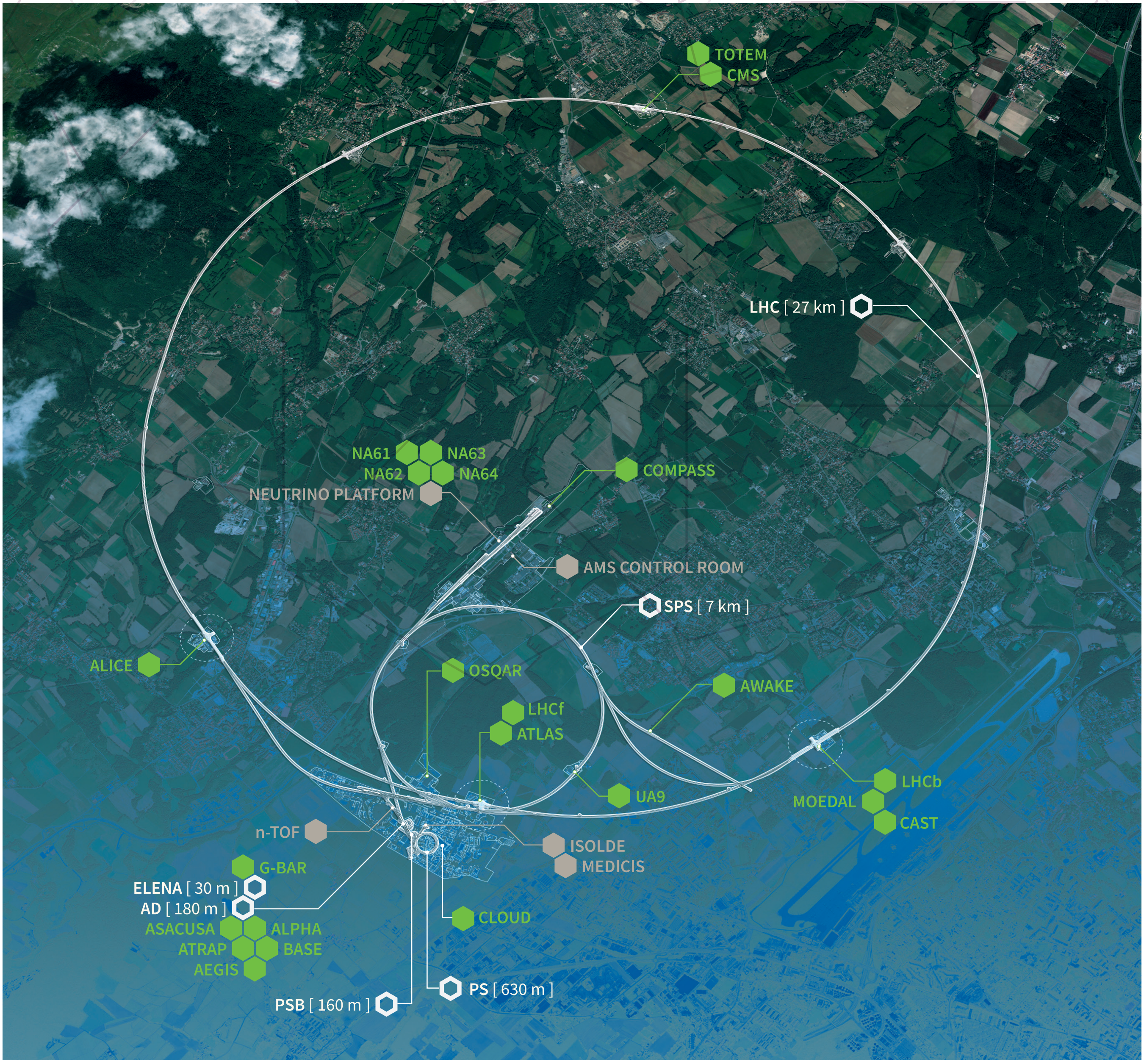
EXPLORING THE NATURE OF THE UNIVERSE

CERN's mission is to explore the fundamental structure of our universe by operating a unique network of accelerators that collide beams of particles or direct them to fixed-target experiments. Giant detectors record the results of these collisions, feeding the data to thousands of physicists at CERN and beyond for analysis.

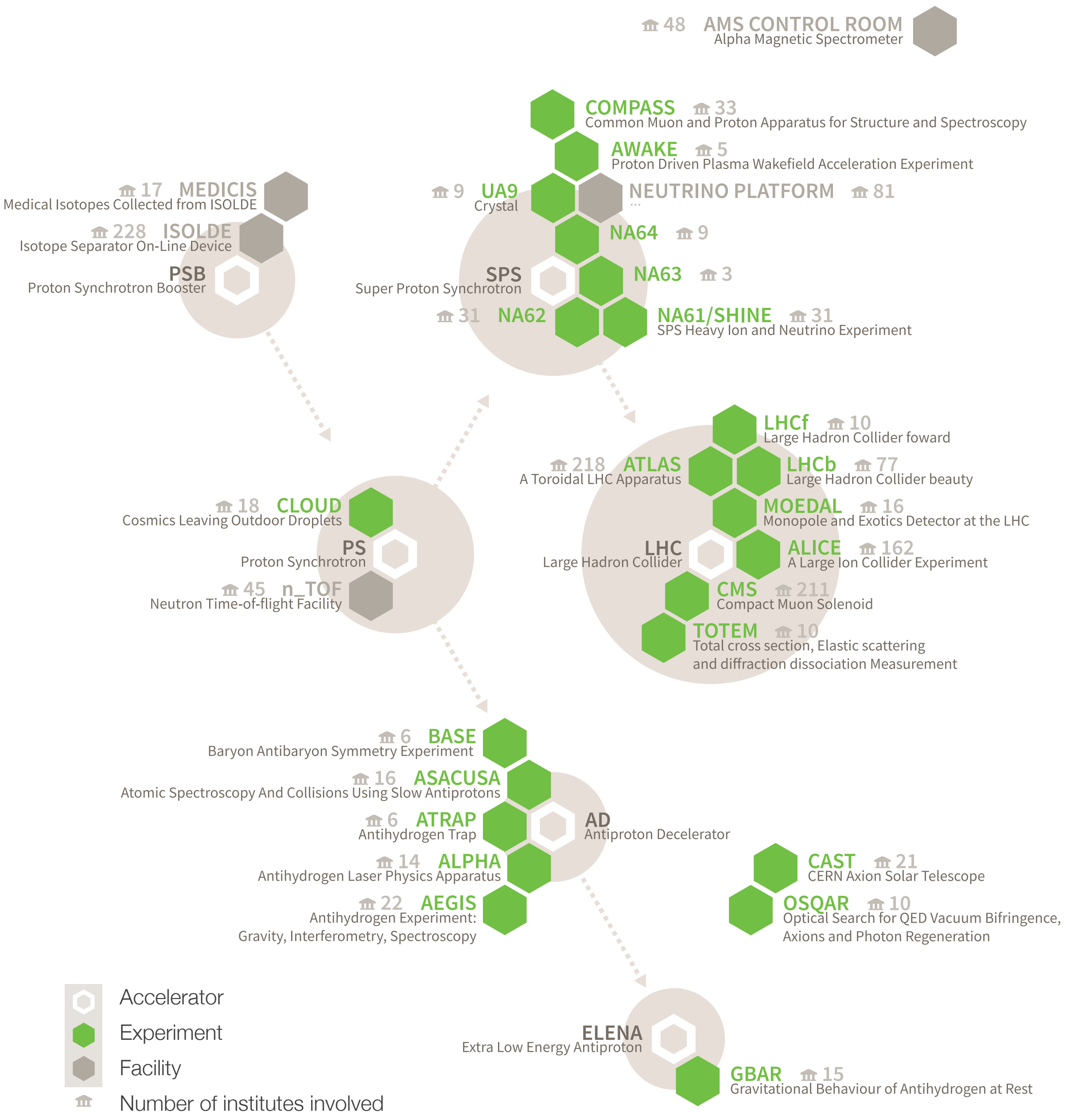
CERN'S ACCELERATOR COMPLEX AND THE EXPERIMENTS THAT IT FEEDS



The Large Hadron Collider (LHC) is CERN's flagship accelerator. It collides beams of protons inside four large experiments – ALICE, ATLAS, CMS and LHCb. 2017 saw the machine's second major run at a centre-of-mass energy of 13 TeV. The machine's impressive performance required ATLAS and CMS to develop new tools to cope with the record collision rates. A total of 70 petabytes of data was recorded by the LHC experiments, over 330 scientific papers were published, and some 2700 PhD students took part in analyses.

2017 was also the 25th anniversary of the LHC experimental programme, ATLAS and CMS having submitted their letters of intent in 1992, followed by ALICE and LHCb.

New knowledge gained from the LHC experiments and other experiments across CERN's physics programme included a closer understanding of the Higgs boson, stringent tests of the Standard Model of particle physics, seminal measurements of antimatter and fresh perspectives on the existence of new particles and forces.



CERN's interconnected accelerators serve multiple experiments and facilities that are used by physicists in several hundreds of institutes around the world.

Physicists from the LHC experiments discussing results. Around 10 000 physicists are involved in the experiments. (OPEN-PHO-EXP-2017-002)

HIGGS BOSON UNDER THE MICROSCOPE

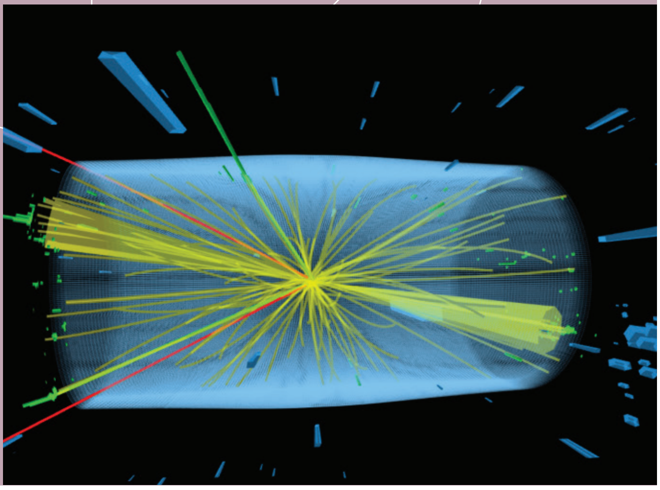
With 4 July 2017 marking the fifth anniversary of the discovery of the Higgs boson by ATLAS and CMS, the two experiments reported a wealth of new Higgs results during the year. The Standard Model of particle physics (SM) makes very specific predictions about how the Higgs boson interacts with other particles. Testing these predictions at increasing levels of precision is a major research focus at the LHC and at proposed future colliders, since any deviation in the Higgs' behaviour could open the door to new physics.

The Higgs boson was originally discovered via its decay to bosons γγ, ZZ and WW, and these decay processes have now been measured to better precision and in more detail with additional LHC data at 13 TeV. The complex decays and couplings of the Higgs to third-generation bottom, top and tau fermions were also well established by ATLAS and CMS in 2017.

The two experiments reported the first evidence for the decay of the Higgs to a pair of bottom quarks, and probed couplings between the Higgs boson and the top quark for the first time. CMS presented a five-sigma observation of the Higgs decay to a pair of taus, while ATLAS combined the cleanest Higgs boson channels to measure cross-sections with unprecedented precision.

OVER 330 SCIENTIFIC PAPERS WERE PUBLISHED IN 2017 AND SOME 2700 PHD STUDENTS TOOK PART IN ANALYSES.

A candidate Higgs boson event from proton–proton collisions recorded by CMS in 2016, showing the production of a pair of muons and two-high energy jets. (CMS-PHO-EVENTS-2016-007-3)



STANDARD MODEL TESTED TO NEW LIMITS

ATLAS and CMS published many beautiful results that subject the Standard Model to heightened levels of scrutiny. The large LHC datasets now available allow the collaborations to move into precision physics and gain sensitivity to extremely rare processes. Examples include ultra-precise measurements of the cross-sections for certain interactions, the masses of key particles such as the W and Higgs bosons, and electroweak WW production. ATLAS found the first direct evidence for light-by-light scattering in high-energy lead–lead collisions, an extremely rare process predicted by quantum electrodynamics (QED), and CMS made a precision measurement of the electroweak mixing angle $\sin^2\Theta$ from Run-1 data.

Precision measurements of the top quark, the least understood of the quarks so far owing to its large mass, remain a hotbed for searches for physics beyond the Standard Model. In addition to precision measurements of the top-quark mass, ATLAS measured the angular distributions of tops and their decay products and found the first evidence for a new type of rare single-top production. CMS also looked at rare top-quark processes such as the production of a single top quark and the production of four tops at once, and reported the first observation of top quarks in proton–lead collisions. In the summer, the two experiments joined forces to report measurements of asymmetries in top-quark production at the LHC, a promising avenue in the search for signs of new physics.

The LHCb experiment filled important gaps in the Standard Model during 2017, beginning with the discovery of the doubly-charmed (and doubly-charged) baryon, Ξ_{cc}^{++}. Predicted to exist by the Standard Model but never previously observed, this and similar states still to be observed could provide a rich source of information on the theory of the strong force, quantum chromodynamics (QCD). LHCb then announced that it had observed the rarest decay of the B^0 meson ever, catching it decaying into a proton-antiproton pair, which occurs in around one out of every 100 million decays. The collaboration also reported the first observation by a single experiment of the rare process whereby a B meson decays into a pair of muons, along with the first measurement of the effective lifetime of the decay, and used novel charmonium-spectroscopy techniques to make precision mass and width measurements of the X_{c1} and X_{c2} mesons. Finally, LHCb reported the first hints of CP violation in baryons, which, if seen with greater significance in future LHC data, would be a milestone in our understanding of charge-parity (CP) violation and the cosmic matter–antimatter imbalance.

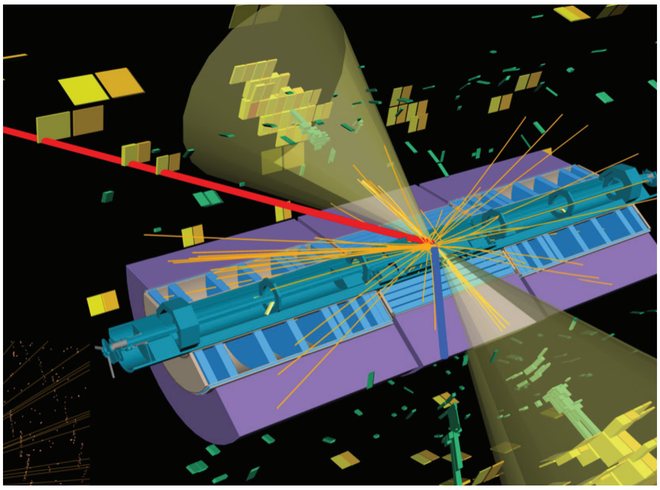
Heavy-ion collisions also allow physicists to study rarely produced particles, such as antihelium nuclei and hyper-nuclei (containing a Λ baryon, which has a strange quark), thereby improving knowledge of the strong force. The ALICE collaboration obtained the most precise measurement of the lifetime of “hypertritons” (bound states of a proton, neutron and Λ baryon) in lead–lead collisions, while an analysis of correlations between charged and neutral kaons allowed the collaboration to favour the tetraquark nature of the long-established $a_0(980)$ meson. ALICE also measured the production of the antimatter partner of the alpha particle, the heaviest antinucleus observed so far.

As the year drew to a close, the TOTEM experiment – which studies very glancing proton collisions using detectors located 220 m either side of the CMS experiment – presented strong evidence for the existence of a three-gluon compound called an odderon. Predicted in the 1970s, the odderon had never previously been observed and the TOTEM results have implications for the cross-section of proton–proton collisions at the LHC and future high-energy colliders.

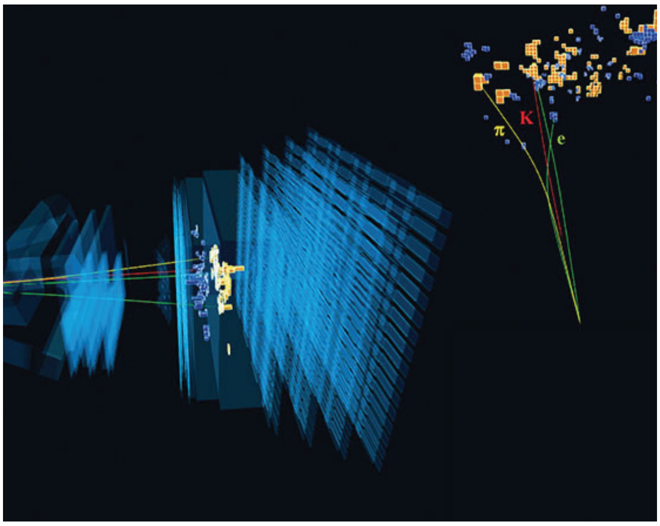
SEARCHING FOR NEW PHYSICS

The Standard Model describes almost everything that has ever been measured in particle physics. Yet the distinct patterns that its particles fall into, and its silence on major issues such as gravity and dark matter, strongly suggest that new particles and forces exist beyond the scope of this almost 50-year-old theoretical framework.

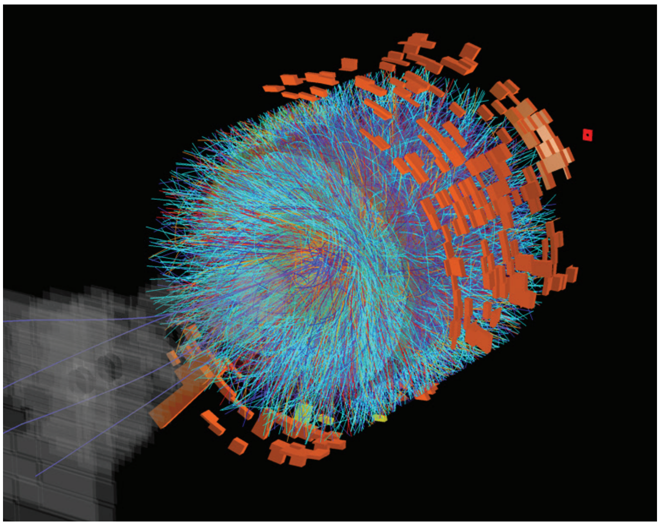
ATLAS and CMS performed numerous searches for new physics during 2017. ATLAS pushed lower the limits on the masses of supersymmetric particles beyond 2 TeV and explored challenging regimes such as compressed-spectra supersymmetry, while CMS carried out several supersymmetry searches in the electroweak sector and explored experimentally challenging final states with low missing energy. ATLAS also reported its first search results for new heavy particles, including dark matter, from Run 2 data so far, a full diboson-resonance search including six channels based on Run-1 data, and a search for long-lived particles at 13 TeV. CMS extended its search for dark-matter particles via di-jet signatures and set tighter limits on new-physics processes including the seesaw mechanism, along



Display of a candidate top-antitop event from proton-proton collisions recorded by ATLAS in 2016. (ATLAS-PHOTO-2018-016-1)



The decay of a B^0 meson into a K^{*0} and an electron–positron pair in the LHCb detector, which is used for a sensitive test of lepton universality in the Standard Model. (OPEN-PHO-EXP-2018-004-1)



The results of a collision between two xenon nuclei inside the ALICE detector, which is optimised for the study of heavy-ion collisions. (ALICE-EVENTDISPLAY-2017-007-1)

with setting better constraints on the possible existence of microscopic black holes, string balls and other exotic objects. All results of searches at the ATLAS and CMS experiments are so far consistent with the Standard Model explanations, allowing physicists to eliminate regions of the possible new-physics landscape.

The LHCb experiment is also hunting for new physics, specialising in less direct searches based on ultra-precise measurements of Standard Model processes. LHCb's 2017 analyses produced further intriguing results that potentially challenge lepton universality. This tenet of the theory says that all leptons are treated equally by the Standard Model forces, so finding any difference would suggest that new particles are at work in the quantum loops of the vacuum. LHCb saw hints of lepton universality violation in their Run-1 data by studying the ratios of decay rates for processes such as B -> K*μμ and B -> K*ee. In a related sector, where lepton universality is studied by means of ratios between B -> D*τν and B -> D*μν decay rates, hints of anomalies in decay ratios, previously reported by the BaBar and Belle experiments in the US and Japan, were also seen by LHCb in the Run-1 data. The hints of non-SM behaviour do not constitute firm observations yet, as they are limited by the amount of data available from Run 1, and updates with the larger dataset from Run 2, which began in 2015, are eagerly awaited.

The possibility that dark-matter particles may interact via an unknown force felt only feebly by Standard Model particles motivated LHCb to search for "dark" photons, setting tight new constraints on the coupling strength between dark and conventional photons. Also exploring the dark universe is the CAST experiment, in which a large superconducting magnet is pointed towards the sun to search for dark-matter axions as well as solar chameleons (candidates for the dark energy sector). Further results from the unique CAST set-up are expected in 2018.

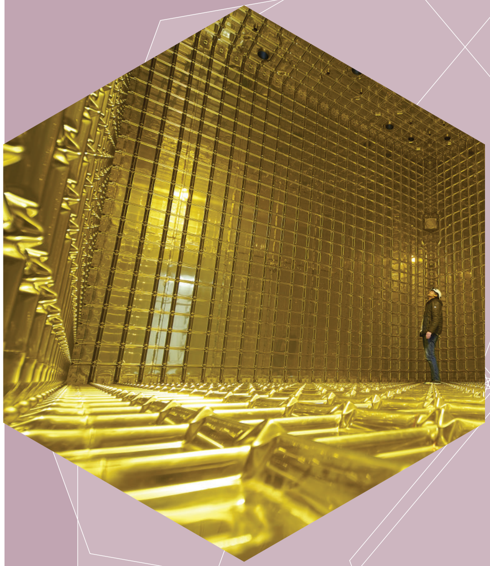
EXPLORING THE DYNAMICS OF THE INFANT UNIVERSE

In addition to colliding protons, the LHC collides lead and other heavy ions to generate a larger, fiercer collision environment. This fireball of extreme temperature and density, called the quark-gluon plasma (QGP), is thought to be a close approximation to the universe in its first moments of existence. In contrast to ordinary matter, where quarks and gluons are confined inside protons and neutrons, the quarks and gluons in the QGP can influence each other over much larger distances. Studying this state therefore allows powerful tests of the theory that describes the strong force, quantum chromodynamics.

In 2017, based on data collected during special heavy-ion runs in 2015 and 2016, the ALICE collaboration continued to probe the QGP from all angles. A major goal is to understand how this primordial state evolved from its creation to "freeze-out" less than a thousandth of a billionth of a billionth of a second later, after which the QGP condensed into protons, neutrons and other hadrons. Specifically, ALICE reported new measurements of the shape of the QGP fireball at freeze-out, and probed its dynamics using heavy quarks and J/ψ mesons to measure a crucial quantity called elliptic flow in a variety of ways.

Measurements reported by ALICE in 2017 provide the strongest evidence to date that QGP-like conditions are also created in proton–proton (pp) collisions. ALICE observed enhanced production of strange particles, historically considered to be one of the manifestations of QGP formation, in high-multiplicity pp interactions. These observations open new directions for theoretical and experimental studies of pp and heavy-ion collisions – directions which are being explored by all four LHC experiments.

MYSTERIOUS NEUTRINOS



Inside one of the protoDUNE detectors, which are being designed for the far detectors of the Deep Underground Neutrino Experiment (DUNE) in the US. (CERN-PHOTO-201710-248-3)

The study of neutrinos is a major focus of the global high-energy physics programme, in particular the questions of whether these lightest of all particles violate charge parity (CP) symmetry and how they obtain their tiny masses in the first place. The CERN Neutrino Platform supports European participation in accelerator-based neutrino projects in the US and Japan, and significant progress in detector technology was made during 2017 for upcoming neutrino experiments.

An extension of the EHN1 facility in CERN's North Area provided charged beams and test space for neutrino detectors. R&D has been progressing apace to demonstrate large-scale liquid-argon time-projection chamber (TPC) technology, including the cryostats and detectors. Following the completion of a major refurbishment at CERN, the 600-tonne ICARUS detector (comprising two modules) was transported to the US in July to take part in Fermilab's short-baseline neutrino programme. In parallel, the 3x1x1-metre liquid-argon TPC demonstrator was completed; cosmic-ray tracks were observed and the construction of two larger cryostats with an internal volume of 8x8x8-metre each was completed, ready for the installation of prototype detectors for the international DUNE experiment in the US.

Towards the end of the year, a magnetic muon detector, Baby MIND, was shipped to Japan, where it will play an important role in understanding neutrino oscillations at the T2K experiment. The 75-tonne device was designed, built and tested with beam at CERN during 2017. Dedicated neutrino-physics activities also took place in CERN's Experimental and Theoretical Physics departments.

50 YEARS OF USER SCIENCE AT ISOLDE

The year 2017 marked the fiftieth anniversary of ISOLDE's delivery of radioactive isotopes for a wide variety of research in physics and, in the past few years, biophysics and medical physics. A total of 42 experiments were carried out in 2017, covering studies on the structure of exotic nuclei (rare combinations of protons and neutrons) via nuclear decay spectroscopy, mass measurements, laser spectroscopy and reactions with post-accelerated radioactive beams. Researchers also used radioactive probes as spies for solid-state physics, studies of fundamental interactions and biochemical experiments.

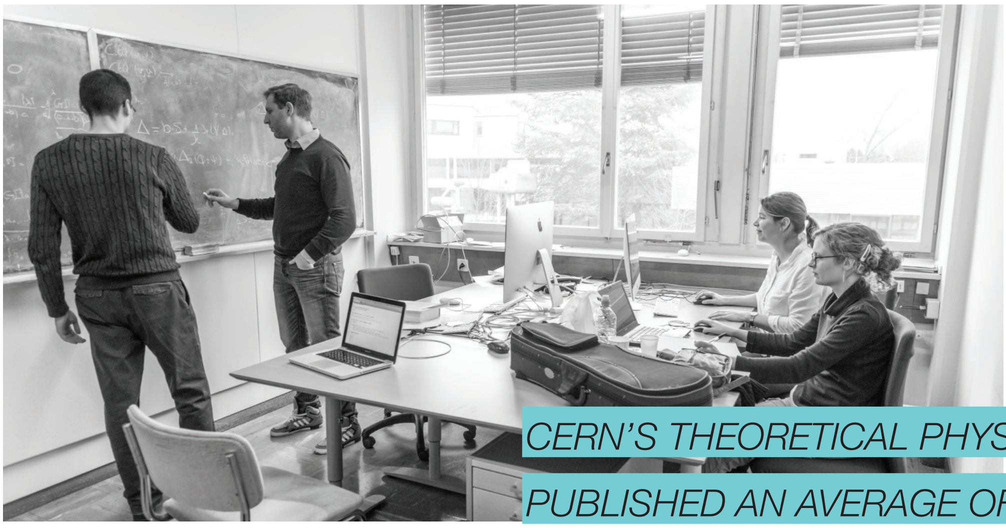
Highlights were the first experiments at the new HIE-ISOLDE post-accelerator, the third cryomodule for which was installed in spring as part of a major upgrade to increase the energy of ISOLDE's beams. The upgraded facility provided beams for 12 physics experiments with reaccelerated beams at three beamlines from July onwards. These included a study of the shape of selenium-70 and experiments with copper that revealed the doubly magic nature of nickel nuclei.

ISOLDE has served more than 1800 users since the first post-accelerated beams were provided in 2001, and continues to host cutting-edge science. 2017 also saw the switch-on of MEDICIS (see p. 33), a new facility that uses the remaining protons that pass through the ISOLDE targets for the production of radioisotopes for medical research applications. MEDICIS has links with research hospitals in the region, where the isotopes produced can be used to develop new cancer therapies or nuclear diagnostics tools.

THEORY THRIVES

In 2017, CERN's Theoretical Physics department (TH) produced cutting-edge research supporting the activities of the Laboratory and serving the international theoretical physics community. Topics included string theory, quantum field theory, the physics of (and beyond) the Standard Model, QCD, collider physics, heavy flavours, lattice field theory, high-temperature quantum field theory, heavy ions, cosmology and astroparticle physics – leading to the publication of about one paper per day during the year.

Notable examples include: a precise prediction of vector-bosons plus jets at the LHC, which allows improved sensitivity to possible dark-matter signals; a way of probing the time structure of the quark-gluon plasma by bringing together top-quark and heavy-ion physics; a thorough study of the theoretical interpretation of cosmic-ray antimatter; an exploration of the properties and phenomenological consequences of clockwork/linear dilaton theories; a



Inside an office of CERN's Theoretical Physics department. (CERN-PHOTO-201602-026-9)

CERN’S THEORETICAL PHYSICS DEPARTMENT PUBLISHED AN AVERAGE OF ONE PAPER PER DAY IN 2017.

quantitative study of how high energy can help precision measurements at hadron colliders; and a calculation of sub-leading corrections to the Veneziano amplitude and a proof of their universality.

In 2017, TH hosted 932 scientists (37 associates, 560 paid visitors and 335 unpaid visitors) and 68 fellows. The department also arranged between five and eight seminars per week, hosted six theory institutes and organised seven workshops and meetings.

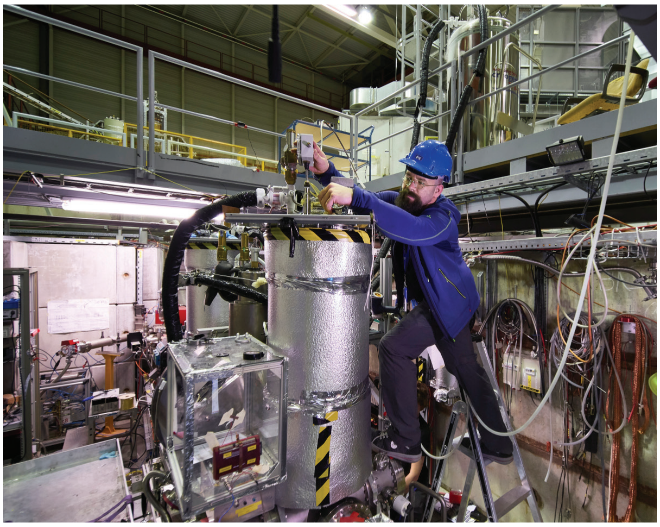
ANTIMATTER AND THE LOW-ENERGY FRONTIER

CERN’s Antiproton Decelerator (AD) is a unique facility providing low-energy antiprotons for precise spectroscopy, gravitational and other measurements. The first antiatoms were created at its predecessor facility, LEAR, in the mid-1990s, and today researchers at the AD are making ever more precise comparisons between matter and antimatter to test nature’s fundamental symmetries. The AD supports a community of around 200 scientists and engineers and hosts five operational experiments – ALPHA, AEgIS, ASACUSA, ATRAP and BASE – with a sixth called GBAR in preparation.

In 2017, the ALPHA collaboration continued to build on the previous year’s seminal measurement of the spectral structure of antihydrogen, by measuring its hyperfine splitting. These and further analyses from ALPHA represent the culmination of a decades-long quest to perform spectroscopy of antiatoms, and open the door to precision tests of charge-parity-time symmetry and to searches for effects beyond the Standard Model.

ASACUSA published key results regarding an alternative method to ALPHA to probe the hyperfine splitting of antihydrogen “in-flight”, demonstrating that the technique works well for hydrogen atoms. The team also reported on progress towards an improved measurement of the antiproton-to-electron mass ratio using spectroscopy of antiprotonic helium atoms.

2017 was a highly productive year for BASE, which performed the most precise measurements yet of the antiproton magnetic moment – 350 times better than the collaboration’s previous result less than a year earlier. The measurement was more precise than that of the proton, representing the first time that antimatter had been measured more precisely than matter. But the record didn’t last for long: by the end of the year, members of the BASE team had used a double-trap apparatus to measure the proton magnetic moment to a precision five times higher, showing that the two values agree at the level of 1.5 parts per billion.



BASE spokesperson working on his experiment at the Antiproton Decelerator. (CERN-PHOTO-201710-255-6).

AEgIS reported important progress towards the first pulsed production of antihydrogen via charge exchange, in particular with the successful excitation of positronium in the experiment's 1T magnet. ATRAP also reported important technical progress towards laser-cooling of antihydrogen atoms and expect results from the forthcoming 2018 run. Great progress was made throughout the year towards the GBAR experiment, which plans to measure the effect of gravity on antihydrogen atoms. It will be the first experiment to be fed antiprotons by the new ELENA ring at the AD (see p. 47), which will reduce the antiproton energy further to increase the trapping efficiency of the experiments.

EXPERIMENTS IN THE LINE OF FIRE

In parallel to their roles as injectors to the LHC, the PS Booster, PS and SPS accelerators provide beams to a variety of facilities and experiments, with around 20 such fixed-target projects supporting a community of over 1200 physicists.

NA58 (COMPASS), at the SPS, completed data-taking to investigate the nucleon's 3D structure using a muon beam and a spectrometer with a liquid hydrogen target. The upcoming 2018 run is expected to improve the significance of the result.

NA61 continued its study of heavy-ion collisions in fixed-target mode, as well as measuring particle production in targets used for neutrino projects in Japan and the US. This year the experiment also ran with xenon ions for the first time. NA62, devoted to the study of very rare kaon decays as a possible window on new physics, had a successful run in 2017 that saw it accumulate about three trillion kaon decays. The excellent resolution of the new detector allowed NA62 to extend the search for heavy neutral leptons up to close to the kaon mass, and analysis of ultra-rare kaon decays is progressing well with data-taking continuing in 2018. NA64 (SHINE) extended its searches for dark-sector particles, continuing to provide interesting limits on possible dark-matter candidates.

CLOUD, which takes beam from the PS, is a multidisciplinary experiment that studies the influence of cosmic rays on aerosols and cloud formation, with implications for the understanding of climate change. Its 2017 run focused on marine nucleation and growth involving iodine compounds, pure biogenic nucleation and growth under realistic environmental conditions, and anthropogenic nucleation and growth under polluted urban conditions.

Participants at the second Physics Beyond Colliders workshop held at CERN in November. (OPEN-PHO-EXP-2017-04)

PHYSICS BEYOND COLLIDERS

The Physics Beyond Colliders (PBC) initiative was launched in 2016 to explore opportunities offered by CERN's accelerator complex that are complementary to high-energy collider experiments. Throughout 2017, the PBC study continued to investigate future opportunities at CERN, with a second general workshop taking place in November with more than 230 physicists in attendance. The effort has already spawned new collaborations between different groups at CERN and with external institutes, and significant progress is already visible in many areas.

The interplay between potential future operation of the existing SPS fixed-target experiments (NA61, NA62, NA64, COMPASS) and the installation of new proposed detectors (NA64++, MUonE, DIRAC++, NA60++) has started to be addressed from both the accelerator and physics perspective. The technical study of the SPS proton beam-dump facility and the optimisation of the SHiP detector for investigating the hidden sector are also advancing well. Different options for fixed-target experiments at the LHC, for instance using gas targets or crystal extraction, are under investigation, and the novel idea of a gamma factory is also gaining traction.

The design study of a storage ring for a proton electric-dipole-moment measurement is progressing, and non-accelerator projects such as the future IAXO helioscope, proposed as a successor of CAST for the search for solar axions, are being discussed. Numerous other activities are under consideration, and the PBC study will conclude with a report by the end of 2018, in time for the update of the European Strategy for Particle Physics.