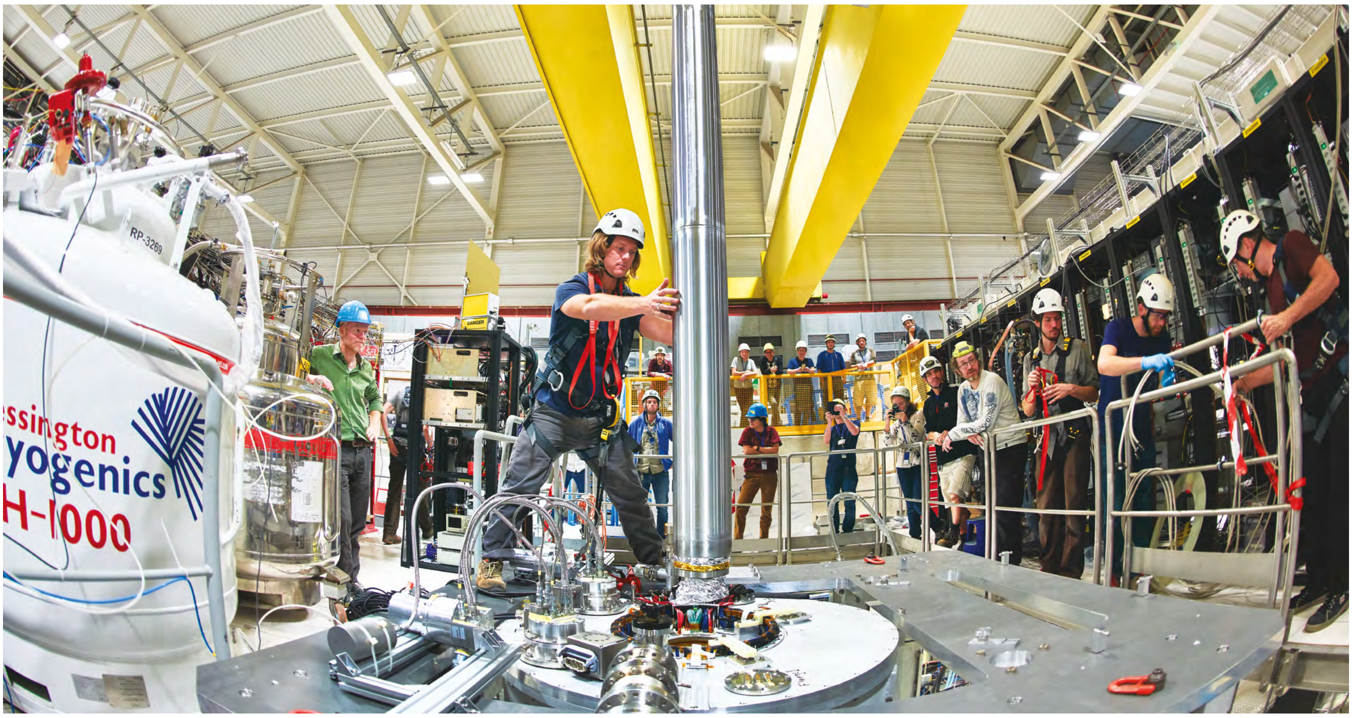
THEORY DEPARTMENT

In 2023, 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 304 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 processes; an efficient approach for preparing vacuum states for quantum simulation of strongly interacting local quantum field theories; an estimation of the background of gravitational waves generated in the frequency band of the LISA space probe by pairs of black holes originating from stars; a demonstration that it is conceivable to detect the quantum nature of gravitational radiation; a computational method to construct certain mathematical quantities called scattering amplitudes in three and four spacetime dimensions; and a determination, using data from heavy-ion runs of the LHC, of the thickness of the neutron skin of lead-208 nuclei.

The department made fundamental contributions to all working groups on the physics of the LHC, the High-Luminosity LHC (page 43) 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).

The department hosted 779 external scientists and held seven theory institutes, 11 topical workshops and two physics schools.



Insertion of the ALPHA-g apparatus at CERN's Antimatter Factory. (CERN-PHOTO-201810-267-19)

ANTIMATTER INSPECTIONS

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 2023, low-energy antiprotons from the ELENA ring, which slows down antiprotons even further than the facility's Antiproton Decelerator, were routinely delivered to the ALPHA, AEgIS, ASACUSA, BASE and GBAR experiments. Meanwhile, progress was made in the development of the PUMA experiment and a variant of BASE called BASE-STEP, which aim to transport antimatter to other facilities for nuclear physics and antimatter studies, respectively.

A physics highlight in 2023 was the demonstration by the ALPHA collaboration that, within the precision of its ALPHA-g apparatus, atoms of antihydrogen – a positron orbiting an antiproton – fall to Earth in the same way as their matter equivalents. The result is a milestone in the study of the properties and behaviour of antimatter and paves the way for high-precision measurements of the gravitational behaviour of antihydrogen.

The year also saw notable results from AEgIS and GBAR, which also aim to measure the acceleration of antihydrogen in Earth's gravitational field. AEgIS succeeded in cooling with laser light a sample of positronium, an electron orbiting a positron. The result will not only help AEgIS achieve the above goal but will also open the door for a whole new set of antimatter studies, including the production of a matter–antimatter Bose–Einstein condensate that emits laser-like gamma rays. GBAR reported the successful production of some 20 antihydrogen antiatoms, an achievement that validates the experiment's "in-flight" approach of producing antihydrogen and means that GBAR is now one of a very select club of experiments that has succeeded in synthesising antihydrogen atoms.

INVESTIGATIONS AT ISOLDE

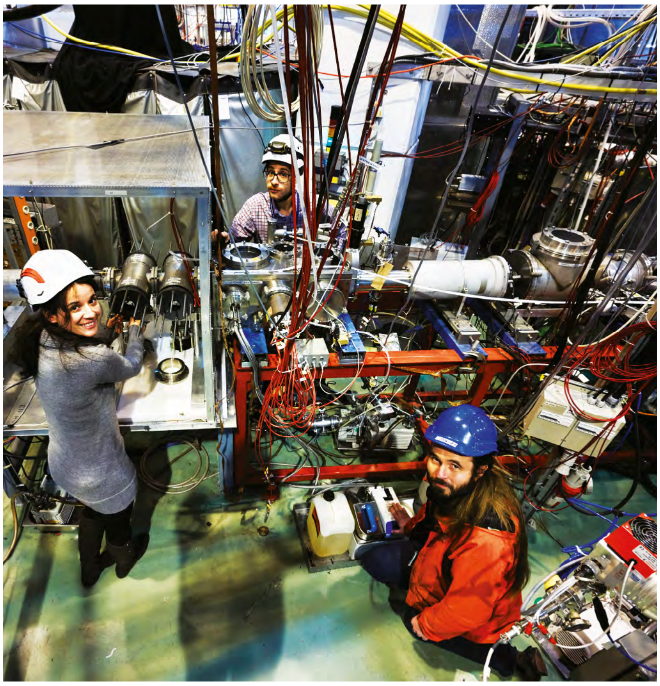
ISOLDE directs a 1.4-GeV proton beam from the PS Booster (page 23) to a target station in order to produce beams of radioactive isotopes for a wide range of studies. These beams can be reaccelerated to energies close to 10 MeV per nucleon using the HIE-ISOLDE linear accelerator. In 2023, the facility delivered radioactive beams to 59 experiments, from April to November.

Physics highlights from 2023 include a study that revealed that the radius of the exotic nucleus of aluminium ^{26m}Al is much larger than previously thought. The result, obtained by measuring the response of the nucleus to laser light in experiments conducted at ISOLDE and at the Accelerator Laboratory in Jyväskylä, Finland, sheds light on the effects of the weak force on quarks. More concretely, the result leads to a weakening of the current apparent tension – with the expected value of 1 – in the sum of the respective probabilities of the down quark, the strange quark and the bottom quark transforming into the up quark.

Another highlight was the finding that neutron-deficient gold nuclei also undergo shape shifting, whereby nuclei alternate dramatically from football to rugby ball shapes when single neutrons are removed from the nucleus. The finding was obtained using three set-ups in combination at ISOLDE (called RILIS, Windmill and ISOLTRAP). It is only the third example of this phenomenon to be observed, coming a little over 50 years after the first discovery in the light mercury nuclei, also at ISOLDE, and it shows that shape shifting still poses a tremendous challenge for nuclear theory.

ISOLDE also allowed the determination of the energy necessary to bring the atomic nucleus of indium-99 from its ground state to a long-lived excited state called an isomer. The result follows an earlier ISOLDE measurement of indium-99 in the ground state, offering an even closer look at the "doubly magic" tin-100 nucleus and guiding researchers in their efforts to develop a description of the nucleus from first principles.

The energy and lifetime of the thorium-229 isomer, which could form the basis of a nuclear clock, have also been measured with higher precision than before, following the observation – reported in 2022 and published in 2023 – of the so-called radiative decay of the isomer to the ground state.



The ISOLDE set-up used to study the exotic nucleus of aluminium. *(CERN-PHOTO-201911-394-15)*

FIXED-TARGET EXPERIMENTS AND MORE

Significant outcomes were also obtained in 2023 from other CERN-based experiments, many of which are fed by particle beams from the PS and SPS accelerators (page 23). Examples include a result from the CLOUD experiment, which studies how aerosol particles form and grow from mixtures of vapours in atmospheric conditions in a large chamber. The CLOUD measurements showed that iodine oxoacids greatly boost the formation rate of sulfuric acid particles, implying that climate models are substantially underestimating the formation rates of aerosol particles in marine and polar regions.

The NA61/SHINE experiment also shone in 2023 with numerous results, notably the observation of an unexpectedly large breaking of a symmetry of nature known as isospin symmetry in the production of charged and neutral kaons in high-energy nucleus–nucleus collisions. The result calls for more measurements and theoretical studies to establish the origin of the large symmetry breaking.

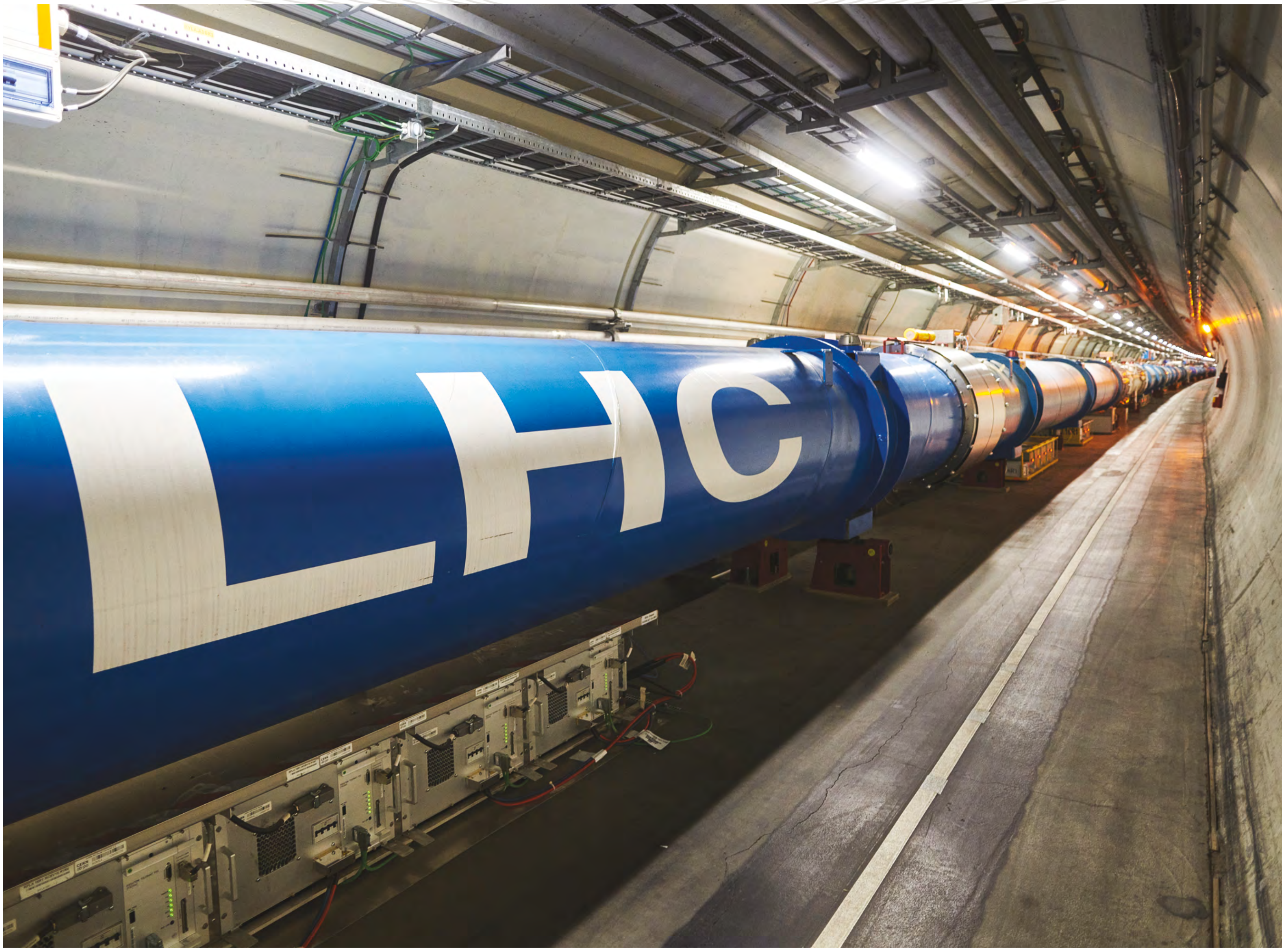
Other examples are the results of the latest searches for dark matter conducted with the NA62 and NA64 experiments. Searching for a rare kaon decay and for possible contributions from dark bosons to that decay, NA62 placed some of the most stringent bounds on dark bosons and excluded axions as a possible explanation for the ATOMKI anomaly, confirming its previous findings. NA64, which hunts for dark-matter particles that interact with Standard Model particles through a possible dark photon, set the most sensitive limits to date on dark-photon couplings to photons for dark-photon masses below 0.35 GeV. Another highlight was the release of final measurements of the Drell-Yan process taken by the COMPASS experiment, which concluded in 2022 and was succeeded by the AMBER experiment. The results are relevant for understanding the internal structure of nucleons and pave the way for new experiments aiming to perform similar measurements.

The experimental hall where the NA61/SHINE and other North Area (NA) experiments are located. *(CERN-PHOTO-202104-058-21)*

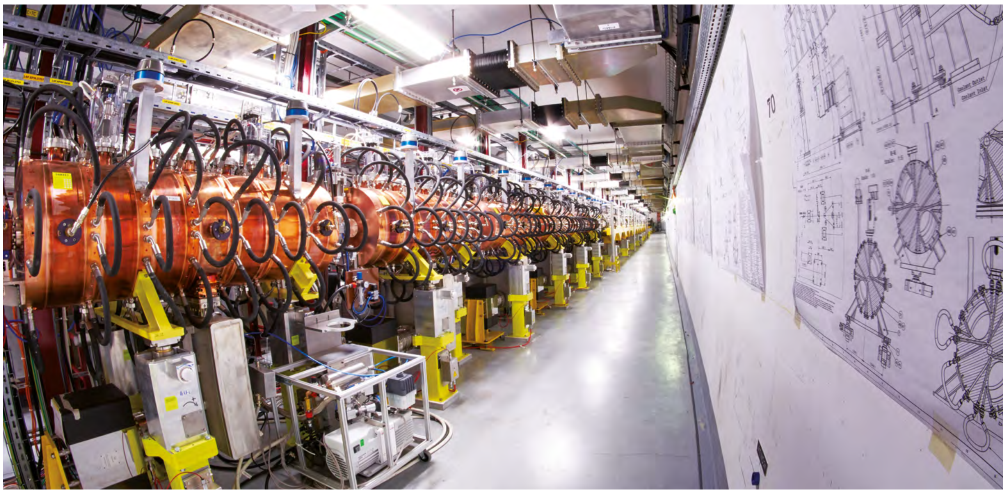
DISCOVERY MACHINES

To study the infinitesimally small, CERN operates a unique complex of accelerators and experiments. The accelerators drive subatomic particles to near-light speeds. In the LHC, counter-rotating beams of particles produce collisions at the centre of huge detectors, which record what happens. Hundreds of physicists, engineers and technicians operate and maintain these sophisticated installations.

2023 was a year of ups and downs for the CERN accelerator complex, particularly for the Large Hadron Collider (LHC). On 21 April, the first proton collisions took place in the LHC experiments at an energy of 13.6 TeV. In the autumn, the accelerator complex switched to running with ions, enabling the first LHC lead-ion physics run for five years. The injectors delivered beams that met the parameters of the LHC Injectors Upgrade (LIU) project, achieving the beam intensity and brightness that will be required for the High-Luminosity LHC (HL-LHC) upgrade (page 43). LHC operations were marked by three major challenges, which required the teams involved to perform some feats of ingenuity to overcome them.



In the autumn, lead-ion beams circulated in the LHC for the first time during Run 3. (CERN-PHOTO-202109-138-6)



Linac4 is the first link in CERN's proton accelerator chain.
(CERN-PHOTO-201704-093-11)

EVER-MORE-EFFECTIVE INJECTORS

Following the 2022–2023 year-end technical stop (YETS), which was extended by two weeks in accordance with efforts to reduce energy consumption, the accelerators were restarted one by one. **Linear Accelerator 4 (Linac4)**, the first link in the proton accelerator chain, accelerated its first H- ion beam of 2023 on 13 February. Its ion source had been upgraded during the YETS, making it possible to increase the beam intensity from 25 mA to 35 mA after passing through the first accelerating structure. Studies aimed at improving the performance of Linac4 and the Proton Synchrotron Booster (PSB) were carried out in the autumn (see box below).

On 3 March, the first beam was injected into the **Proton Synchrotron Booster (PSB)**. The PSB performed reliably throughout the year, but a problem with the coils of the main quadrupoles persisted; the issue is caused by corrosion due to the presence of sulphur in the cooling water. Measures to mitigate this have been taken and the coils are scheduled to be replaced in the longer term.

On 10 March, the teams restarted the **Proton Synchrotron (PS)**. During the YETS, the beamlines between the PS and the **Super Proton Synchrotron (SPS)** were upgraded, making the beam transfer even more efficient. The PS met the requirements of AD/ELENA, the East Area experiments and the irradiation facilities, in particular CLOUD, CHARM and IRRAD. The n_TOF facility actually received 14% more protons than planned. Throughout the year, the beam for the North Area was produced in the PS in an innovative way thanks to a new configuration of the accelerators' radiofrequency systems, using barrier buckets that were tested in 2022, combined with the multiturn extraction (MTE) approach, which has been used for several years now. This considerably reduced beam loss during extraction from the PS. The PS beam delivered to the LHC also met the specifications of the LIU project.

Lastly, on 17 March, beam commissioning began in the SPS. Upgrades were also carried out in the SPS during the YETS; in particular, four modules of the injection system were upgraded to reduce the amount of beam-induced heating. The SPS performed well throughout the year, achieving an overall beam availability of 86% – a significant increase compared with previous years.

Following an extensive push to improve the parameters of the beam delivered to the LHC, an intensity of 2.2×10^{11} protons per bunch – very close to the value required for the HL-LHC – was achieved at the end of the 2023 run.

PUSHING THE LIMITS OF LINAC4 AND THE PS BOOSTER

On 30 October, the machine experts adjusted the parameters of the Linac4 source and succeeded in extracting a 48 mA beam. The teams were also able to adjust the operating cycles used to deliver beams to the LHC, the AD, n_TOF and the SPS North Area such that the beams matched the new beam parameters.
In addition, the teams tested the intensity that could be reached with the cycle used to send beams to ISOLDE. The nominal intensity of the beam sent to ISOLDE, delivered by the four PS Booster rings, is normally 3.2×10^{13} protons per cycle. During the test, the experts succeeded in doubling the beam intensity in three of the four rings without any significant increase in beam loss. This performance was obtained for a relatively short time, and its stability for longer periods remains to be proven. In the future, with this kind of beam intensity, it should be possible to deliver an unprecedented 6×10^{13} protons per cycle.

360° view of the hall of the Antiproton Decelerator, also known as the "antimatter factory". (CERN-PHOTO-202004-064-1)

In addition to providing beam to the LHC, the SPS serves the fixed-target experiments in the North Area, as well as the AWAKE experiment and the HiRadMat facility, all of which enjoyed a beam availability in excess of 98%. All the objectives for the experiments were met.

The CLEAR facility, which is used to test equipment and perform research with electron beams, operated for 39 weeks in 2023. In total, 21 experiments were approved and carried out.

A NEW INTENSITY RECORD FOR ANTIPROTON BEAMS

The antiproton physics season began on 30 June, following a delay caused by the detection in March of a water leak in a particular quadrupole of the **Antiproton Decelerator (AD)**. The magnet had to be removed and repaired in the workshop, then reinstalled and recommissioned.

The experiments at **ELENA** (Extra Low-Energy Antiproton deceleration ring) received 122 days of beam rather than the initially planned 172. To partially compensate for this, the teams extended the run by 12 days, until 13 November. The aim was to make the most of the time available for the experiments without compromising the many activities planned for the YETS.

In October, the AD/ELENA antiproton beam set new intensity records. A record intensity of 4.9×10^7 antiprotons was injected into the AD thanks to optimised settings in the upstream injectors. The intensity of the extracted antiproton beam gradually increased from 3.1×10^7 antiprotons to 4×10^7 antiprotons in September. This result was achieved thanks to the meticulous work carried out by the AD team to better understand the beam dynamics.

After being decelerated in the AD, the beam of antiprotons is injected into the ELENA machine, where, after further deceleration, the antiprotons are divided into four bunches that can be individually extracted and sent to the various experiments studying antimatter: ALPHA, AEgIS, ASACUSA, BASE, GBAR, PUMA and BASE-STEP. In September, these experiments regularly received 8×10^6 antiprotons per bunch and, following the optimisation carried out in the AD in October, this figure went up to 9.7×10^6 antiprotons per bunch – a new intensity record for ELENA.

CUTTING-EDGE NUCLEAR PHYSICS

When the beams from the PS Booster collide with the **ISOLDE** (Isotope Separator Online Detector) targets, rare radioactive isotopes of various periodic-table elements are produced, some of which are then selected using a combination of lasers and electric and magnetic fields to produce radioactive beams. These beams, which are either used at low energies or reaccelerated by the linear accelerator HIE-ISOLDE (High-Intensity and Energy ISOLDE), are steered towards several experiment facilities that cover a wide range of disciplines, from the study of nuclear structure and decay to astrophysics, condensed matter physics and life sciences.

Between April and November, the ISOLDE facility delivered radioactive beams to 59 different experiments. In an article published in May that received a lot of media attention, an international team working at ISOLDE announced that they had taken a key step towards building a nuclear clock based on the periodic transition between two states of the thorium-229 nucleus (page 21).

A YEAR OF UPS AND DOWNS

In the first months of the year, the LHC's luminosity production reached exceptional levels. This was made possible by the remarkable flexibility and mastery of the teams in charge of operations. However, several unforeseen developments affected beam availability.

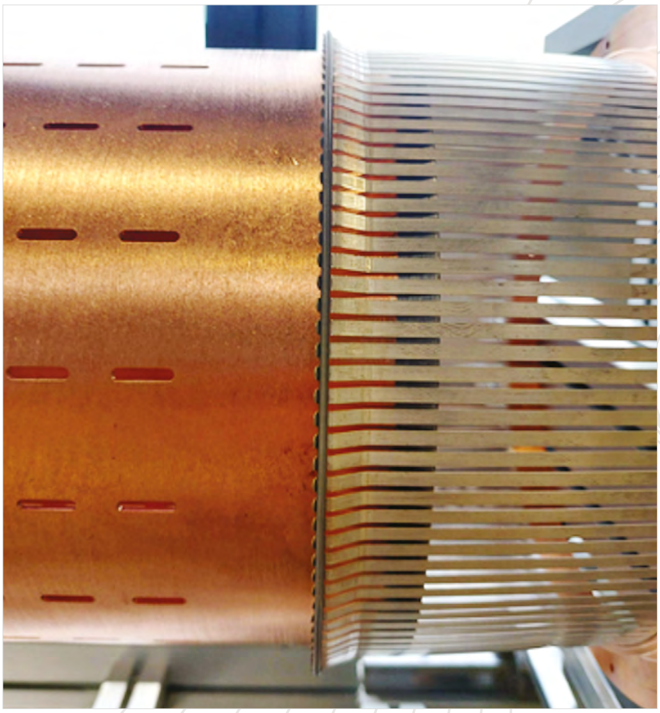
On 22 March, just before the cold check-out of the machine got under way, a crystal collimator broke during transport. Repairs began the same day, and the collimator was substituted temporarily with a vacuum chamber. The crystal collimator, which is only required for lead-ion runs, was repaired and reinstalled in June. Beam injection finally took place on 28 March, only one day behind schedule.

On 1 April, a power outage at LHC Point 4 brought beam commissioning to an abrupt halt. Two sectors, including the radiofrequency cavities at Point 4, warmed up. The helium pressure in the cavities rose and the safety release valves came into play, relieving the overpressure in the cavities. Two rupture discs, additional safety components, also opened. They were promptly replaced and, the following morning, the cavities were refilled with liquid helium and the cool-down restarted. Beam commissioning resumed on 4 April.

On 21 April, one day ahead of schedule, the LHC engineer-in-charge declared "stable beams" at 6.8 TeV, signalling the start of the 2023 data-taking season and of the "intensity ramp-up" phase for the LHC. On 11 May, the LHC made its final step up in intensity to 2400 bunches per beam.

On 25 May, the LHC was affected by the first of three major issues that occurred in 2023: the beam was dumped during acceleration in two consecutive fills. Both beam dumps were triggered by "slow local losses" (see mini box) near Point 1 (the ATLAS experiment). X-ray imaging investigations and beam-loss studies led to the conclusion that one of the radiofrequency finger modules in a warm section was heating up or arcing, degrading the vacuum in that area and causing the slow local beam losses. Various teams worked in the LHC tunnel to replace the defective module and then conducted another vacuum pump-down.

"Slow local losses" happen when some beam particles get lost in specific parts of the ring when interacting with the gas molecules in the degraded vacuum. This process takes some time before the threshold to dump the beam is reached.



The radiofrequency finger module (seen on the right-hand side) ensures low-impedance (low-resistivity) electrical connectivity between the LHC vacuum chambers. When this electrical connection is not good enough, it can make the circulating beam unstable and cause its quality to deteriorate, or create losses that can lead to a beam dump. (CERN-HOMEWEB-PHO-2023-078-1)

On 30 May, beams were injected and circulated to check the vacuum conditions. As a precaution, the bunch intensity was nevertheless limited to 1.6×10^{11} protons per bunch (as opposed to 1.8×10^{11}).

On 19 June, LHC operation was paused for one week to allow the technical teams to carry out preventive and corrective maintenance on the machine and its subsystems. Following the stop, special physics runs were conducted, along with a short intensity ramp-up to revalidate the LHC machine for luminosity production.

At the beginning of July, the machine delivered beam availability of 76%, with more than half of the beam time devoted to stable beam for physics. A record stored beam energy of 425 MJ with 2464 bunches of 1.6×10^{11} protons was achieved.

On 17 July, the second major issue of the year occurred when LHC beams were dumped due to an electrical disturbance on the general electricity grid caused by a tree falling on power lines in Switzerland. As a result, several superconducting magnets quenched, one of which led to a leak of helium into the insulation vacuum between the cold masses of an inner triplet assembly. Repairing this leak required a six-week halt of the LHC beams (see box below).

A SMALL LEAK WITH BIG CONSEQUENCES

On 17 July, the LHC beams were dumped due to an electrical anomaly on the general electricity grid. Following the beam dump, several superconducting magnets quenched, i.e. lost their superconducting state.

Although the quench protection system (QPS) brought the magnets out of their superconducting state in a controlled and homogenous manner, the mechanical stresses they experienced caused a small leak to appear at the interconnection of two inner triplet magnets located to the left of Point 8 (the LHCb experiment) between the cryogenic circuit, which contains the liquid helium, and the insulation vacuum that separates the cold magnet from the wall of the cryostat. The helium gas entered the insulation vacuum, cooling down the cryostat body and causing condensation to form and freeze on the outside.

The cryogenic team drew up a novel recovery scenario: to avoid warming up the entire sector to room temperature, in which case more than three months would have been required to bring the sector back to beam conditions, they decided to leave the sector to drift up slowly in temperature, with all the liquid helium removed from the magnets and all the cryogenic lines depressurised, for a limited duration estimated at a maximum of 10 days.

Just one week after the incident, the magnet and vacuum teams opened the large bellows around the location of the leak to replace the faulty component – a bellow – with a spare one (easier said than done, as a completely new in-situ welding strategy had to be developed as the work progressed). On 28 July, the repaired interconnection was closed again. Cool-down started on 1 August, just in time to avoid a complete warm-up.

The response teams opened the interconnection between the inner triplet magnets positioned to the left of Point 8. The helium leak was located on one of the bellows. *(CERN-PHOTO-202307-179-46)*

(Middle image) The faulty bellow is replaced. The machine experts insert the instrumentation into the new bellow. *(CERN-HOMEWEB-PHO-2023-138-1)*

The teams acted extraordinarily swiftly. The leak was repaired thanks to a joint effort and the interconnection was closed up again. *(CERN-PHOTO-202307-179-13)*

As a result of the technical problems encountered, the integrated proton–proton luminosity in 2023 was 32 fb^{-1} for ATLAS and CMS – well below the target of 75 fb^{-1}. On 30 August, beams were once again injected into the LHC to launch the heavy-ion physics run (see box).

The third major issue of the year occurred on 31 August, when a leak in the vacuum system was detected at Point 8 in a TDIS (target dump injection segmented) device, which absorbs the beam in the event of an issue during the injection process. On 8 September, another leak occurred in an identical component. In both cases, the vacuum team took swift action, identified the source of the leaks and made temporary repairs. However, the number of bunches per injected beam had to be reduced.

The first heavy-ion collisions in the LHC took place on 26 September, and an intensity of 1240 bunches per beam was reached on 6 October. Despite this success, two issues arose: beam losses during the last part of the acceleration ramp, which caused the beam to be dumped, and a high level of background noise in an area of the ALICE detector where the circulating beam interacts with the collimators. The latter issue was resolved thanks to close collaboration between experts from the ALICE experiment and the LHC machine.

To address the beam loss issue, the thresholds of the beam loss monitors that are distributed around the LHC and serve as input for the beam dump system were increased, without compromising the safety and reliability of the accelerators. This and other adjustments allowed the losses during acceleration to be kept below the dump threshold and beams of 1240 bunches to be collided.

RETURN OF THE LEAD IONS

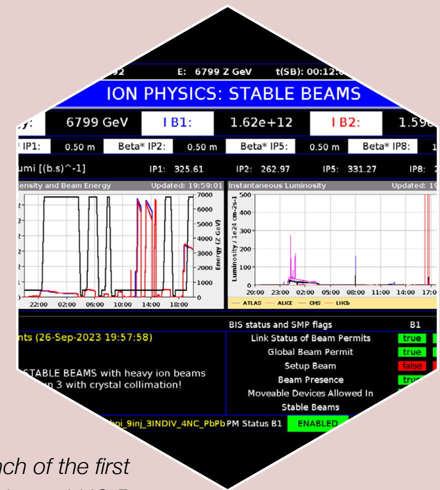
On 26 September, the injector complex began a five-week lead-ion physics run. The preparation of the ion sources (in Linac3 and LEIR) begins months before beams are sent to the PS and other downstream machines.

In the SPS, the "momentum slip-stacking" technique, 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, was successfully used for the first time in operating mode.

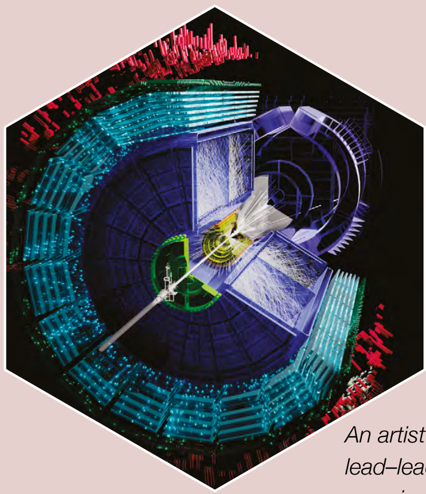
Thus, for the first time in five years (apart from a two-day pilot run at the end of 2022), the LHC delivered lead ions to its four major experiments: ALICE, ATLAS, CMS and LHCb. Lead nuclei were collided at a record energy of 5.36 TeV per nucleon pair, compared with 5.02 TeV during previous runs, and the collision rate increased tenfold. This run made it possible to validate the performance of the crystal collimators, which were also successfully used for the first time in operating mode.

In addition, lead-ion beams were sent to the SPS North Area, in particular to the NA61/SHINE experiment, their main ion user, with optimised beam parameters.

In the last two weeks of the run, the PS sent lead ions to the East Area, where the CHIMERA facility irradiates electronic devices with high-energy heavy ions to study the effects of cosmic radiation on the electronics used in the CERN accelerators and experiments and for space missions and aviation.



26 September: the launch of the first lead-ion physics campaign of LHC Run 3.
(CERN-HOMEWEB-PHO-2024-022-1)



An artist's image of the first 2023 lead–lead collisions in the ALICE experiment.
(ALICE-PHO-GEN-2022-009-2)

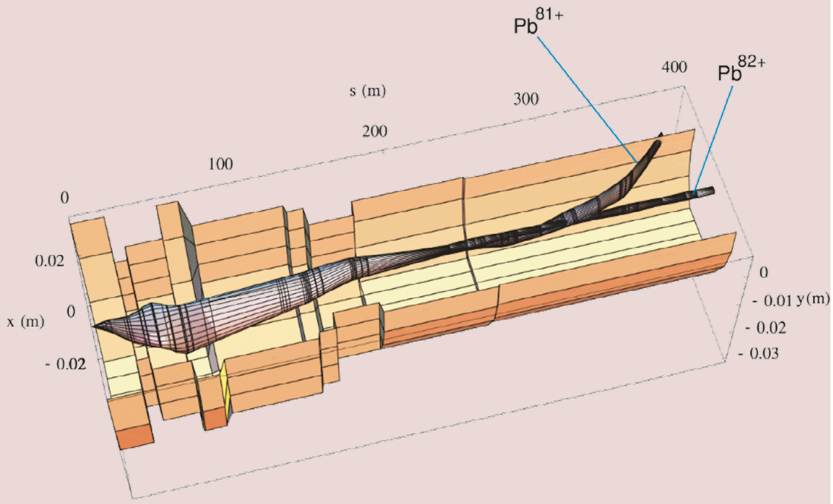
In 2023, ATLAS operated with 93.7% data-taking efficiency for proton–proton collisions. The detector recorded a pile-up rate (the number of collisions per proton bunch crossing) of up to 60, compared with a maximum of 54 in 2022. Significant progress was made with the commissioning of the systems that had been installed as part of the Phase 1 upgrades of the detector. For CMS, data-taking efficiency was 92%, with a maximum pile-up rate of 61. In the CMS muon spectrometer, the new gas-recovery system was commissioned, reducing greenhouse gas emissions compared with 2022. All the LHCb subdetectors were commissioned in 2023, with the exception of the new upstream tracker, whose commissioning will continue in 2024. At the start of the year, an incident with the LHCb vertex locator (VELO) detector compromised data taking in 2023. Thanks to the SPS slip-stacking technique, the ALICE experiment achieved a record maximum luminosity of 6.4 x 10^{27} $cm^{-2}s^{-1}$ during lead–lead collisions. Following the detector upgrade that was carried out during the second long shutdown, the experiment also recorded its highest integrated luminosity since the LHC began operation, equivalent to 12 x 10^9 lead–lead collisions.

The 2023 LHC run ended on 30 October with a planned quench (see box), marking the start of the 2023–2024 YETS.

IN 2023, FOR THE FIRST TIME IN FIVE YEARS, THE LHC DELIVERED LEAD IONS TO THE FOUR LARGE EXPERIMENTS.

THE 2023 RUN ENDS WITH A QUENCH

The last 2023 LHC beams were dumped on 30 October following a magnet quench. This may seem strange, as magnet quenches are not normally predictable and every effort is made to avoid them during beam operation. This time, the LHC machine experts wanted to experimentally validate the quench limit of the superconducting magnets, i.e. the amount of energy that they can withstand before they quench and lose their superconducting properties. For this purpose, the experts deliberately caused controlled beam losses in a superconducting magnet. Establishing this quench limit experimentally complements the many simulations that have already been made and enhances knowledge of the LHC machine, ready for the planned doubling of the stored beam energy at the HL-LHC.



A schematic representation of quench simulations. On the left-hand side is the interaction point, where the lead-ion collisions take place. On the right, the beam is de-squeezed (de-focused) while being transported downstream of the interaction point. At around 300 m downstream, the Pb81⁺ secondary beam clearly separates from the Pb82⁺ main beam. At 400 m, it is lost and deposits its energy. (CERN-HOMEWEB-PHO-2023-126-1)


The construction of the Prévessin Data Centre was completed on time and on budget at the end of 2023. *(CERN-PHOTO-202402-041-69)*

DELIVERING EXCELLENCE IN COMPUTING DAILY AT CERN AND WORLDWIDE

CERN's rapidly evolving and complex landscape of computing relies on a variety of multifaceted activities, which support the daily life of the Laboratory and allow it to remain at the forefront of technological advancement. In 2023, the CERN IT department again achieved a series of outstanding results and broke new records. To cite just a few: CERN officially entered the exabyte era for its disk storage capacity; the new Data Centre was completed; a new support service for users – IT SOS – was launched; the Open Quantum Institute was officially announced; and Indico achieved an impressive 400 000 users spread across the world. This is not forgetting the daily work of experts who make sure that the activities of CERN – from email to databases, cloud computing and the thousands of applications that are managed by the Organization – keep working smoothly and flawlessly.

About 8000 different users connect every day to one of the 10 000 applications that are made available at CERN through the single sign-on system, a complex software environment to navigate.

A day at CERN typically begins with checking emails. In 2023, around 32 000 mailboxes were migrated to Exchange Online and the Dovecot/OX and Exchange 2010 systems were decommissioned. The whole process went very smoothly thanks to careful planning and execution.

The CERN IT department supports an impressive range of databases used for administrative and research-related purposes. Over 5 PB of data are stored and managed by the CERN database services. The migration from Elasticsearch to OpenSearch was completed in 2023, with 87 clusters running the latest OpenSearch release at the end of 2023. In addition, a major upgrade campaign involving more than 600 database instances was carried out on the Database on Demand (DBOD) service, which empowers users to create and manage database instances using a simple and intuitive web interface developed at CERN.

The CERN IT services support an impressive 11 000 websites, 1700 Platform-as-a-Service (PaaS) applications, 264 Java applications and 500 Kubernetes clusters for Cloud computing. In 2023, a large percentage of these platforms – including Drupal, WordPress and GitLab – underwent either clean-up or major improvement campaigns. The growing open science data community celebrated the release of over 1 PB of open data from the CMS and LHCb experiments.

With over 300 active servers located in 52 different countries and with some 400 000 users, Indico is "the" CERN-developed event manager tool. In just 20 years – from its first inception as an additional functionality of the CERN Document Service (CDS) to the comprehensive tool that it is today – Indico has grown to cover all aspects of event management for as many as 145 000 different events. In 2023, version 3.3 was released, introducing improved accessibility. The application is now more suitable for people with a visual impairment who use screen readers. The JACoW conferences have adopted Indico, and a new governance process was kick-started with the United Nations Office in Geneva.

Zenodo – the multi-disciplinary repository developed and hosted by CERN – celebrated its tenth anniversary with a huge recognition from the European Commission (EC). The EC has identified the Organization, in particular the team of developers in the IT department, as the unique beneficiary of a special grant to carry out the HORIZON-ZEN project that aims to make publicly funded research data FAIR (Findable, Accessible, Interoperable, Reusable). HORIZON-ZEN will build on the widely appreciated features of Zenodo, which allows users to submit data, software and all research-related digital artifacts of up to 50 GB in all formats and from any stage of the research lifecycle.

Information repositories managed by CERN IT – such as Zenodo, CDS, Indico, CERN Open Data, GitLab, CodiMD and others – are mandated to store research data and documents in CERN's data centres for the very long term. In order to align with standard digital preservation recommendations (OAIS), a new strategy was designed in May with a central platform that can offer specialised digital preservation services for the various repositories.

A VARIED COMPUTING ENVIRONMENT FOR A VARIETY OF EXPERT USERS

The computing needs of the Organization, in terms of both operating systems and machines, are in constant evolution and the IT teams work relentlessly to align with the evolving needs of the users. Adopting agile methodologies facilitates rapid development cycles, ensuring that software applications are not only robust but also adaptive to changing dynamics.

The CERN private cloud hosts about 14 000 virtual machines, which were migrated over the course of several months in 2023 to allow the upgrade of the underlying hypervisor infrastructure from CERN CentOS 7 to Enterprise Linux 8. The deadline for the teams involved is June 2024, when CentOS 7 will be decommissioned.

The Laboratory's Windows and Mac infrastructure is also constantly evolving. Last year, a fleet of over 10 000 endpoint devices and 1600 servers managed by IT in different support models underwent software updates, operating system migrations and licence renewal or replacement. In parallel, the teams have started to work on planning the future of device management at CERN.

In October, the CERN IT department launched IT Support On Site (IT-SOS). Conveniently located in a room in Restaurant 2, the IT-SOS service offers support to users who prefer to solve their IT problems in person.

CONNECTING THE CAMPUS

Networks at CERN play a pivotal role in shaping how we connect, collaborate and share data and information in general.

Starting with the phone services, 2023 saw the decommissioning of the Alcatel PABX after more than 33 years of loyal service. 5150 fixed phone users migrated to the open-source CERNphone application during the year and a new function was developed for the TONE PABX to manage calls to the Service Desk, Control Centre and Fire and Rescue service. The introduction of the new GSM contract (with 5G & LoRa services) went very smoothly. 2023 also saw the end of a four-year project to modernise the campus network, requiring the replacement of over 800 switches and nearly 100 routers. In parallel, the software infrastructure was also updated to improve cyber security protection by enabling the separation of end-user traffic from that of building management security systems.

THE NEW DATA CENTRE

The construction of the Prévessin Data Centre (PDC), which started in 2022, was completed on time and on budget at the end of 2023. The new Data Centre complements the Meyrin Data Centre (MDC) and will house processing devices such as CPUs and business continuity/disaster recovery units, while the storage capacity will remain in the MDC. The new building makes use of the latest cooling technologies and will recover heat energy to warm other buildings on site.

The internal monitoring services at the Meyrin and Prévessin data centres have been streamlined, meaning that the console operator service can be suspended at the end of March 2024.

BREAKING ALL RECORDS IN DATA STORAGE

Efficient data storage is the backbone of any organisation's computing infrastructure. Throughout its history, CERN has been investing in cutting-edge storage solutions to enhance data accessibility and security while allowing seamless data management and reduced operational overhead. The colossal challenge of managing exabytes of data requires the adoption of storage architectures that can ensure data redundancy and resilience. This means that, even in the event of hardware failures, data integrity is maintained and services remain uninterrupted with no data loss.

For the first time, in 2023, CERN disk storage capacity passed the threshold of one million terabytes (equivalent to 1 exabyte), distributed over some 111 000 devices that form CERN's data storage capacity. These disks, most of which are used to store physics data, are orchestrated by CERN's open-source software solution, EOS, which was created to meet the LHC's extreme computing requirements. The data reading rate also achieved record thresholds, with a peak at 1 TB/s.

2023 was also the kick-off year for the ALICE O2 project. During the LHC lead-ion run, 40 PB of data were collected with an astonishing 100% availability of the storage system. This is not just a record performance but rather proof that the storage service is rock solid and ready for future LHC runs.

The Worldwide LHC Computing Grid connects around 160 data centres distributed across 40 countries.

THE DATA CENTRES DISTRIBUTED ACROSS 40 COUNTRIES ALLOWED THE EXPERIMENTS TO USE MORE THAN ONE MILLION COMPUTER CORES AND A TOTAL OF ABOUT 3 EB OF STORAGE.

SUPPLYING THE BEST TOOLS TO THE SCIENTIFIC COMMUNITY WORLDWIDE

The **Worldwide LHC Computing Grid (WLCG)** successfully met the challenges of Run 3 data taking. All LHC experiments benefited from the large amounts of computing resources provided by the collaboration. The data centres (around 160) distributed across 40 countries allowed the experiments to use more than one million computer cores and a total of about 3 EB of storage. In December, Serbia signed a Memorandum of Understanding with WLCG, marking a decisive step towards the country becoming the eighth Tier 1 centre.

Designed to provide opportunities and resources for CERN researchers to develop innovative computing technologies for future challenges, **CERN openlab** has continued to incubate projects ranging from evaluating new materials for long-term digital storage to developing digital twin technologies for scientific applications. CERN openlab is now ready to launch the next phase, which will start in 2024.

In 2023, BioDynaMo, one of the CERN openlab projects, was awarded the Best Artifact Award. The award recognises the exceptional quality and impact of the simulation platform, which allows scientists to run complex simulations, particularly in the fields of biology and medicine. The innovative computational model allows, for example, the simulation of a vascular tumour growth with a volume of 400 mm^3 using a total of 92.4 million agents. It will be further developed in 2024.

COMMITTING TO A POSITIVE IMPACT ON SOCIETY

In the framework of the continued efforts made to strengthen synergies with other international organisations, in 2023 CERN and the World Food Programme (WFP) signed a memorandum of cooperation paving the way for joint initiatives in which CERN's cutting-edge technologies – including artificial intelligence and quantum computing – will be made available to support WFP's global efforts in the fight against hunger.

As quantum computing is increasingly regarded as a transformative technology, the CERN **Quantum Technology Initiative (QTI)** continues to explore the potential applications of quantum computing in solving the complex problems faced by the scientific community. The first phase of the QTI was completed in 2023, and it will be followed by QTI 2, which is starting in 2024.

The year 2023 saw the announcement of the **Open Quantum Institute**, a three-year CERN-based programme that seeks to make quantum computing resources and technical expertise available to projects designed to support the UN's Sustainable Development Goals (SDGs). Hosted by CERN and coordinated by the IT department, the OQI was designed by the Geneva Science and Diplomacy Anticipator (GESDA) in collaboration with some 130 experts and is funded by UBS as lead support partner.

EMPOWERING MINDS

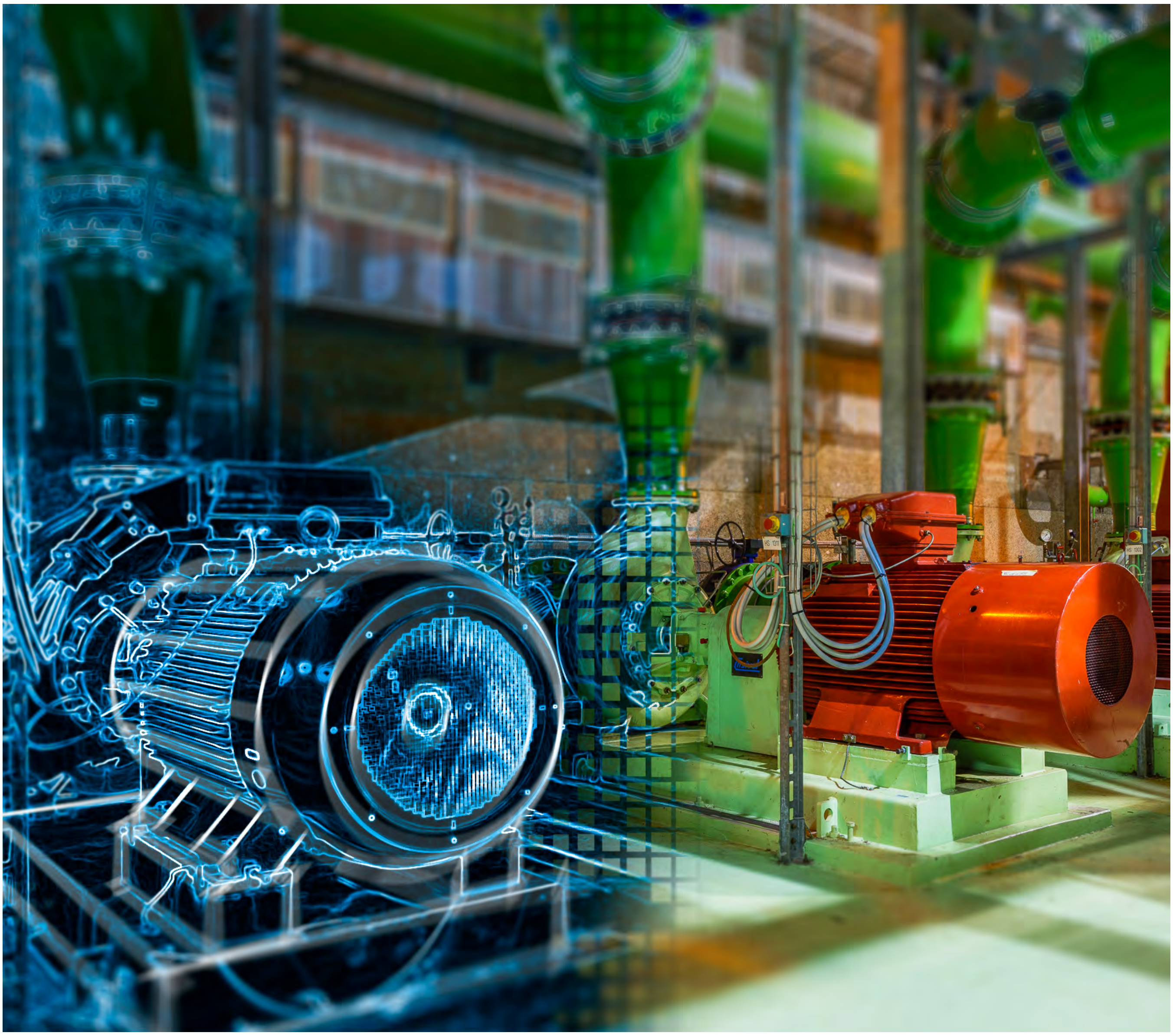
Education and training delivered within CERN's cutting-edge computing environment have the potential to empower young individuals with the skills and knowledge needed to thrive in today's digital world.

For the first time, four CERN Schools of Computing (CSC) were organised in the same year. In March, the Inverted CERN School of Computing presented a rich programme given by former CSC students in a wide area of topics, attracting over 200 participants to take part in the lectures and exercises. During the summer, 132 students in total took part in the Main CSC and two thematic schools in Tartu, Estonia, and Split, Croatia, with curricula including topics such as physics computing, software engineering, data technologies, security in research computing infrastructures and heterogeneous architectures.

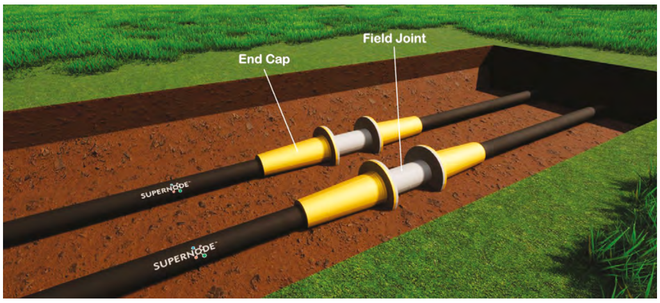
During the summer of 2023, the CERN openlab summer students filled the campus with their energy and motivation for nine weeks. Out of 2400 applications, around 30 students from about 20 countries were selected to take part in the programme, which included a lecture programme given by 19 lecturers as well as on-site visits. The students were accompanied in their work by their supervisors, who introduced them to their projects. At the end of their stay, the students presented their projects in a series of lightning talks.

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. Collaboration within CERN's Member and Associate Member States includes the transfer of CERN's knowledge to companies and research institutes, involvement in EU projects and the procurement of equipment and services.



CERN and ABB Motion collaborated to reduce the energy consumption of CERN's cooling and ventilation systems.
(OPEN-PHO-MISC-2023-007-2)



In the framework of CIPEA, CERN and Irish company SuperNode started a collaboration on superconductivity that could greatly improve energy transmission and accelerate the transition to renewable energy.

CERN INNOVATION PROGRAMME ON ENVIRONMENTAL APPLICATIONS (CIPEA) ENTERS A NEW PHASE

In 2023, the CERN Innovation Programme on Environmental Applications (CIPEA) made progress in converting ideas for environmental applications based on CERN know-how, as suggested by the CERN community, into significant projects. Eight new projects were initiated, five of which resulted in contracts with external partners, and began to produce results.

TAKING CANCER TREATMENT TO THE NEXT LEVEL

In December 2019, two former CERN physicists embarked on a journey to revolutionise proton therapy. Today, TERAPET, a medtech startup, has a team of 15 people, has raised 11 MCHF in total and recently celebrated the successful clinical tests of its first device, Qualyscan. With the support of a third co-founder, external funding and an R&D collaboration with CERN funded for three years (2020–2023) by the Innosuisse Innovation Project Fund, TERAPET has made significant strides in developing innovative medical devices that use CERN's expertise in scintillating crystals.

At the end of the year, work began on the construction of the FLASH facility's bunker at CHUV. It will house the accelerator and the treatment room.

CONSTRUCTION OF FLASH FACILITY BEGINS AT THE LAUSANNE UNIVERSITY HOSPITAL

2023 saw the start of the construction of a revolutionary radiotherapy facility that is the result of a collaboration between CERN, the Lausanne University Hospital (CHUV) and THERYQ, a medical technology company which, thanks to this project, has increased its team of experts in a variety of fields by 20. The aim of the facility is to revolutionise cancer radiation therapy by accelerating electron beams to 100–200 MeV while delivering a precise dose in under 100 milliseconds. This technique, known as FLASH, can treat tumours up to 20 cm deep and minimise damage to healthy surrounding tissue compared to other methods.

ENERGY-SAVING OPPORTUNITY FOR CERN COOLING AND VENTILATION MOTORS IDENTIFIED

In a joint research project, ABB and CERN developed a roadmap for reducing the energy consumption of CERN's cooling and ventilation system via data-driven energy efficiency audits. These systems are responsible for the cooling and ventilation of CERN's accelerator complex, experimental areas and data centres. The roadmap identified a savings potential of 17.4% across a total of 800 motors.

FROM CERN TO JUPITER

In April, ESA's Jupiter Icy Moons Explorer (Juice) spacecraft was launched on its journey to Jupiter. This historic, eight-year-long trip will end with a technical challenge: the planet's exceptionally strong magnetic field traps very high-energy electrons and can cause huge damage to electronic devices. Before embarking on its journey, Juice's critical components were tested at CERN, in the only facility on Earth capable of replicating Jupiter's harsh radiative environment, to make sure that they could withstand such conditions.

ESA's latest interplanetary spacecraft, Juice, lifted off on an Ariane 5 rocket from Europe's Spaceport to begin its eight-year journey to Jupiter.

CERN JOINS THE EUROPEAN QUANTUM INDUSTRY CONSORTIUM

In June, the European Quantum Industry Consortium (QuIC) welcomed CERN as an Associate Member to its community, which aims to boost the European quantum-technology industry's competitiveness and economic growth.

CERN VENTURE CONNECT: 24 PARTNERS, FAST ACCESS TO FIVE TECHNOLOGIES

CERN
Venture Connect

The innovation process needs help to bring together the right people and technologies and the necessary funding to see ideas come to fruition. The new CERN Venture Connect (CVC) programme aims to do just this by connecting entrepreneurs, providing them with fast access to a selection of CERN technologies and introducing them to investors and incubators who can help them succeed. Launched in July 2023, the programme has extensive support from an entrepreneurial ecosystem composed of 24 partners across Europe.

More examples of CERN's knowledge-transfer activities in 2023 can be found at:
https://report2023-kt.web.cern.ch

THE TIMING COMMUNITY GETS SYNCHRONISED: LAUNCH OF THE WHITE RABBIT COLLABORATION

The development of White Rabbit technology started at CERN more than ten years ago with the goal of synchronising the accelerators with picosecond accuracy. Over the past decade, this open-source solution, named after a character from *Alice in Wonderland*, has gained recognition in various industries as the benchmark for high-precision synchronisation. Its applications extend far beyond high-energy physics, finding uses in other research facilities and in commercial sectors alike. At end of the year, CERN launched a membership-based global community, called the White Rabbit Collaboration, to meet the latest needs of users and facilitate industry's uptake of this technology.

A FIRST STEP TOWARDS LOW-CARBON AVIATION

In 2023, the collaboration between CERN and Airbus UpNext passed its first milestone with the assembly and testing at CERN of a superconducting power-line demonstrator called SCALE (Super-Conductors for Aviation with Low Emissions). It has been established that using superconducting materials can reduce the weight of an aircraft's power line by a factor of more than 10, so this demonstrator plays an important role in assessing the potential of superconductivity to reduce weight and therefore contribute to the decarbonisation of future aircraft.

The project combines CERN's expertise in superconducting technologies with the innovative aircraft design and manufacturing capabilities of Airbus.

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 2023, CERN was involved in over 60 EU projects (excluding H2020 MCSA individual fellowships and Horizon Europe MSCA postdoctoral fellowships) and coordinated 18 such projects, with a total European Commission contribution to CERN amounting to some 41 million euros. Seven projects with a strong knowledge-transfer component (AIDAinnova, ATTRACT1B, ATTRACT2, HEARTS, I.FAST, PRISMAP and RADNEXT) are coordinated by CERN. Total EU funding for these seven projects amounts to around 73 million euros, distributed among the participating institutes and companies.

CERN SOFTWARE TO BECOME A CENTRAL HUB FOR EU RESEARCH DATA

For more than ten years, Zenodo, a CERN-born data repository, has been evolving to be able to store the scientific data for an increasing number of research communities and to meet the needs of more scientific disciplines. Today, it is used by more than 8000 research organisations worldwide and records over 53 million hits per year. Now, a new initiative, HORIZON-ZEN, is taking the software to the next level. Started in June 2023, this Horizon Europe project funded by the European Union aims to make the database the prime repository for EU research data (page 29).

INNOVATING TO ENSURE EUROPEAN ACCESS TO SPACE

Space is an extreme environment where cosmic radiation, consisting of high-energy particles, is damaging to advanced electronic components such as those found in satellites. In 2023, CERN joined other partners in academia and industry in the EU-funded project HEARTS (High-Energy Accelerators for Radiation Testing and Shielding), whose aim is to provide access to high-energy heavy-ion radiation testing facilities for electronics, shielding and radiobiology. As part of the project, two testing facilities at CERN and GSI (Germany) will be updated and made available for space industries and academia according to an agreed schedule. The project will be instrumental in ensuring European access to space.

HEARTS will equip the CHARM heavy-ion facility, located at CERN, to meet the needs of the space community in testing the effects of radiation on electronic components and systems.
(CERN-PHOTO-202101-002-2)

ATTRACT CHOSEN AS ONE OF THE MOST RELEVANT PROJECTS FOR THE NEW EUROPEAN INNOVATION AGENDA

During the latest workshop on innovation ecosystems, which took place in Brussels, the ATTRACT project was selected as one of the top-five initiatives that are significantly relevant to the New European Innovation Agenda. One of the special features highlighted by the European Commission was the ATTRACT Academy, which gives more than 700 young European innovators the opportunity to design and manage their own projects applying high-tech solutions for sustainability.

DOING BUSINESS WITH CERN

In 2023, the Organization significantly increased its expenditure on orders and contracts, which reached a total of 573 MCHF, a 20% rise compared to the previous year. This increase reflects higher investment across all main categories, including utilities, supplies, services and expenditure for the LHC experiments.

Two agreements to purchase solar power were concluded in 2023, ready for signature in 2024. Encapsulating the Organization's strategic approach to energy management, these agreements will cover 10% of CERN's electricity consumption during LHC runs and 30% during shutdowns, securing part of CERN's electricity supply at a set price and reducing the impact of market volatility.

A pivotal development in 2023 was the endorsement of the CERN Environmentally Responsible Procurement (CERP) Policy by the Enlarged Directorate, signifying a commitment to embed environmental responsibility throughout all phases of the procurement process. This strategic move is aligned with CERN's dedication to sustainable practices and responsible energy management, which was further solidified by its successful application for ISO 50001 certification for a period of three years. This certification underscores CERN's commitment to excellence and sustainability in its operations (page 40).

The site consolidation and new buildings programme led to the award of a contract for the provision of consultancy and work supervision services for the construction of the new Building 777, as well as to several contracts for the renovation of Building 60 and for construction and refurbishment work throughout the CERN site.

92 companies from across CERN Member and Associate Member States took part in CERN's thematic forum on civil engineering.
(CERN-HOMEWEB-PHO-2023-096-1)

A new type of thematic industry outreach events was introduced, succeeding the "Country at CERN" initiative. In this framework, the Procurement service organised two thematic events focused on areas such as civil engineering and electronics manufacturing (which CERN will soon require in large quantities). The plenary sessions of these two events attracted around 150 participants.

All in all, 2023 procurement activities involved over 25 500 orders of various types, in addition to 29 500 orders for the CERN Stores and 300 contracts, including 53 R&D collaboration agreements.

INSPIRING AND EDUCATING

To inform citizens of all ages and enthuse them with the wonder of the science and technology underpinning CERN's research, to engage them in the impact of CERN's research on our daily lives, and to inspire students to pursue careers in science and engineering continues to be one of the pillars of CERN's mission.

On 8 October, Science Gateway, CERN's new education and outreach centre, opened its doors to visitors from around the world. Close to 72 000 people visited in 2023 alone.

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1) CERN-PHOTO-202309-218-10
2) CERN-PHOTO-202310-241-31
3) CERN-PHOTO-202312-294-249
4) CERN-PHOTO-202310-256-18
5) CERN-PHOTO-202310-244-114
6) OPEN-PHO-LIFE-2023-085-4

WELCOMING VISITORS IN THE ICONIC CERN SCIENCE GATEWAY

Between opening to the public on 8 October and the end of the year, close to 72 000 visitors of all ages from more than 120 countries enjoyed the remarkable range of activities that CERN's new flagship education and outreach centre offers.

After three years of construction and content development, CERN Science Gateway was inaugurated on 7 October with the participation of the President of the Swiss Confederation, ministers and other high-level authorities from CERN's Member and Associate Member States, the project's donors and partners in CERN's research, education and outreach. The overall cost of CERN Science Gateway was 100 million Swiss francs, funded through donations.

Visitors to CERN Science Gateway discover three different universes in the exhibitions, where 54 hands-on experiments, 125 videos of CERN people, 50 real objects and four art commissions bring to life the research, technology and community of CERN. The exhibitions are accessible by design: they are accessible to wheelchairs, have subtitled films, and tactile content and audio descriptions for blind and visually impaired visitors.

Much in demand by school groups, but also by families and individual visitors, 270 enquiry-based laboratory workshops reached over 5200 participants. A total of 10 different workshops have been developed and delivered for 5-year-olds and older.

Science shows, designed to introduce scientific topics in a theatre-like style, are also on offer at CERN Science Gateway, targeted to a wide range of audiences. By the end of 2023, 40 science show sessions had been delivered to more than 2500 participants.

The emblematic guided tours of CERN now start at Science Gateway, connecting to the other visitor offers. Close to 183 000 people took part in guided tours in 2023, including the new visit itinerary at SM18. Those who were not able to travel to CERN had the chance to get to know the Laboratory online: around 3700 people took part in 107 virtual tours for schools and the general public.

More than 3000 people of different ages took part in 12 events developed specifically for the general public, hosted either at CERN Science Gateway or the beloved Globe of Science and Innovation. Ranging from workshops and talks to theatre and art performances, CERN's public events offer a platform for open dialogue around fundamental research and societal challenges.

EMPOWERING TEACHERS AND STUDENTS

After 25 years, CERN's teacher programmes have proudly reached 14 600 teachers from 107 countries. In 2023, a total of 27 national and international programmes welcomed 801 teachers from 55 countries, placing them well on track to reach pre-COVID-19 levels. The Ukrainian teacher programme remained online, reaching 70 teachers.

The Beamline for Schools competition completed its 10th edition, with another record-breaking participation: 379 proposals from teams representing 68 countries. As in the past three editions, two of the winning teams, from the USA and Pakistan, conducted their winning proposals at CERN, with a third team, from the Netherlands, being invited to DESY in Germany.

The CERN Solvay Education Programme, established between CERN and the science company Solvay, produced 12 new education videos, which collected 2.2 million online views. A core component of this programme is the annual student camp: in 2023, over 600 applications from more than 60 countries were received, with 30 students being selected for the first camp held in October.

In its pilot phase, the *Hands-on Physics* project, developed in collaboration with one of the Science Gateway donors, encompasses the development of a hands-on kit for Italian middle-schools. In 2023, 750 kits were produced and distributed to over 650 teachers, all of whom were trained to use the kits.

Beamline for Schools is a physics competition for high-school students from around the world. In 2023, the 10th edition was run, with winning teams developing their proposals at CERN and at DESY in Germany. (CERN-PHOTO-202309-229-5)

Women from CERN, EPFL, LAPP and the University of Geneva engaged with over 5000 students in the local area to mark the International Day of Women and Girls in Science. (OPEN-PHO-LIFE-2023-008-8)

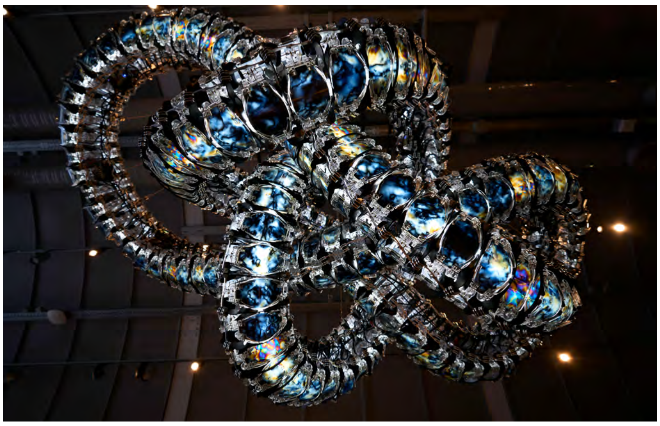
ENGAGING WITH STAKEHOLDERS AND COMMUNITIES

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 remains a key moment. In 2023, around 100 female scientists and engineers from CERN, EPFL, the University of Geneva and the Annecy Particle Physics Laboratory (LAPP) visited over 200 classrooms in the local region to talk to some 5100 pupils about their careers as women in science and engineering.

A newsletter dedicated to the FCC Feasibility Study (page 46) was launched, with regular updates on the study and its links to communities in the area of the potential tunnel.

CERN's travelling exhibitions visited three cities in Germany, reaching an estimated 53 000 visitors.

The Arts at CERN programme continued to bridge the worlds of art and science through artistic residencies, commissions and exhibitions. Artworks developed by former artists in residence were part of the exhibition "Time. From Dürer to Bonvicini " at Kunsthaus Zurich. The exhibition "Dark Matters", at Science Gallery Melbourne, was a collaboration between the gallery, the ARC Centre of Excellence for Dark Matter Particle Physics and Arts at CERN. It featured artworks resulting from the CERN programme, presented to Australian audiences for the first time.



Yunchul Kim's Chroma VII installation in CERN Science Gateway's Exploring the Unknown exhibition. (CERN PHOTO-202310-305-8)

The *CERN Courier*, a reference magazine for the high-energy physics community, published six issues, including a special issue dedicated to education and outreach and an "In focus" issue on "Enabling Technologies". It reached more than 23 000 subscribers worldwide, and garnered over 11 000 followers on X and 3500 on LinkedIn.

Communicating with and engaging the CERN community is important for community-building. In addition to the CERN Bulletin (with 20 000 electronic subscriptions), the new CERN CampusApp, developed by several CERN departments, includes relevant news and updates for the community.

Visits by decision makers from Member States, Associate Member States and beyond are key to maintaining long-term support for CERN's mission. A total of 170 high-level delegations visited CERN in 2023.

SUSTAINING DIGITAL REACH AND INCREASING ENGAGEMENT

CERN's strong digital presence continued in 2023, with approximately 3.5 million unique visitors making 13.7 million visits to the main website (based on extrapolated data).

CERN's community of followers on social media increased to 4.7 million, with posts being viewed 117 million times. Social media users also engaged with CERN posts, with 3.7 million actions (including likes and shares) taken in response to the posts.

WORLDWIDE MEDIA INTEREST

Media interest in CERN exceeded pre-COVID-19 levels: 662 journalists visited CERN on 123 organised media visits, and just over 190 000 press clippings were registered. The inauguration of CERN Science Gateway was of particular interest for the media: 83 journalists from 58 outlets attended, and media coverage generated more than 2000 clippings in outlets from around the world.

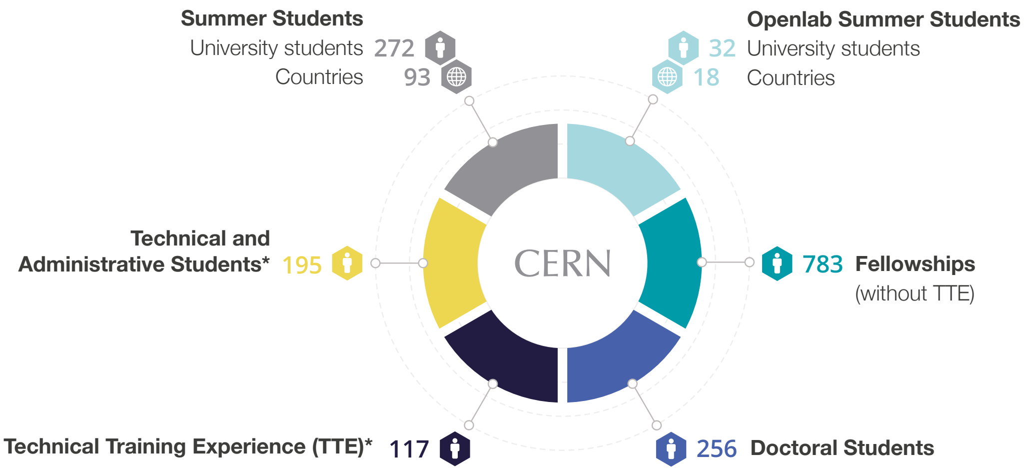
Media visits by journalists from CERN's Member States sustain interest in and support for CERN. Two online national media visits were organised for 12 journalists from 8 Hungarian media outlets and 12 journalists from 12 German outlets.

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 2023, some 1002 graduates and fellows, 465 doctoral, technical and administrative students and more than 270 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 so far nine Ukrainian nationals have 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 attended the openlab Summer Student programme (page 31). Ukrainian summer students who were unable to come to CERN benefited from a comprehensive online version of this key programme. In addition, a remote internship programme specifically for Ukrainian students was launched at the end of 2023.

CERN WELCOMED MORE THAN 300 SUMMER STUDENTS FROM OVER 90 COUNTRIES TO ITS SITES.

Training programmes at CERN



* as of 31.12.2023

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 its site or lives in the vicinity of its installations. Furthermore, CERN strives to limit its impact on the environment.

ENVIRONMENTALLY RESPONSIBLE RESEARCH

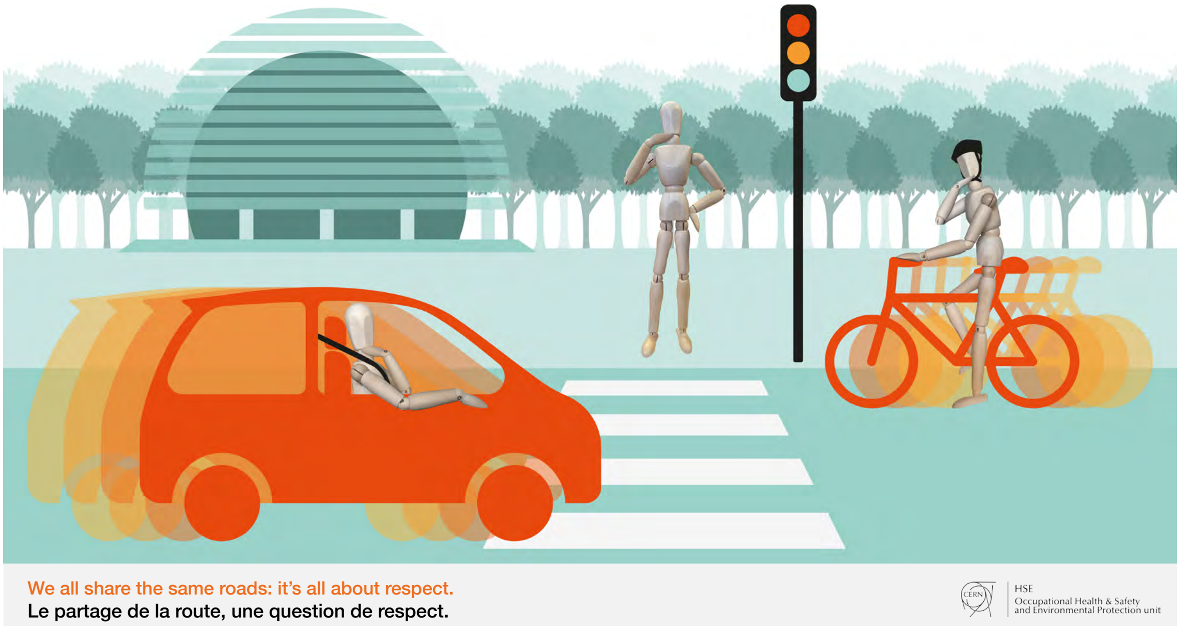
CERN's third Environment Report was published on 4 December 2023. The report, spanning 2021–2022, chronicles the advancements made in key environmental domains, including biodiversity, land use, waste and noise. The report details the specific measures taken to reach the Organization's priority objectives, such as reducing direct greenhouse gas emissions and limiting the rise in water and electricity consumption.

As part of its commitment to sustainable research, CERN sought ISO 50001 certification, which was awarded in February 2023. The ISO 50001 standard specifies the requirement for systems and processes to continuously improve energy performance.

CERN-WIDE SAFETY OBJECTIVES

The CERN Safety Policy, which spans all areas of occupational health and safety, environmental and radiation protection and the safe operation of CERN's facilities, sets out the Organization's commitment to the continuous improvement of safety.

In this context, CERN regularly sets safety objectives, both annually and for the longer term. These include measures to prepare for the next long shutdown of the accelerator complex, such as improving electrical safety, reducing radioactive waste products and increasing awareness of life-saving actions in the event of an emergency. In terms of environmental protection, specific annual objectives to mitigate noise and improve the quality of effluents



Road safety awareness campaign.

released into local watercourses complement the long-term objectives set out in the Environment Report.

THE HSE OPERATIONAL RESPONSE PROJECT

The HSE Operational Response (HOR) project, launched in May 2022 and set to run until 2025, aims 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. The project comprises several work packages.

In 2023, particular progress was made on the work package concerning the occupational health management plan, with the delivery of a revised, risk-based occupational medicine framework, tailored to the individual's medical condition. The Medical Service successfully addressed the backlog of periodic visits for employed members of the personnel, which had accumulated in particular due to the COVID-19 pandemic. This will ensure optimal and sustained monitoring of the personnel in 2024.

The work package on emergency response focuses on situations with adverse environmental consequences. In 2023, information regarding the sources of environmental hazards and the corresponding prevention and protection devices was integrated in the CERN Geographical Information System portal, from which evacuation plans can also now be generated. The CERN Fire and Rescue Service collaborated with the HSE Environment group to establish an intervention procedure and an inventory of technical means to respond to situations posing environmental risks.

Finally, the work package on inspections and safety reviews focused on re-evaluating the role of territorial safety officers with the objective of ensuring that they are suitably equipped and supported.

SAFETY TRAINING

A new learning programme, "Safety Matters for Supervisors", has been developed and will be rolled out in 2024 as an integral part of the learning and development path for managers. It covers the duties and resources of managers regarding occupational health and safety, psycho-social risks and environmental protection.
To raise safety awareness more generally, newcomers now receive basic safety information in the form of a flyer, and a "Safety at CERN" video has been produced for the CERN community alongside topic-specific communications.

96 300 e-learning safety courses followed
920 classroom safety courses delivered to
6000 people
4950 service desk tickets answered

CERN WAS AWARDED THE ISO 50001 CERTIFICATION FOR ENERGY MANAGEMENT IN FEBRUARY 2023.

Extracting tritium from equipment and other material in which it is present.

MELTING CERN'S METALLIC RADIOACTIVE WASTE: THE MAST PROJECT COMPLETES SUCCESSFULLY

Interaction with particle beams can lead to the activation of equipment present inside the accelerator complex. When this equipment is removed during maintenance and consolidation of CERN's facilities, it becomes radioactive waste. This waste consists mainly of large metal components, cables and ventilation filters and is eliminated in dedicated facilities in CERN's Host States, France and Switzerland.

According to the level of activity, CERN's radioactive waste is classified as "candidate for clearance", "very low-level" (TFA) or "low- and intermediate-level" (FMA) waste.

About 90% of the volume of all of CERN's FMA waste is metallic. Melting is the most promising technique to treat FMA metallic radioactive waste: it reduces the waste volume optimally, allows accurate radiological characterisation, achieves detritiation and minimises handling.

The Melting of Activated Steel (MAST) project was set up in 2019 with the objective of running a pilot campaign for the treatment and elimination of CERN's metallic FMA waste by melting. Following successful melting of pilot batches at the end of 2022, the resulting ingots were disposed of in the French final repository by 15 June 2023. This project was key to establishing an efficient elimination pathway for the yearly disposal of up to 16 m^3 of FMA metallic waste in France.

BUILDING FOR THE FUTURE

In CERN's pursuit of new frontiers in fundamental science, its team of physicists, engineers and technicians are engaged in the innovation, design and construction of the next generation of accelerators and detectors. Currently, the focus is on the High-Luminosity Large Hadron Collider (HL-LHC), CERN's upcoming flagship machine, with production of its challenging hardware fully under way. Simultaneously, plans are being crafted for pioneering machines that will shape the scientific landscape in the longer-term future.

Testing of a niobium-tin quadrupole magnet assembled at CERN. The tests on these magnets were successful, marking a key milestone for the HL-LHC project in 2023. (CERN-PHOTO-202311-263-32)

Tests at CERN of the first D2 prototype separation-recombination dipole, built in Italy by the national institute for particle physics, INFN. *(CERN-PHOTO-202303-078-8)*

The future of particle physics in Europe is mapped out by the European Strategy for Particle Physics, which was last updated in 2020. The top priority is to commission the HL-LHC from 2029 onwards. For the longer term, the Strategy called for the study of a circular electron-positron collider, operating as a Higgs factory in a new tunnel. In addition to these two initiatives, CERN's research and technology programme offers a wide variety of diverse projects.

HIGH-LUMINOSITY LHC PROJECT

The aim of the High-Luminosity LHC (HL-LHC) project is to increase the number of collisions produced during the designated operating period, the "integrated luminosity", by a factor of ten compared to the goals of the original LHC machine. The project calls on a host of innovative technologies that took many years of engineering and prototyping to develop. Much of this new equipment went into series production in 2023 and some is already available to be installed.

Increasing luminosity requires, among other things, new magnet systems. Twenty-four quadrupole magnets known as "triplets" will focus the particle beams more strongly before they intersect at the heart of the ATLAS and CMS experiments. The magnets are made of a brittle superconducting material called niobium-tin (Nb_3Sn), which is being used in a particle accelerator for the very first time to allow magnetic fields to be pushed to higher levels than ever before.

There are two variants of these quadrupoles. The shorter (4.2-m) quadrupoles are being built in the United States and the longer (7.2-m) ones at CERN. A cryomodule containing two short quadrupoles was tested and validated in the United States and delivered to CERN at the end of the year. Thanks to improvements to the manufacturing processes, a third long prototype has been successfully tested and two series magnets have also achieved nominal performance. This is a key step on the way to validating the Nb_3Sn technology. With this success under their belts, the teams have forged ahead with the series production of the long quadrupoles. Production of the associated corrector magnets has also progressed well, and those produced by INFN's LASA laboratory in Italy have even been fully validated and delivered.

SUCCESSFUL TESTS VALIDATED NIOBIUM-TIN SUPERCONDUCTORS FOR MAGNETS.

The particle beams circulating in opposite directions will be guided into collision at the interaction point and then separated again by special dipole magnets – the D1 and D2 separation-recombination magnets – which are under construction in Japan and Italy respectively. The first two prototypes of both have passed their cold tests at CERN and the first D2 pre-series magnet has been delivered.

Crab cavities are another crucial component used to increase luminosity. In the LHC, the two counter-circulating proton beams meet at a small crossing angle at the collision point of the experiments. The crab cavities have the ability to "tilt" the proton bunches in each beam, maximising their overlap at the collision point. Two types of crab cavity, radiofrequency dipole (RFD) and double-quarter wave (DQW), are being built. The first series-produced DQW cavity was cold-tested at CERN and far exceeded the acceptance criteria. Series production continues in Germany. A cryomodule comprising two RFD cavities, assembled in the United Kingdom, has also been delivered but will need to undergo some repairs before being installed for beam tests in the SPS machine in 2025.

Installation of a new crystal collimator in the LHC for in situ tests during lead ion running. *(CERN-PHOTO-202302-036-4)*

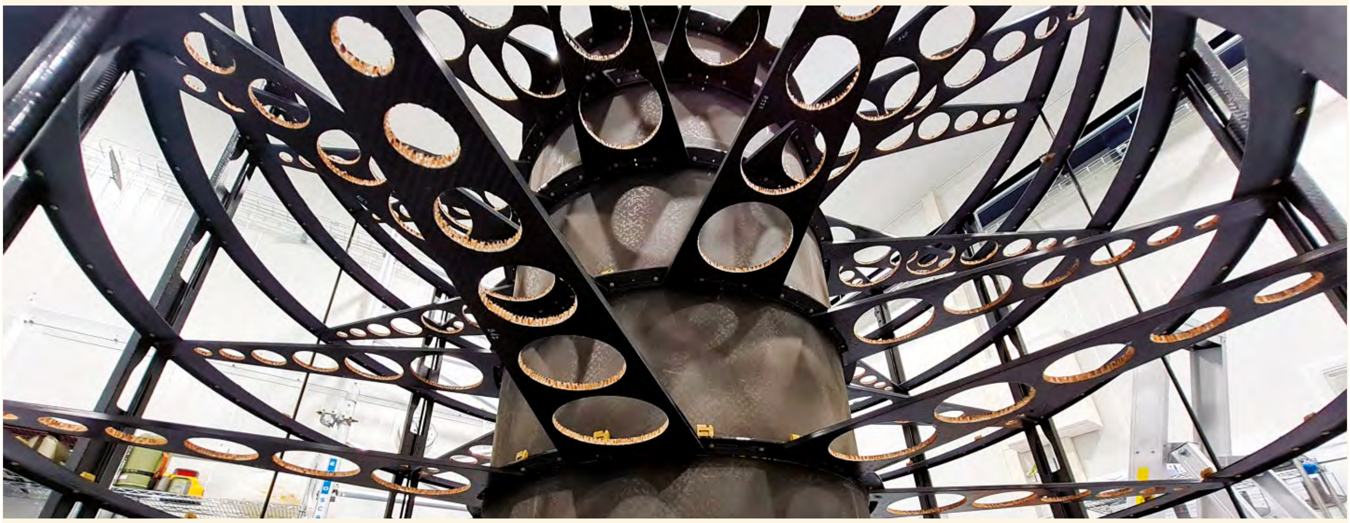
With the increase in luminosity, notably due to a greater number of particles in circulation, the machine protection system needs to be upgraded. More than 80 new collimators and passive absorbers need to be installed or modified. These devices absorb particles that stray from the beam core and risk damaging the machine. Sixteen additional collimators were installed during the second long shutdown and new collimator prototypes have been developed at CERN. In particular, crystal collimators were installed in the LHC and used during lead ion running in 2023. This allowed a much-improved beam cleaning technique to be demonstrated, and it has now been validated for use in high-luminosity ion operation.

Electricity will be supplied to the new magnets by high-temperature superconducting links, using magnesium diboride superconductors, transporting currents of up to 120 000 amps across distances of up to 100 metres. The cables will be housed in a flexible cryostat that will keep the temperature below 25 Kelvin. A full link containing 19 cables and their connection systems has been produced and will be installed on the inner-triplet test bench in 2024.

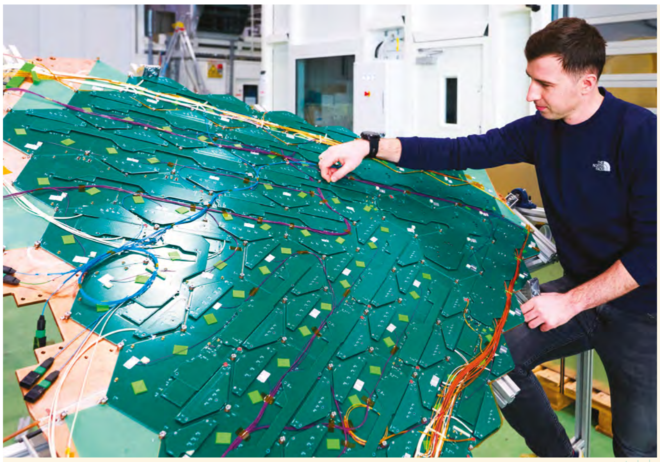
Installation of a 90-m-long test bench, known as the “IT String”, has begun in the SM18 magnet test hall. It will test all the new equipment to be installed on either side of the ATLAS and CMS detectors under real conditions, and will allow the integration, interconnection and operation of the individual components as well as the overall system to be validated. All the technical infrastructure has been installed, including the power converters and the 1.9 K cryogenic distribution line, which is now operational. The IT String will continue to test magnets and other HL-LHC components in 2024.

THE EXPERIMENTS HEAD FOR HIGH LUMINOSITY

High-luminosity running will bring about an unprecedented pile-up of collisions in the heart of the ATLAS and CMS detectors, with some 140 to 200 collisions per crossing compared to about 60 at present. The ATLAS and CMS collaborations have ambitious detector upgrade programmes, with the aim of increasing the rate of data transfer and the granularity of the subdetectors, as well as their radiation hardness. The ALICE and LHCb collaborations have also been working for a number of years on programmes to replace and upgrade their subdetectors.



Construction of the delicate carbon structures for the end-caps of the new ATLAS inner tracker at NIKHEF (Netherlands). *(ATLAS-PHOTO-2024-007-34)*



Model for testing the module assembly of a slice of the CMS high-granularity calorimeter. *(CERN-PHOTO-202402-055-23)*

ATLAS is developing a trigger system that is ten times faster than the existing one and getting ready to replace the readout electronics of several subdetectors. The collaboration has produced a global trigger prototype, designed to combine the information from each trigger system with the information from the high-resolution calorimeters, with a view to the final decision.

The prototype readout boards for the electromagnetic calorimeter performed well in tests. A high-granularity timing detector is being developed to distinguish between events taking place simultaneously. The first hybrid modules have been tested with beam and have displayed a time resolution of 70 picoseconds, which is compatible with the final objective of less than 50 picoseconds.

Another flagship project is the replacement of the inner tracker with a new inner tracker made entirely of silicon, comprising nine layers of silicon pixels and strips. Silicon pixel and strip production has progressed. The pre-production phase of the ASIC readout chips was launched and some have been validated during beam tests. Production of the delicate and complex carbon support structures, including the cooling system, progressed well.

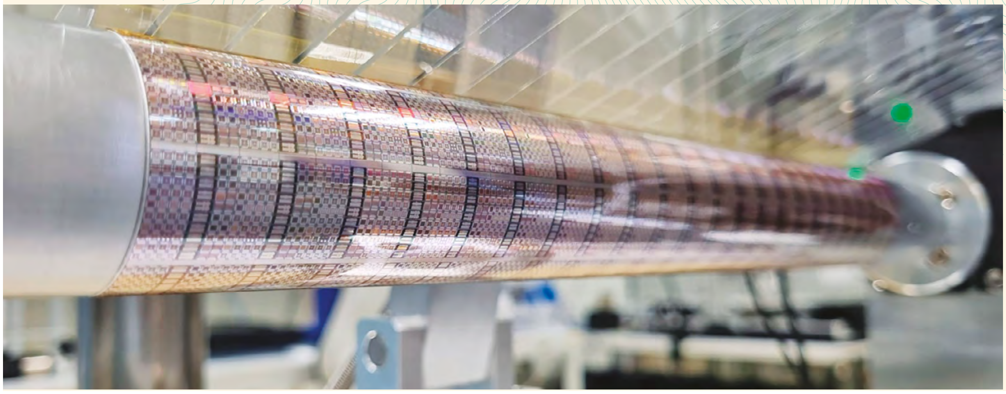
CMS is replacing its tracker and end-cap calorimeters with a high-granularity calorimeter (HGCAL). The engineering design review of both new detectors has been completed. The various sensors have also been qualified. The HGCAL will have 6.4 million channels, 100 times more than the existing calorimeter. The first absorbers have been manufactured and validated. A prototype comprising the various sensors and the full electronics chain (trigger plus acquisition) has been tested on a beamline at the SPS. The barrel section of the calorimeter will be equipped with new electronics – the prototype new electronic boards have been successfully tested on a supermodule under real conditions in beam.

The outer part of the new tracker will comprise 2 billion micropixels and the inner part 42 million silicon strips. The various sensors are under or close to production and the integration tests have progressed well. The sensors for the new and ultra-precise barrel MIP timing detector have been produced. The new trigger system passed the integration tests while connected to various subdetectors.

ALICE is planning two major upgrades for Run 4: a new inner tracker and the addition of a forward calorimeter. The first three layers of the existing tracker will be replaced by a more accurate vertex detector (ITS3) positioned closer to the collision point and using monolithic active pixel sensors. The sensors and their readout system are printed on the same substrate, which can be bent in order to follow the cylindrical geometry of the detector. A prototype wafer-scale silicon sensor has been produced to test the technology.

The forward calorimeter (FoCal) has a high-granularity electromagnetic part, with alternating tungsten and silicon plates, and a hadronic part made of plastic scintillating fibres inserted inside copper tubes. The prototypes of both calorimeters have been tested, separately and jointly, with beams from the SPS. The technical design reports for both detectors have been submitted to the LHC Experiments Committee. The R&D for ALICE3, a completely new detector for Runs 5 and 6, is in progress.

Most of the high-luminosity upgrades to the **LHCb** detector were done during Long Shutdown 2, including the installation of VELO, a new vertex detector that has the distinguishing feature of cramming all its sensors close to the interaction point. The detector was installed in 2022 but suffered an accident at the beginning of 2023 when its aluminium enclosure, which insulates it from the primary vacuum of the LHC, was deformed, leading to data-taking in degraded mode for the whole year. The replacement operation finally took place during the 2023–2024 year-end technical stop. The technical design reports for the upgrade of the Cherenkov detectors (RICH) and the electromagnetic calorimeter have been submitted to the LHC Experiments Committee.



The ALICE experiment's new vertex detector uses monolithic active pixel sensors that can be bent to follow the cylindrical geometry of the detector. *(ALICE-PHO-GEN-004-21)*

Artist's impression of the Future Circular Collider electron-positron machine (FCC-ee). (OPEN-PHO-CIVIL-2024-001-21)

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY

The Future Circular Collider project envisages the construction of a very large circular electron–positron collider (FCC-ee) by around 2045. The tunnel could then be used in a second phase to house a hadron collider (FCC-hh). The FCC collaboration comprises 130 institutes in 31 countries. In 2023, a report was submitted to the CERN Council and its subordinate bodies for a mid-term review of the Feasibility Study. This 700-page document describes the technical characteristics of the two colliders and the associated infrastructure, the physics goals, the planned detectors and the studies relating to the civil engineering, the placement and the environment, and provides an analysis of the costs, the funding model and the socio-economic benefits for the region.

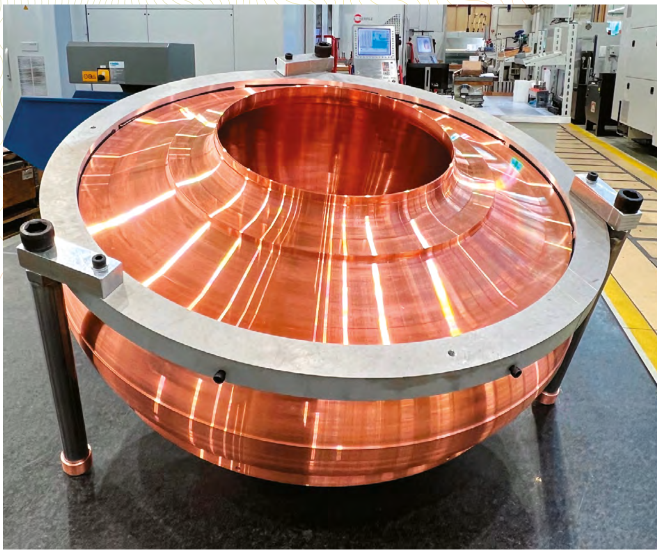
AN OPTIMISED PLACEMENT

After extensive studies, the optimal placement in the region between France and Geneva has been chosen from about a hundred different possibilities. The layout was devised in collaboration with the French and Swiss authorities and local experts, and involves a 90.7-km tunnel with eight underground caverns, four of which will house experiments, connected to the surface sites by twelve access shafts. It takes into account the geology, electrical power network, road connections, and urban and environmental integration. Field studies have been performed, especially to document the present environmental status, and numerous meetings have been held with the 41 local communities in France and Switzerland that sit on the path of the accelerator.

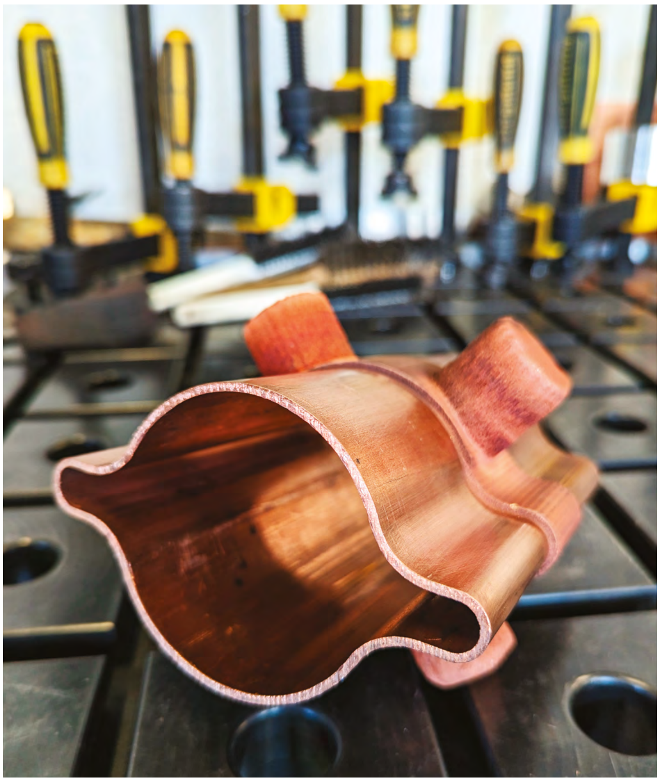
The civil engineering study involved a 3D geological model that was finalised in 2023 and will be complemented by a campaign of geophysical studies and geological investigations, planned with the Host States. The reuse of excavated materials, primarily molasse rock, is an important consideration. The results of an international contest to imagine innovative means of reusing these materials were unveiled in 2023. One of the proposals is to transform the molasse into fertile soil for agricultural or forestry use. A plot of land has been set aside at LHC Point 5 to test the use of such soil as part of the *OpenSky Laboratory* project.

PUSHING THE BOUNDARIES OF TECHNOLOGY

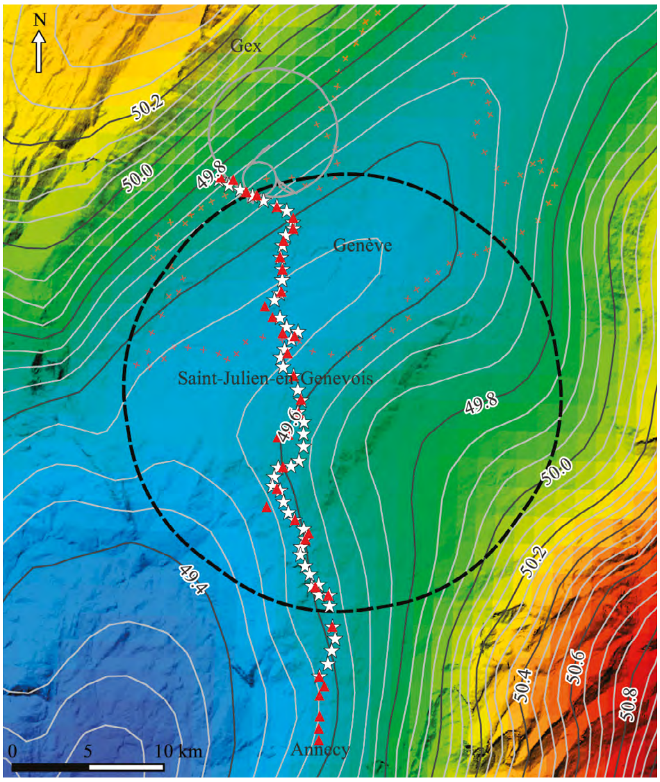
The construction of a machine as ambitious as the FCC calls for technological breakthroughs. Innovative technologies developed in this context can be interesting for many accelerator projects and beyond. The full FCC-ee



A full-size radiofrequency cavity was bulk-machined in CERN's Main Workshop. (OPEN-PHO-ACCEL-2024-010)



Prototype vacuum chamber extrusion equipped with cold-sprayed bosses on which the beam position monitors will be mounted. *(OPEN-PHO-ACCEL-2024-011)*



Map showing the gravity field measurements (red triangles and white stars) in the region covered by the FCC (shown by the dotted line). These measurements help refine the existing geodetic reference system. *(OPEN-PHO-CIVIL-2024-002-1)*

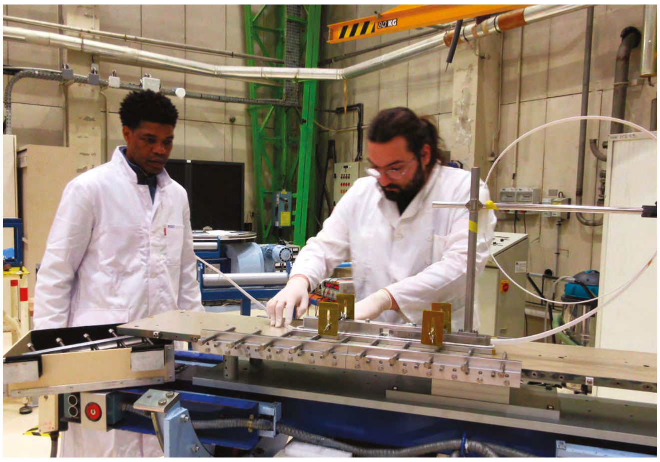
programme will require a large number of superconducting radiofrequency (SRF) cavities. Development work is under way within the SRF programme to improve the efficiency of the cavities and to reduce their power consumption. Hydroforming or machining the cavities from the bulk material avoids, for example, imperfections around the welds and provides significantly better surfaces to obtain a higher-quality niobium superconducting coating. Prototypes of small (1.3 GHz) cavities have been produced by hydroforming in cooperation with the Japanese laboratory KEK. The niobium coatings on small 1.3 GHz cavities, bulk-machined in the CERN workshop, have demonstrated excellent performance. This result shows the clear potential for the challenging FCC specifications to be met. A first full-size 400 MHz cavity has been machined from bulk copper at CERN.

Much R&D work is being done around the vacuum chambers and their components, including the instrumentation and the synchrotron radiation absorbers. Synchrotron radiation is one of the limiting factors for electron machines. The use of cold spraying to produce the mini-blocks on which the beam position monitors will be mounted has been tested and has proven successful. This method gives greater precision and manufacturing repeatability. It is an important development because the collider will be equipped with about 7000 of these monitors.

The geodesy challenges are of a scale matching that of the machine itself. Development of a geodetic infrastructure in the French-Swiss region began in 2023. It will extend and refine the existing geodetic reference systems and contain topographical and geological data and variations in the gravity field. It is being developed in partnership with the Federal Topography Office (Switzerland), the National Institute of Geographical and Forestry Information (France) and the ETH Zürich and HEIG-VD institutes.

MORE POWERFUL MAGNETS

The hadron collider, FCC-hh, will require magnets that are capable of producing magnetic fields of unprecedented strength. The high-field magnet (HFM) programme was launched in 2021 and is now in full swing. The principal objective is to develop niobium-tin (Nb_3Sn) technology in order to produce 14-Tesla bending magnets and then to push quickly ahead with research into high-temperature superconducting (HTS) magnets, which would allow higher fields to be reached while at the same time reducing the cooling power required. In 2023, the programme welcomed new research institutes into the fold. Several national laboratories (CEA, CIEMAT, INFN, PSI) set up cutting-edge R&D facilities where Nb_3Sn and HTS coils are now being produced. New facilities for research into superconducting materials have been inaugurated at CNR-SPIN in Italy, where the potential of iron-based superconductors will be investigated, and at the KIT Institute in Germany, where methods for optimising ReBCO-coated wires – the only HTS tape available in industry for high fields – will be studied for their potential use in accelerator magnets. These developments are undertaken in close collaboration with CERN, which provides advice, technical expertise and material support.



Production of a prototype coil at CEA (France) as part of the CERN-CEA collaboration for the development of niobium-tin high-field superconducting magnets.

LINEAR COLLIDERS

The Compact LInear Collider (CLIC) is a linear electron-positron collider proposal with three stages ranging from 380 GeV up to 3 TeV. Work on the underlying X-band acceleration structures and nanobeam technology continued, and prototype accelerating structures were tested. This technology has important industrial and medical applications, notably through a collaboration with the Lausanne University Hospital (CHUV) and French industry, aimed at developing a new radiotherapy technique (page 33).

The International Linear Collider (ILC) project moved ahead with the start-up of the ILC Technology Network (ITN). In this context, an agreement has been signed between CERN and KEK (Japan). The EAJADE project, financed within Europe's Marie Skłodowska-Curie programme, has been launched and will facilitate the exchange of accelerator experts in Europe, the United States and Japan on the subject of Higgs factories.

MUON COLLIDERS

A muon collider project is being studied by the International Muon Collider Collaboration (IMCC). Collisions of muons at up to 10 TeV centre-of-mass energies could be reached, far higher than those that can be obtained with electrons. Major technological challenges will need to be overcome, relating in particular to the very short lifespan of muons. In 2023, the collaboration launched the MuCol project, co-funded by the European Union, aimed at intensifying R&D efforts around radiofrequency cavities, magnets and muon cooling systems. Studies of muon beam production and dynamics are in progress. At the end of 2023, the P5 Panel, which is responsible for setting the strategic direction of particle physics in the United States, identified muon colliders as an important R&D endeavour and recommended that American research institutes join the IMCC.

NEUTRINO RESEARCH

CERN contributes to global neutrino research efforts via its Neutrino Platform, at which theoretical studies are performed and detectors are developed for projects in the United States and Japan.

The US project LBNF/DUNE provides for a neutrino beam to be sent from Fermilab in Illinois to the giant detector of the Deep Underground Neutrino Experiment, known as DUNE, 1300 kilometres away in South Dakota. CERN is producing and testing prototypes of this detector and will be supplying the final cryostats.

The first full-size cryostat for the US was built in Spain in 2023. The last two prototypes for DUNE have now been installed in the immense cryostats of CERN's Neutrino Platform. The first is testing a vertical drift chamber using

A vertical drift chamber has been installed in one cryostat of the prototypes for DUNE. *(CERN-PHOTO-202308-195-28)* large printed circuits known as charge readout planes (CRP). The first vertical drift chamber module has been installed with four prototype CRP plates, which have been tested. In the second cryostat, a horizontal drift chamber comprising an anode plane assembly (APA), four layers of wires with different inclinations, is being tested. A prototype made up of four APAs has been installed in the cryostat. Both prototype detectors will be tested in 2024.

The CERN Neutrino Platform is also contributing to T2K, a facility in Japan where a neutrino beam is sent 295 km from J-PARC to Super-Kamiokande. The CERN team is assisting with the upgrade of the ND280 near detector, which is located 280 metres from the target that produces the neutrinos. A first time-projection chamber (TPC) and a new gas system have been installed. The second TPC has been assembled and will be installed in 2024.

PHYSICS BEYOND COLLIDERS

The Physics Beyond Colliders programme, launched in 2016, has fostered many initiatives for experiments complementing those conducted with colliders.

Several of these relate to new experiments in the North Area using beams produced by high energy protons from the Super Proton Synchrotron (SPS). Two competing proposals were submitted for the future exploitation of the underground hall known as Experimental Cavern North 3 (ECN3): BDF/SHiP (Beam Dump Facility/Search for Hidden Particles) to search for hypothetical weakly interacting particles that could be candidates for dark matter, and the combination of two experiments, namely HIKE (High Intensity Kaon Experiment) which would continue the ongoing search for rare kaon decays and SHADOWS (Search for Hidden And Dark Objects With the SPS), which has objectives similar to those of BDF/SHiP. Both projects require a high intensity beam. Much effort went into evaluating the two proposals, their physics potential and their technical feasibility.

Several other experiments are being studied in the North Area, some using various types of ions, taking into account the complementarity with the other ion-based experiments. The Forward Physics Facility is a project that would house several experiments in an underground hall some 600 metres away from the ATLAS interaction point in the forward direction. These detectors would be designed to intercept feebly interacting particles and neutrinos produced in high-luminosity LHC collisions. The feasibility study for this new facility progressed well in 2023, notably the design and integration study of the detectors and the geological investigations. Studies of the effects of the vibrations expected during the civil engineering work showed that excavation could take place in parallel with HL-LHC operation.

Another project proposes use of the particles of the LHC's transverse beam "halo". Such particles could be deflected by a two-crystal arrangement to allow studies of the electric and magnetic dipole moment of short-lived charmed particles. Tests with crystals were performed using a beam from the SPS in 2023 and a prototype is under development.

A conceptual feasibility study has been performed for the AION-100 project, which involves installing a 100-m atomic interferometer in a shaft at LHC Point 4 with a view to dark matter and gravitational wave searches at frequencies that are currently inaccessible.

WAKEFIELD ACCELERATION

The AWAKE experiment is testing the acceleration of electrons using a plasma wakefield generated by proton beams. This technology would make it possible to reach acceleration gradients hundreds of times higher than those of traditional RF cavities. AWAKE has installed and tested a new rubidium vapour plasma source, and preliminary results have shown that the wakefields generated are more intense than with the previous source. A prototype discharge plasma source has also been tested. This modular technology should allow the development of scalable plasma sources.

The AWAKE experiment's new rubidium vapour plasma source.
(CERN-PHOTO-202307-176-35)

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

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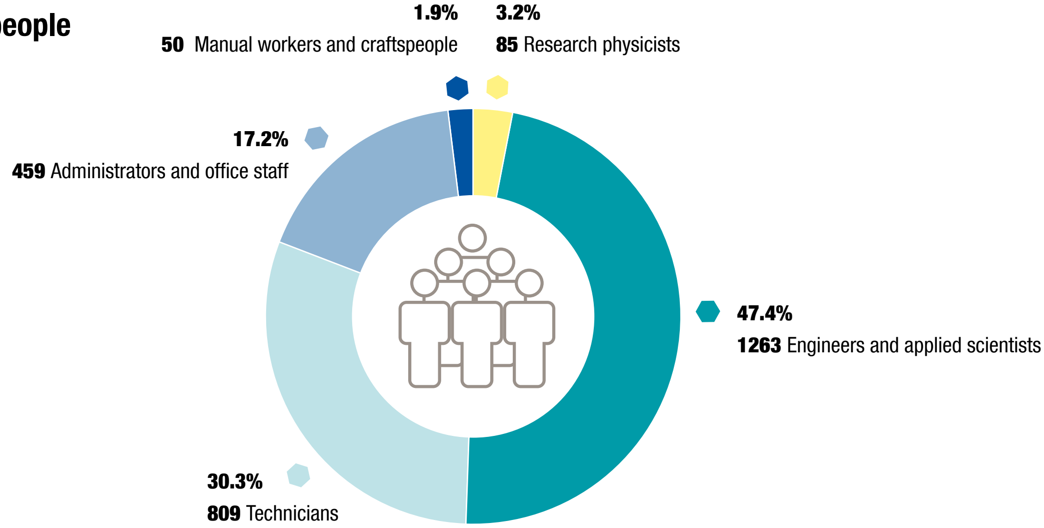
CERN STAFF

Total: 2666 people



EVOLUTION OF STAFF MEMBERS

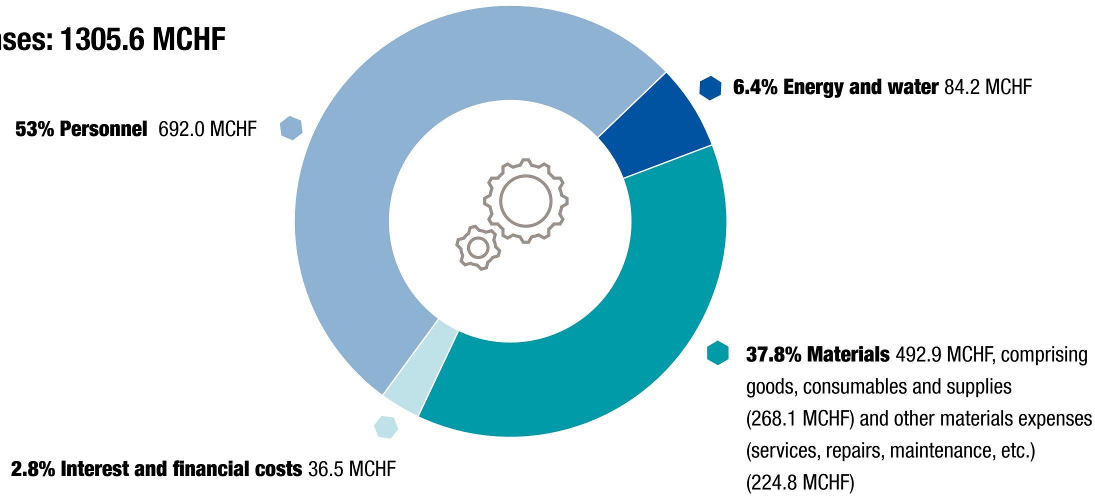
2019	2660
2020	2635
2021	2676
2022	2658
2023	2666

In addition to staff members, in 2023 CERN employed 1002 graduates and fellows (including 68 TTE* technicians), trained 776 students and hosted 990 associates. CERN's infrastructure and services were used by a large scientific community of 12 370 users in 2023.

*The Technical Training Experience (TTE) programme is being phased out and has been absorbed by the new Graduate programme since 2023.

CERN EXPENSES

Total expenses: 1305.6 MCHF



In 2023, 35.7% of CERN's budget was returned to industry through the procurement of supplies and services. CERN strives to ensure a balanced industrial return for its Member States.

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Sixty-ninth 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 2023 Knowledge Transfer annual report is available at:
http://kt.cern/annual-report
The 2023 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

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