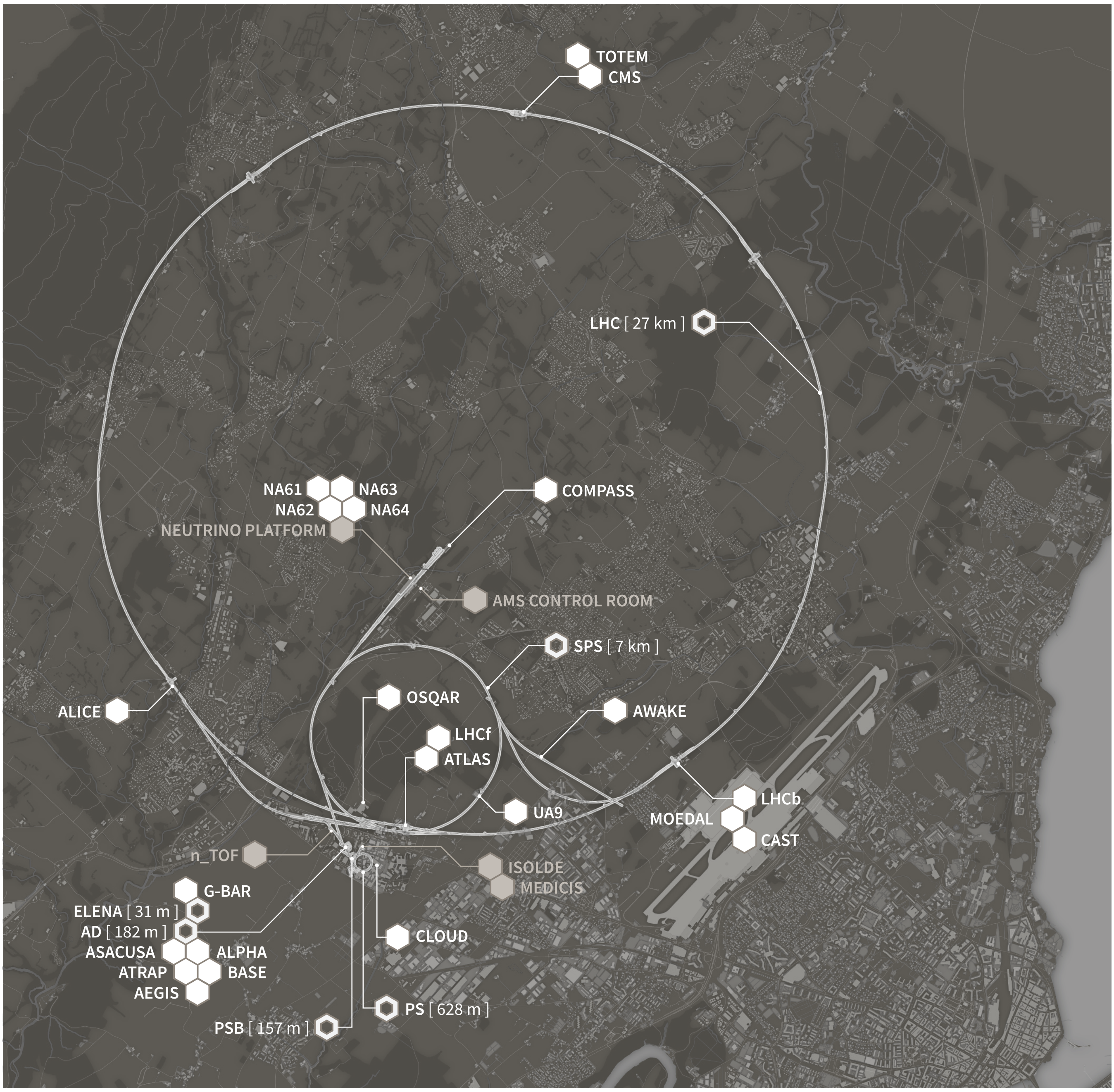
EXPLORING THE NATURE OF THE UNIVERSE

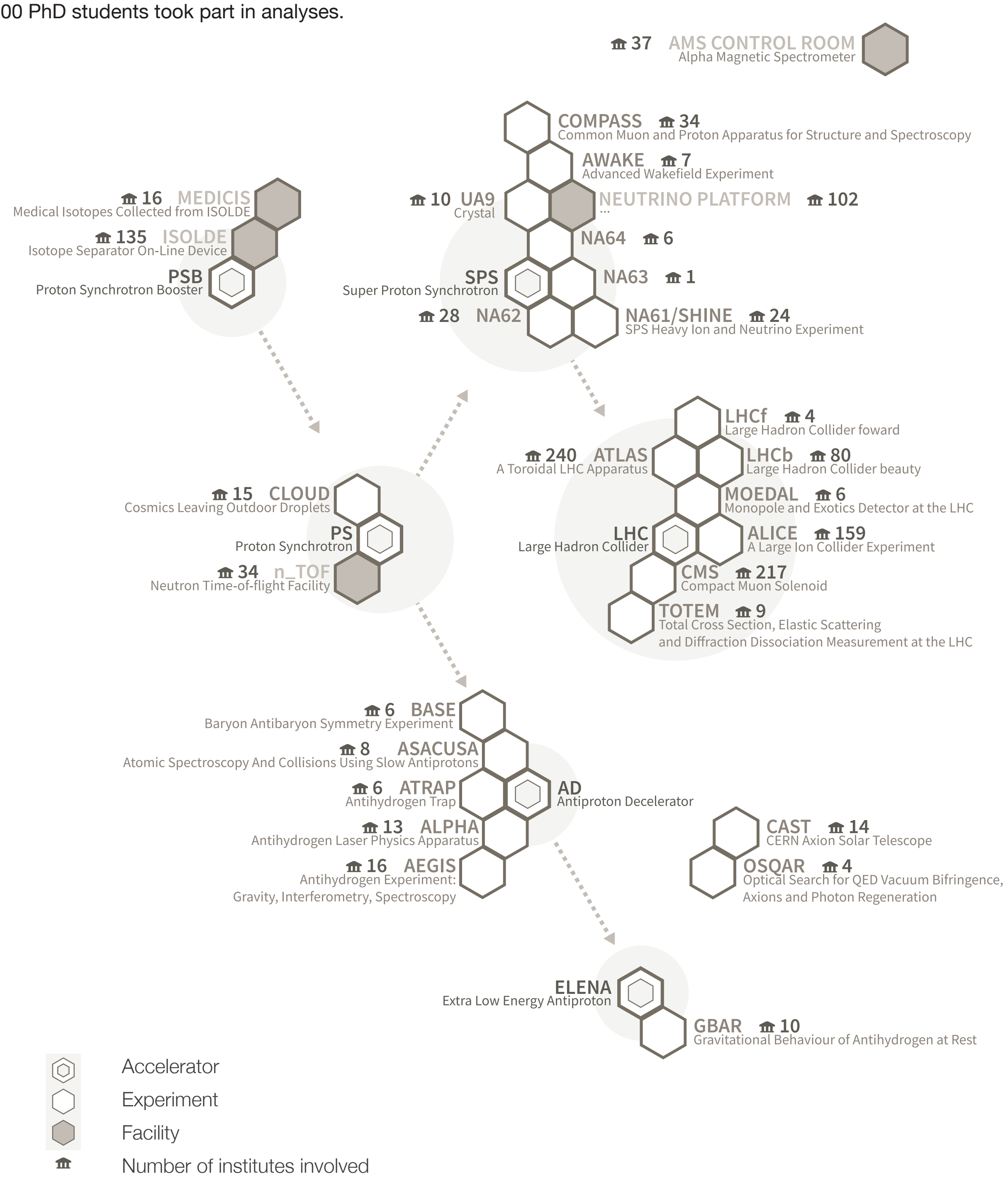
To explore the fundamental structure of the universe, CERN operates a unique network of accelerators that collide particle beams head-on or direct them onto fixed targets. The products of these collisions are recorded by sophisticated detectors and analysed by thousands of physicists at CERN and elsewhere.

CERN's accelerator complex and the experiments that it feeds

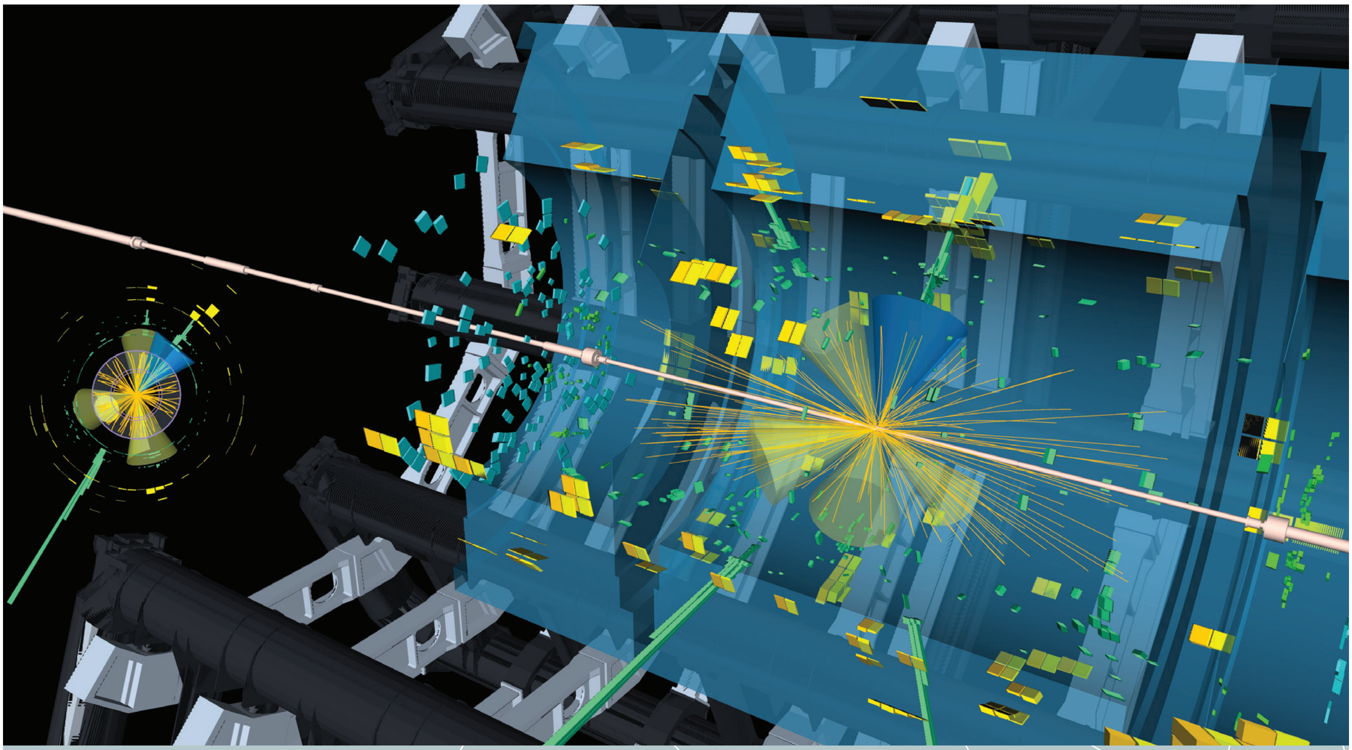


The Large Hadron Collider (LHC) is the world's most powerful particle accelerator. It collides proton beams inside four large experiments – ALICE, ATLAS, CMS and LHCb. The year 2018 saw the end of a very successful second run for the collider (2015–2018), a run during which the machine performed beyond expectations, achieving approximately 16 million billion proton–proton collisions at an energy of 13 TeV (for each of the ATLAS and CMS experiments) and large datasets for lead–lead collisions at an energy of 5.02 TeV per nucleon pair. In 2018, a total of 80 petabytes of data were recorded by the LHC experiments, over 310 scientific papers were published, and more than 2800 PhD students took part in analyses.

Excellent physics results were obtained by analysing these LHC data, as well as data from experiments at other machines in the Laboratory's accelerator complex. The findings have extended physicists' knowledge of what matter is made of at the smallest scales and have sharpened the physics arguments for the forthcoming update of the European Strategy for Particle Physics. The progress made includes precise measurements of the interactions of the Higgs boson with the third-generation fermions, rigorous tests of the Standard Model of particle physics, and ever more sensitive searches for new physics.



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



An ATLAS candidate event for a Higgs boson being produced along with a top–antitop pair. The event contains two photon candidates and six particle jets. (ATLAS-PHOTO-2019-016-3)

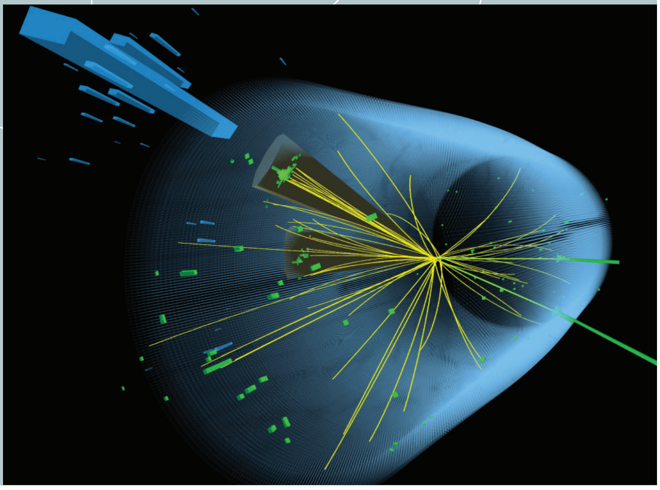
THE LHC IS TESTING PREDICTIONS OF HOW THE HIGGS BOSON INTERACTS WITH OTHER PARTICLES. ANY DEVIATIONS IN BEHAVIOUR COULD POINT TO NEW PHYSICS.

HIGGS BOSON UNDER THE LENS

The Standard Model makes precise predictions on the Higgs boson's interaction with other particles. Testing these predictions is a major line of research at the LHC and at proposed future colliders, because any deviation from the predicted behaviour could point to new physics. This can be done by examining how the Higgs boson transforms, or decays, into lighter particles almost immediately after it is produced. In 2018, both ATLAS and CMS observed the decay of the Higgs into pairs of bottom–antibottom quarks for the first time. Although the Standard Model predicts that this decay mode is the most abundant, such bottom–antibottom pairs are produced in the LHC from a variety of processes unrelated to the Higgs mode, making it challenging to isolate those that come from the Higgs.

Because the top quark is heavier than the Higgs boson, nature prevents a Higgs from decaying into pairs of top–antitop quarks. However, physicists can study Higgs–top-quark interactions by looking for instances where the Higgs boson is produced along with a top–antitop pair, and in 2018 ATLAS and CMS observed this "associated production" in data recorded in previous years. The production rate for this process, as well as for the Higgs decay into pairs of bottom–antibottom quarks, was found to be in agreement with expectations from the Standard Model at the current level of statistical precision.

A CMS candidate event for the Higgs boson decaying to a bottom–antibottom quark pair in association with a Z boson decaying to an electron and its antiparticle. (CMS-PHO-EVENTS-2018-008-1)



TESTING THE STANDARD MODEL

The LHC experiments tested the Standard Model to increased levels of precision and sensitivity in 2018. The top quark remains a source of novel physics measurements and observations. Alongside measurement of the Higgs mass this is a key input for reducing the uncertainties in the predictions of the Standard Model. ATLAS measured the top quark's mass to a precision of 0.3% by combining data from different decay channels. Meanwhile, CMS explored rare production modes of the top quark that are sensitive to signs of physics beyond the Standard Model. The collaboration observed the production of a top quark in association with a Z boson and a second quark, and presented evidence for the production of a top quark along with a photon and another quark. Other highlights from CMS included measurements of known Standard Model processes with improved precision, as well as novel studies in the physics of B mesons.

The Higgs boson's presence affects the probability that the W and Z bosons can bounce or "scatter" off each other. In 2018, ATLAS observed such scattering of pairs of W bosons as well as of a W and a Z boson. Future data will help measure this scattering with greater precision, as physicists look for deviations from predicted values. ATLAS also measured the electroweak mixing angle, a key parameter for defining how the Standard Model unifies the electromagnetic and weak forces, achieving for the first time at the LHC a precision that is competitive with the most precise single-experiment results from the LEP and Tevatron colliders.

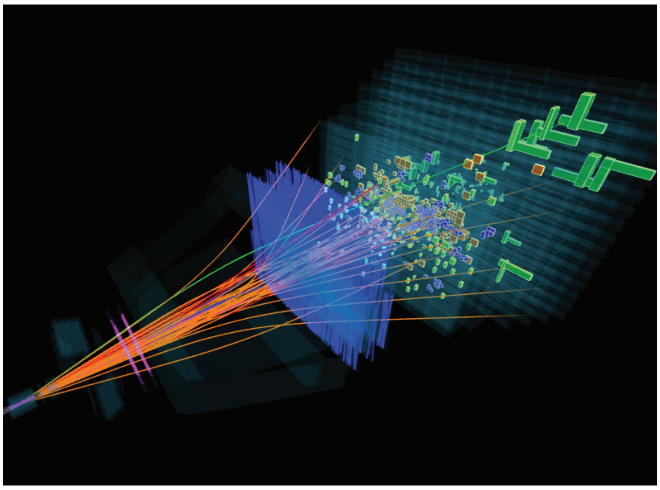
Particle physicists are seeking to explain why the universe is dominated by matter, with almost no antimatter around. This asymmetry could be explained by differences in the way in which matter and antimatter interact via the weak force. The LHCb experiment was built to study these differences, known as charge-parity (CP) violation, and has obtained a variety of precision measurements. In 2018, the LHCb collaboration measured several parameters associated with the so-called Cabibbo–Kobayashi–Maskawa (CKM) matrix, which quantifies possible CP violation among quarks. In particular, the collaboration measured the parameter γ using different methods and obtained a value of 74°, with an uncertainty of about 5° – making it the most precise measurement of this parameter from a single experiment.

The experiment also obtained the first evidence of the rare B_s meson transforming into an excited kaon and two muons, as well as the best limits on the transformation of a B^+ meson into three muons and a neutrino. Other highlights from LHCb were the measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++} , which the collaboration observed for the first time in 2017, and the lifetime of the charmed omega (Ω^0c). The latter was measured to be 268 ± 26 fs, the most precise measurement ever, but the result is nearly four times greater than previous measurements and contradicts earlier predictions.

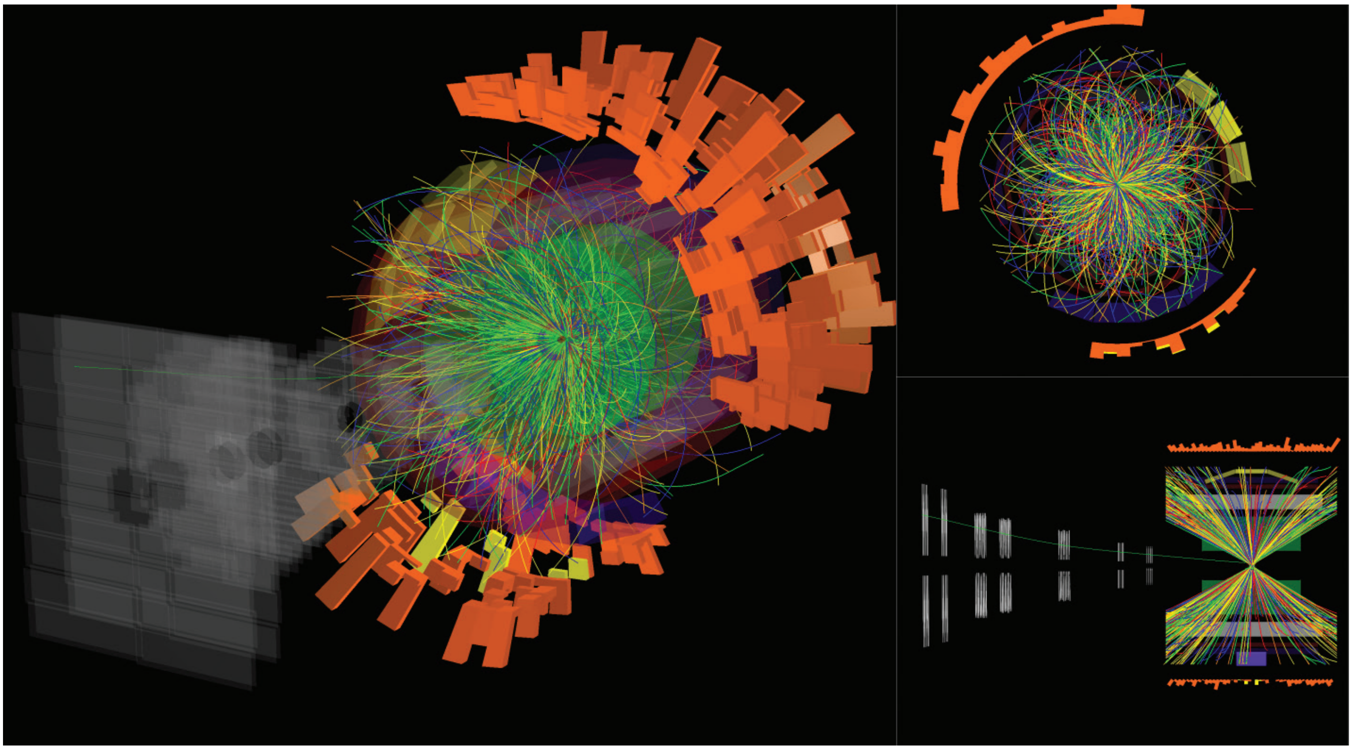
LHCb also operated in fixed-target mode besides its regular collider mode by injecting noble gases such as helium into the beam pipe in between particle bunches. The atoms of these noble gases served as stationary targets for the circulating protons, and LHCb was able to observe the production of J/ψ and D^0 particles in these collisions as well as make the first measurement of the production rate of antiprotons in proton–helium collisions.

The year 2018 also saw the TOTEM experiment, which studies very glancing proton collisions using detectors located 220 m either side of the CMS experiment, uncover possible evidence for a subatomic three-gluon compound called an odderon, first predicted in 1973. The result derives from precise measurements of the probability of proton–proton collisions at high energies, and has implications for our understanding of data produced by the LHC and future colliders.

A proton–proton collision event recorded by LHCb in early 2018.
(OPEN-PHO-EXP-2018-005-2)



THE STANDARD MODEL DOES NOT ACCOUNT FOR DARK MATTER AND DARK ENERGY, STRONGLY SUGGESTING THAT NEW PARTICLES AND FORCES MUST EXIST BEYOND THOSE THAT THE MODEL PREDICTS.



Particle trajectories and energy deposition in the ALICE detector during the first lead-nuclei collisions of 2018.
(ALICE-EVENTDISPLAY-2018-003-1)

SEARCHING FOR NEW PHENOMENA

The Standard Model has successfully passed all the experimental tests that it has been put to, yet the model fails to account for major elements such as dark matter and dark energy, a failure that strongly suggests that new physics is at work and remains to be unravelled.

ATLAS and CMS performed numerous searches for new phenomena during 2018. Examples include the ATLAS search for instances in which extremely massive particles transform into pairs of W and Z bosons, the results of which ruled out the presence of specific types of massive particles up to 4.15 TeV. Another example was the CMS search for exotic Z′ (“Z-prime”) particles, which are predicted by some extensions of the Standard Model. CMS also searched for hypothetical particles known as leptoquarks, which are thought to be hybrids of leptons and quarks. In addition, ATLAS and CMS searched for many different signatures of the presence of dark matter and supersymmetry. In all of these analyses, the collaborations found no evidence for the existence of the underlying hypothetical particles in the various parameters that were explored.

THE HOT EARLY UNIVERSE

The LHC also collides lead nuclei to generate larger and hotter collision systems. These collisions effectively recreate a dense state of free quarks and gluons known as the quark-gluon plasma (QGP), which is thought to have existed in the early universe. Results from the ALICE collaboration, which specialises in these collisions, have shown that the particle jets emerging from lead–lead collisions are narrower (more collimated) than those formed in proton–proton collisions, due to low-energy radiation at large angles from the jet axis caused by interactions between the jet particles and the QGP “soup”.

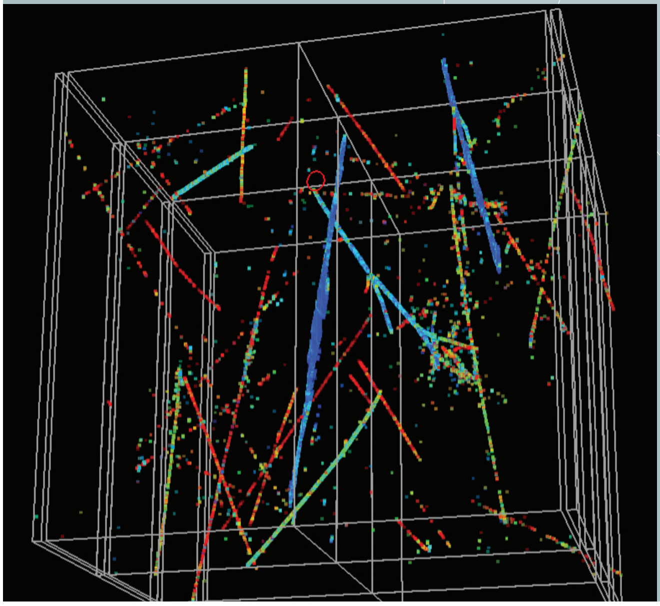
ALICE noted that the production of J/ψ mesons at the LHC was not as suppressed at low transverse momenta as in collisions at the Relativistic Heavy Ion Collider (RHIC) in the US, concluding that the suppression caused by the QGP was countered by the recombination of charm and anticharm quarks into J/ψ mesons. The collaboration also observed that the ratio of Λ_c baryons to D mesons produced in lead–lead collisions was higher than in proton–proton and proton–lead collisions. This behaviour is expected if the charm quarks bind with other quarks in the QGP around them and form baryons and mesons. The detailed dynamics of these processes will be studied precisely with datasets that ALICE will collect in future runs of the LHC. Furthermore, ALICE noted that this Λ_c-to-D ratio was higher than expected from theoretical calculations, even in proton–proton and proton–lead collisions.

CHASING NEUTRINOS

Neutrinos, the lightest known massive particles, continue to be a major focus of worldwide research in high-energy physics. Questions surrounding neutrinos include how they acquire their masses and whether they violate CP symmetry. In 2018, the collaboration behind the OPERA experiment, which is located at the Gran Sasso Laboratory in Italy and was designed to prove that muon-neutrinos can oscillate into tau-neutrinos by studying muon-neutrino beams sent from CERN 730 km away, described the observation of a total of ten candidate events for a conversion from a muon- to a tau-neutrino, demonstrating unambiguously that muon-neutrinos transform into tau neutrinos on their journey from CERN to Gran Sasso.

Meanwhile, the ATLAS and CMS collaborations looked for heavy Majorana neutrinos, hypothetical particles that may balance out the very small neutrino masses via the so-called seesaw mechanism. ATLAS and CMS found no hints of heavy Majorana neutrinos in the parameter ranges that they investigated but these null results are crucial as they allow scientists to place stringent constraints on the theoretical models.

CERN's Neutrino Platform was established to support European participation in accelerator-based neutrino projects in the USA and Japan, and provides charged beams and test space for large neutrino detectors. The developments in 2018 included completion of the construction of two large-membrane cryostats housing 6 x 6 x 6 m^3 prototypes for the future, much larger liquid-argon DUNE detector at the US Long Baseline Neutrino Facility using "single-phase" and "dual-phase" time projection chamber technologies. Single-phase ProtoDUNE, the first large prototype, was commissioned in 2018 and recorded its first particle tracks in tests at CERN, demonstrating the viability of the technology on a large scale and marking an important step towards DUNE.

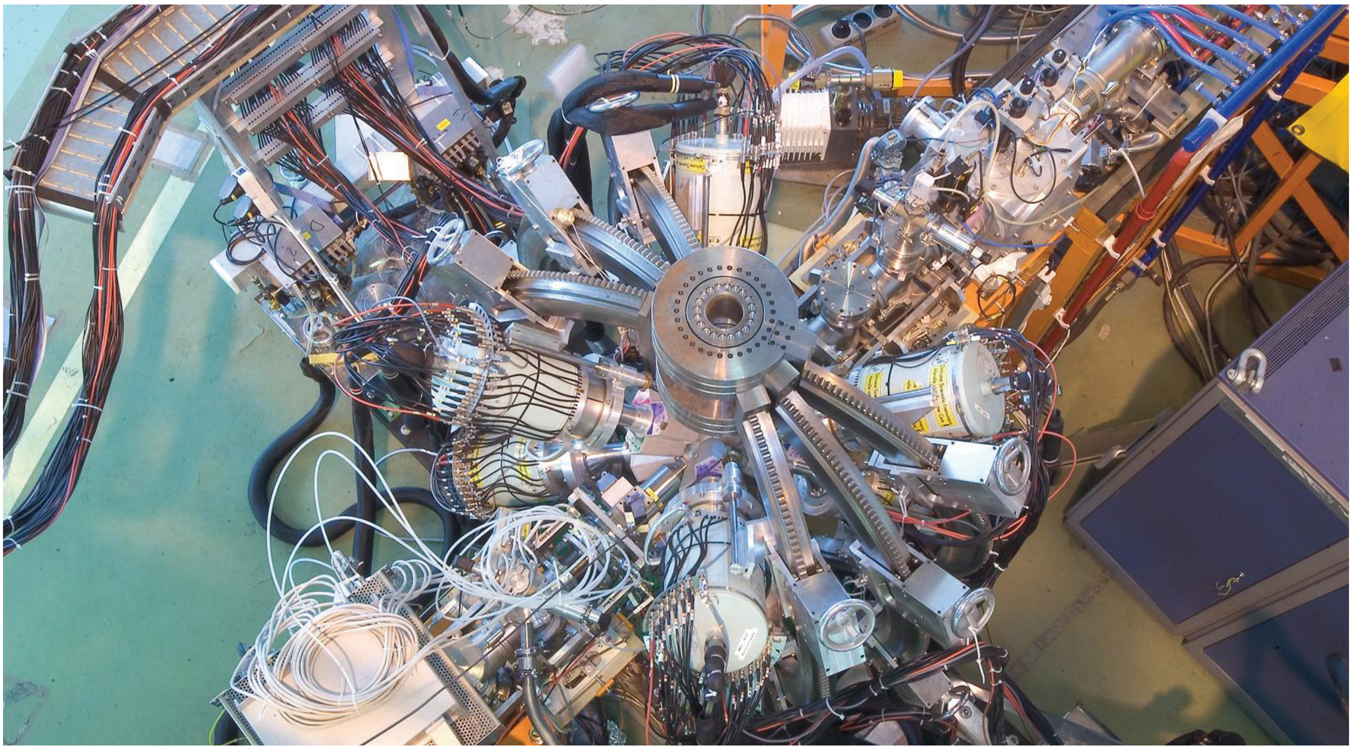


Inside the dual-phase ProtoDUNE, which is under construction and is expected to start operation in 2019. (CERN-PHOTO-201803-085-1)

Three-dimensional event display recorded by the single-phase ProtoDUNE detector at CERN.

THE MAGIC OF EXOTIC BEAMS

ISOLDE is CERN's long-running nuclear-research facility. It directs a 1.4 GeV proton beam from the PS Booster at a target station to generate exotic radioactive-ion beams for studies of the structure of atomic nuclei and other purposes. These beams can be re-accelerated using the REX/HIE-ISOLDE linear accelerators (linacs). An energy upgrade of the HIE-ISOLDE superconducting linac was completed and will enable beams with an energy of up to about 10 MeV per nucleon even for neutron-rich nuclei. A record total of 51 experiments were carried out by users from around the world. Of these, 14 experiments used 18 different beams from HIE-ISOLDE, while 37 low-energy experiments used more than 80 different isotopes.



The MINIBALL gamma-ray detector array at the HIE-ISOLDE accelerator. *(CERN-EX-0506009-07)*

Highlights from 2018 include the first direct proof by the MINIBALL and HIE-ISOLDE collaborations that the nucleus of tin-132 (^{132}Sn), which was considered to be “doubly magic”, does indeed merit this special status. Such nuclei have complete proton and neutron shells and are exceptionally stable. The result was the first to emerge from HIE-ISOLDE and shows that the facility is key to unravelling the inner workings of atomic nuclei. Another highlight was the revelation and explanation of the full extent of the odd-even shape-staggering of exotic mercury isotopes, whereby the shape of the atomic nuclei dramatically moves between that of a football and that of a rugby ball. The result was possible thanks to an unprecedented combination of experimental elements, such as ISOLDE’s Resonance Ionisation Laser Ion Source (RILIS), and theoretical and computational modelling techniques.

The year 2018 also saw ISOLDE forge, using RILIS, neutron-rich isotopes of the element chromium for the first time and in prodigious quantities. These isotopes were measured by ISOLTRAP, which has been performing mass measurements at ISOLDE for the last 30 years. The new mass values are up to 300 times more precise than previous results, offering new insight into the nuclear structure of chromium isotopes.

THEORY THRIVES

In 2018, CERN’s Theoretical Physics department (TH) produced cutting-edge research supporting the Laboratory’s activities and serving the international theoretical physics community. The research activity in TH covers all areas of relevance to particle physics and, in 2018, led to the submission of 342 papers to the arXiv preprint server.

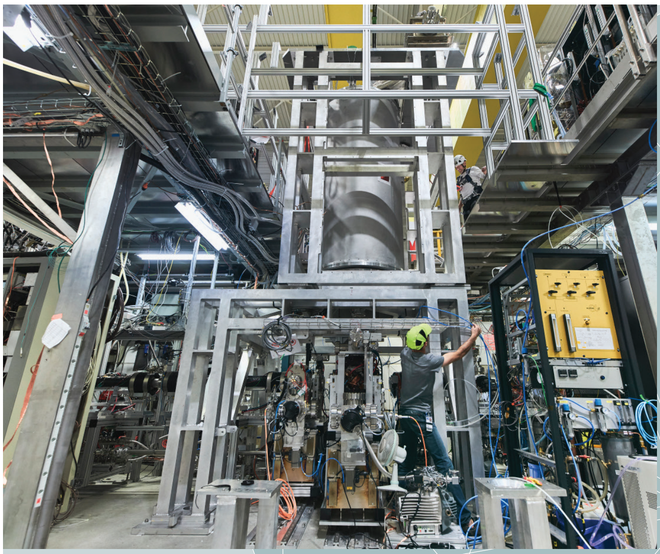
Mathematical studies included the exploration of string theory and quantum field theory, which revealed interesting connections with conjectures related to the properties of gravity in the quantum regime. Much work was devoted to all aspects of the physics studied at the LHC, from precise calculations of processes in the Standard Model to imaginative hypotheses about phenomena that could reveal new physics beyond the Standard Model. Studies in cosmology and astroparticle physics, which are among the core activities of TH, explored the evolution of the early universe and observational methods in order to extract information on dark matter and dark energy. Investigations were done in heavy-ion-collision physics, an active branch of research in TH that studies the properties of matter in extreme conditions, such as those found at the centre of stars. Work was also done in lattice gauge theory, whose goal is to explore the complex properties of strong interactions by simulating the physical space-time on a grid.

TH made fundamental contributions to the LHC Physics Centre at CERN (LPCC), to working groups on the physics of the LHC and the proposed colliders CLIC and FCC and to the Physics Beyond Colliders initiative (see p. 48). It also made important contributions to documents that were submitted as input for the update of the European Strategy for Particle Physics.

EXPERIMENTS ON TARGET

In 2018, great advances were also made in other experiments and projects, many of which are fed by beams from CERN's PS Booster, PS and SPS accelerators (see p. 25). These achievements include production-rate measurements relevant to neutrino physics, and investigation of the emergence of the QGP in heavy-ion collisions in fixed-target mode (NA61/SHINE experiment); studies of rare kaon decays and searches for new heavy neutral leptons (NA62), with the first search for the decay of a positively charged kaon into a positively charged pion and a neutrino–antineutrino pair conducted on the basis of kaon decays "in-flight"; investigations of radiation processes in strong electromagnetic fields (NA63); searches for dark-sector particles (NA64); measurements of neutron-induced processes relevant to nuclear physics and astrophysics (n_TOF); studies of the hadron structure (COMPASS); searches for chameleon particles and axion particles (CAST, OSQAR); the influence of cosmic rays on cloud formation (CLOUD), which is important for modelling climate change; and particle collimation using crystals (UA9).

The NA62 experiment in CERN's North Area. *(NA62-PHO-EXP-2017-001-2)*



The ALPHA-g experiment, seen here being installed in CERN's Antiproton Decelerator hall, received its first beam of antiprotons on 30 October 2018. *(CERN-PHOTO-201810-267-37)*

ANTIMATTER EXPLORATION

CERN's Antiproton Decelerator (AD) supplies low-energy antiprotons for precise spectroscopy, as well as gravitational and other measurements, allowing ever more precise comparisons between the behaviour of matter and antimatter. The AD currently hosts five operational experiments: ALPHA, AEgIS, ASACUSA, ATRAP and BASE. Two other experiments, GBAR and ALPHA-g, which is essentially a vertical version of ALPHA, are in preparation. The new ELENA ring (see p. 46) slows down antiprotons even further so that they are more easily trapped by the experiments.

In 2018, the ALPHA collaboration extended the measurements of the spectral structure of antihydrogen that it had made over the previous couple of years, by obtaining the most-precise-ever direct measurement of antimatter. The team determined the spectral structure of the antihydrogen 1S–2S transition to a precision of a couple of parts in a trillion, heralding a new era of high-precision tests of the differences between matter and antimatter and marking a milestone in the AD's scientific programme. The collaboration also obtained the first measurement of the next transition, the Lyman-alpha (or 1S–2P) transition, and measured its frequency with a precision of a few parts in a hundred million. In addition, it attained the first-ever laser cooling of antihydrogen.

2018 also witnessed good progress from the other AD experiments, including the refinement of the BASE apparatus to allow precise measurements of antiproton properties, and the receipt of the first beams of antiprotons by the GBAR and ALPHA-g experiments, which aim to test whether antimatter falls at the same rate as matter under gravity.