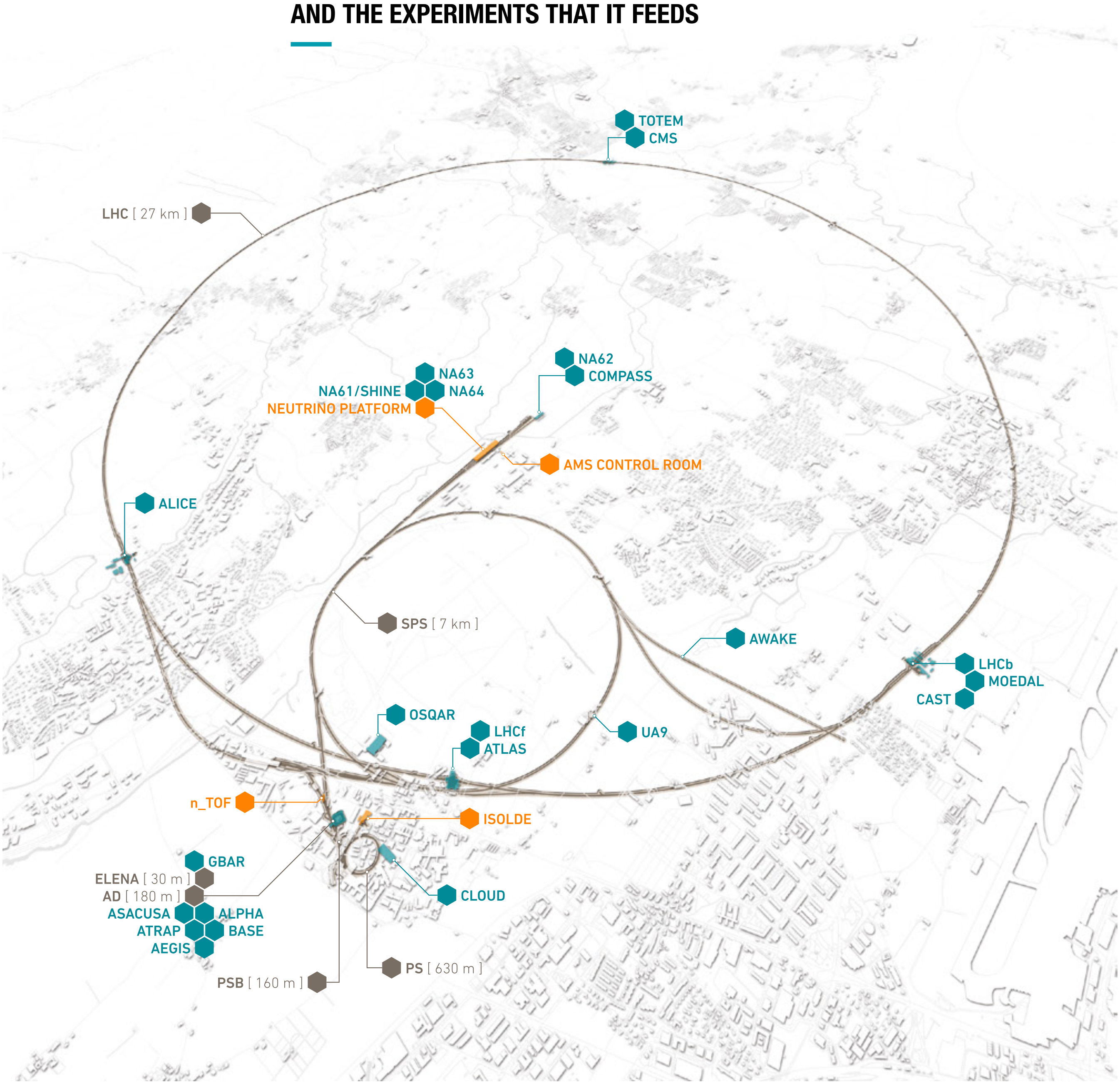
EXPLORING THE NATURE OF THE UNIVERSE

To understand what matter is made of at the smallest scales, physicists from around the world use detectors to study the collisions produced by CERN's particle accelerators. The Laboratory hosts many experiments in its quest to reveal nature's building blocks.

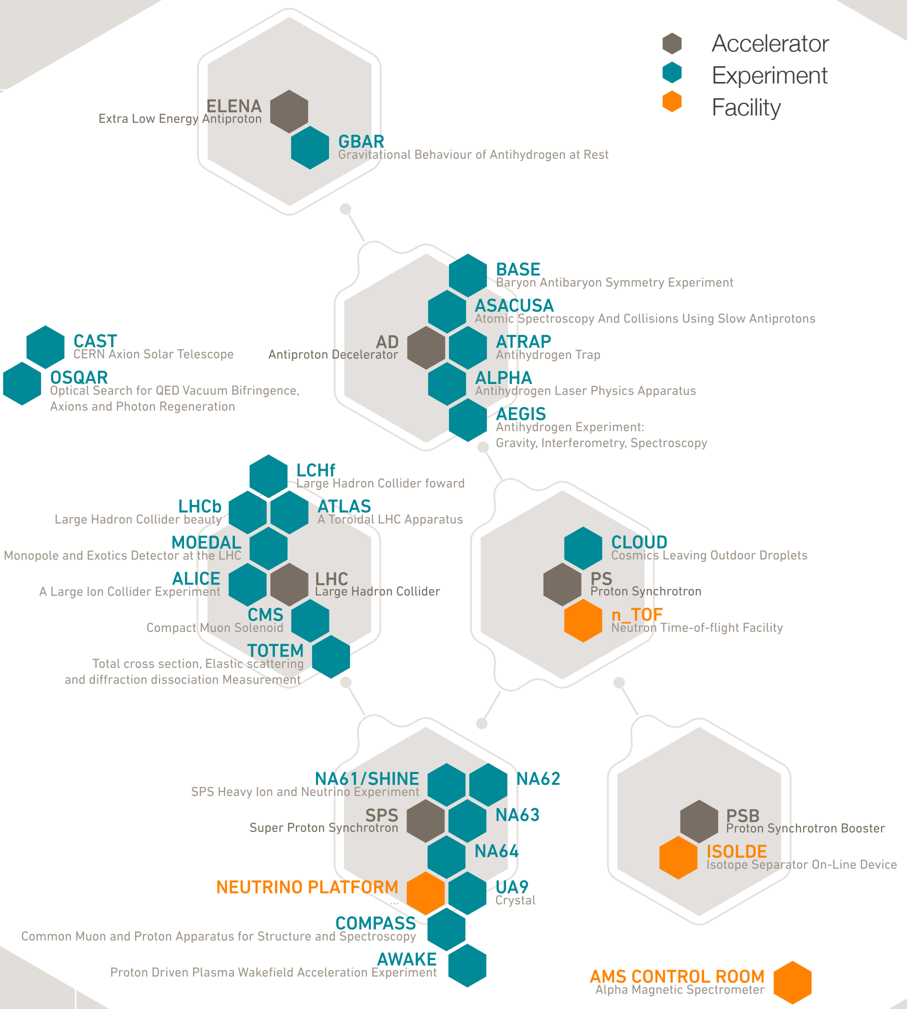
CERN'S ACCELERATOR COMPLEX AND THE EXPERIMENTS THAT IT FEEDS



Focusing an energy of several teraelectronvolts (TeV) into a region measuring a millionth of a millionth of a millimetre across, the Large Hadron Collider (LHC) is the most powerful collider ever built, allowing physicists to explore uncharted subatomic territory. Measuring 27 km in circumference, the LHC produces tens of trillions of proton-proton collisions every day at the centre of four large detectors – ALICE, ATLAS, CMS and LHCb.

Thanks to the superb performance of the LHC during 2016 (see p. 21), the experiments were able to collect over 50% more data than predicted. Hundreds of physics analyses were undertaken and over 300 scientific publications were produced by the LHC experiments during the year, with more than 100 new results approved for the ICHEP conference in Chicago by the middle of the year.

Yet the LHC would not work without the smaller accelerators that feed it, and these too drive numerous complementary experiments at CERN. The results from non-LHC experiments range from highly sensitive tests of antimatter to accurate measurements of cloud formation in the atmosphere. Taken together, they demonstrate the broad diversity of CERN's physics programme in its mission to understand the fundamental laws governing our universe.



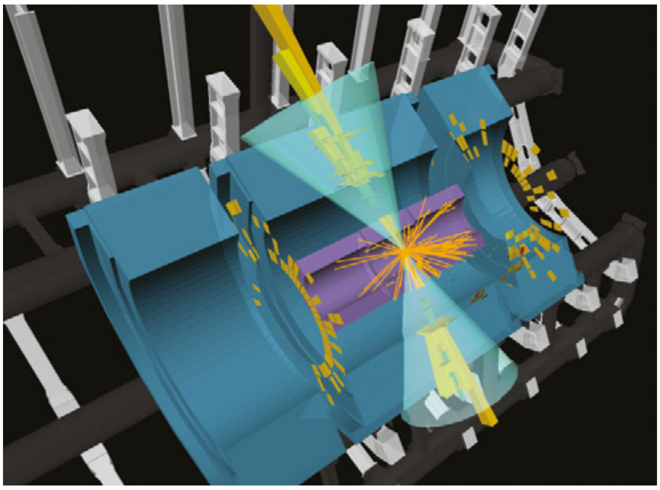
Physicists from LHC experiments working on data analysis. Around 10 000 physicists are involved in the LHC experiments. (OPEN-PHO-EXP-2017-002-1)

PROBING THE ENERGY FRONTIER

All current understanding about the behaviour of fundamental particles is embodied in a theory known as the "Standard Model" of particle physics. However, physicists have good reason to expect that new particles exist beyond those described by this theory. First and foremost, the Standard Model describes only 5% of the universe, the rest being made of invisible dark matter and dark energy. With 2016 marking the second year of running at an unprecedented energy of 13 TeV, the LHC experiments focused on searches for new phenomena, on continuing to chart the Higgs boson at 13 TeV and on understanding the performance of their huge and sophisticated detectors in the higher energy regime.

The general-purpose LHC experiments, ATLAS and CMS, are ideal for searching for direct signs of new particles. Among the physics highlights from these experiments were hotly anticipated updates about an intriguing "bump" first spotted in LHC data during 2015, which hinted that a particle with a mass of around 750 GeV was being produced. After analysing data from 2016, the bump was revealed to be a statistical fluctuation, but the modest excess generated a wave of activity in the theory community and intensified searches for new phenomena by ATLAS and CMS in a similar mass region.

ATLAS and CMS also reported the results of searches for many other new phenomena during 2016, such as those that may arise from additional dimensions of space or from new fundamental symmetries of nature. Analyses at ATLAS and CMS hunting for supersymmetric particles – including updated limits on "gluinos" and "squarks" and first limits on the production of neutralinos (the supersymmetric counterparts of the neutral gauge bosons, the photon and the Higgs particle) at 13 TeV – have already pushed the mass limits beyond those achieved at energies of 7 and 8 TeV in LHC Run 1 between 2010 and 2013. Other dedicated searches concerned possible additional Higgs bosons with different properties. More generic searches for new physics, for instance seeking out "dijet" and "dilepton" resonances, heavy long-lived particles and dark matter candidates, were also updated. In the absence of any signals so far, ATLAS and CMS were able to further constrain the possible properties of such particles.



A "dijet" event selected by ATLAS in its search for new phenomena, in which the two central jets (yellow) have a combined mass of 4.6 TeV. Also shown are energy deposits in the calorimeters, and reconstructed inner detector tracks. (ATLAS-PHOTO-2016-014-8)

In close proximity to the LHCb detector, meanwhile, the MoEDAL experiment published the results of its search for magnetic monopoles – single magnetic charges predicted by Dirac in the 1930s. Alas, none were seen, allowing the MoEDAL collaboration to report during 2016 new mass limits for certain types of these hypothetical particles. With the LHC operating until December, analyses across the LHC experiments continue to scour the 2016 data for evidence of new particles and phenomena.

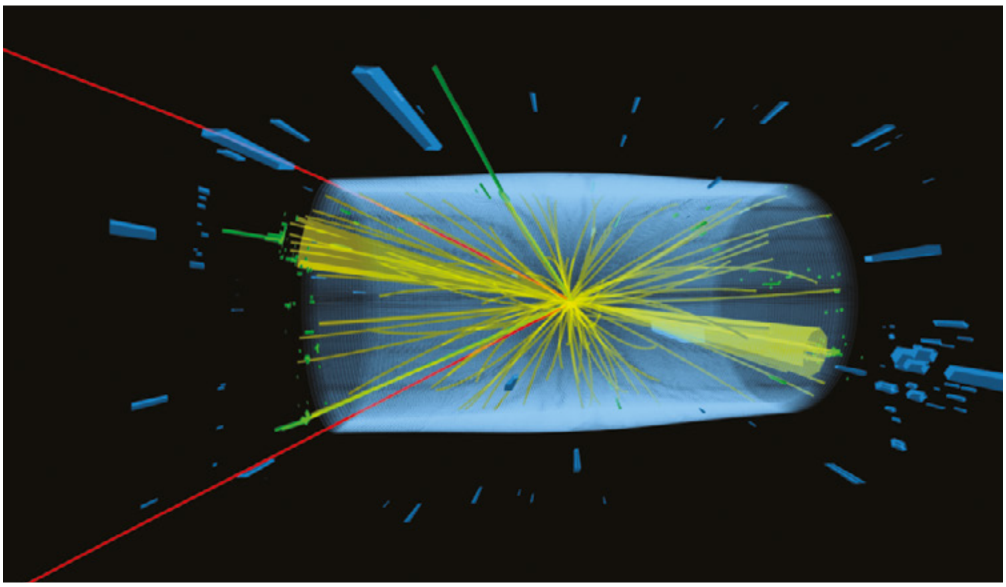
THE HIGGS BOSON AND THE STANDARD MODEL

Discovered by ATLAS and CMS in 2012, almost 50 years after it had been predicted, the Higgs boson is the final particle of the Standard Model. It is also a fundamentally new object called a scalar particle, which is completely different from other particles such as quarks and has connections to many unanswered issues in physics. First spotted at an energy of 8 TeV during LHC Run 1, the Higgs has now been "re-observed" by ATLAS and CMS in the 13 TeV Run 2 data at the rate expected by the Standard Model with a total significance above that seen in Run 1. Given the unique nature of the Higgs boson compared to the other known particles, the observation of additional Higgs production and decay modes, as well as more precise measurements of its couplings to other particles, is one of the main goals of the LHC. Many Higgs measurements were presented in 2016 by ATLAS and CMS, especially at the ICHEP conference, supporting previous findings that, within the current statistical uncertainties, the observed Higgs boson has the properties as predicted by the Standard Model.

Meanwhile, numerous precision measurements of other Standard Model processes were published by ATLAS and CMS during 2016 based on Run 1 data, which represents an extremely well understood and calibrated data sample. These include measurements at a precision of a few per cent or less of inclusive cross-sections that demand the latest "next-to-next-to-leading order" calculations from theory. ATLAS also announced the first measurement of the W boson mass from the LHC with a precision (0.023%) matching that of the best single measurement at other colliders, while both experiments released new measurements of the top quark, including its mass, pair production cross-section and width. Being the heaviest known elementary particle, the top quark is of particular interest in the search for new phenomena. The large dataset of Run 2 will allow such precision studies to progress further to check for any discrepancies between theory and experiment that would signal the existence of physics beyond the Standard Model.

Checking for chinks in Standard Model processes is firmly the business of the LHCb experiment, which concerns itself with the study of particles containing beauty quarks. The increased cross-section for beauty- and charm-flavour hadrons that comes with the higher energy of LHC Run 2 allowed the experiment to collect more than double its previous sample of decays, with many new results increasing the precision of measurements in the flavour sector. An example was the first observation of the ultra-rare decay $B^0 \to K^+K^-$, which has a branching ratio of 8×10^{-8} and is the rarest purely hadronic beauty decay ever observed. LHCb also reported the first measurement of photon polarisation in decays of B_s mesons, and the collaboration is keeping a close eye on some intriguing but not yet significant deviations from the Standard Model in a number of flavour-sector variables.

2016 also saw CERN's NA62 experiment, in which kaons are produced by a beam of protons from the Super Protron Synchrotron (SPS), begin data-taking in its search for extremely rare decays. Since kaon decays are precisely predicted by the Standard Model, any discrepancy between the measured and predicted decay rate may have profound consequences, in particular for fundamental charge parity (CP) symmetry. NA62 collected a large dataset corresponding to almost 10% of the total required statistics, and will operate for at least two more years.



A proton-proton collision event at 13 TeV in the CMS detector showing the characteristic signs of a Higgs boson decay into two high-energy electrons (green), two high-energy muons (red), and two high-energy jets (dark yellow cones). (CMS-PHO-EVENTS-2016-007-3)

Theory thrives

In 2016, CERN's Theoretical Physics department achieved important results across topics ranging from string theory to cosmology, which led to 262 original publications. Examples highlighting the breadth of CERN's theoretical research include: the most precise theoretical prediction of the Higgs boson production cross-section, which is a crucial input to the physics programme of the LHC; a systematic treatment of the leading non-linear effects in baryon acoustic oscillations, which is a key observable in cosmology to test dark energy and constrain neutrino masses; a precise determination of the photon content inside energetic protons, which helps to reduce uncertainties in some of the theory predictions relevant to the LHC; and the exploration of "clockwork" theories, which offer a mechanism for generating light particles with exponentially suppressed interactions.

CERN theory has continued to serve as a vibrant hub for the international community, and during 2016 it hosted 772 scientists, five theory institutes and eight workshops and meetings. Members of the team have contributed to all working groups on LHC physics and led major investigations on the physics opportunities of a 100-TeV hadron collider in the context of CERN's Future Circular Collider study. They also played a leading role in launching new physics research initiatives, both concerning the CERN Neutrino Platform and a new effort surveying the opportunities for physics beyond colliders (see pp. 48-9).

STRONG PHYSICS

Understanding the incredibly strong force that binds protons, neutrons and other hadrons together represents a major challenge. In addressing the nature of the strong force, which is described by quantum chromodynamics (QCD, one of the pillars of the Standard Model), physicists not only learn more about everyday nuclear matter but can also probe the hot and dense quantum fireball that existed immediately after the Big Bang, 13.7 billion years ago. Studying this quark-gluon plasma (QGP) in general requires the LHC to collide heavier particles, typically lead ions. In such collisions, the QGP is formed for less than 10^{-22} of a second, after which the interacting system cools down and falls apart into individual hadrons. However, even this short time is enough to leave a significant imprint on the final-state particle distributions measured by the detectors.

Based on data collected during special heavy-ion runs in 2015 and previous years, the LHC's ALICE experiment has continued its efforts to gain a complete description of the evolution of the QGP. In 2016, the collaboration submitted 25 papers and prepared around 30 new results that were presented at major heavy-ion conferences in June and September. Three main themes dominated the results. The first concerns azimuthal anisotropies of particle production that are produced by the flow of the QGP medium, for which ALICE released first results from Run 2, as well as more detailed measurements of correlations of the azimuthal anisotropies that allow contributions from the initial stages of the collision to be disentangled from the dynamics of the flowing QGP. The second theme concerns various measurements of so-called quarkonia, which are bound states of heavy quarks that dissolve in the hot QGP but can also be formed by recombination of a charm quark and an anti-charm quark in the QGP. The third theme concerns "hard probe" measurements, which use energetic particles and jets to probe the QGP medium.

All measurements show that the higher collision energy of LHC Run 2 (5.02 TeV per nucleon pair instead of 2.76 TeV per nucleon pair in Run 1) produces a hotter QGP that may also be slightly longer-lived. In addition, more precise measurements of flow and flow correlations allow other properties of the QGP, such as the viscosity, to be determined with increasing precision. All four LHC experiments now take part in the heavy-ion programme. In 2016, ATLAS detected light-by-light scattering in the strong electric fields generated in peripheral heavy-ion collisions, while CMS presented several results including the observation of collectivity in proton-proton collisions and a study of chiral anomalous effects in proton-lead collisions.

Other experiments at CERN are studying the patterns of hadrons that emerged from the QGP in the early universe – many of which are exotic cousins of familiar nuclear particles that make up normal matter. During 2016, LHCb reported the observation of three new exotic hadrons and confirmed the existence of a fourth by analysing the full data sample from LHC Run 1. The particles each appear to be "tetraquarks" formed by two quarks and two antiquarks, although the theoretical interpretation of the new states is still under study. Together, LHCb and CMS also searched for but were unable to corroborate a tetraquark state recently spotted by the D0 experiment at Fermilab in the US.

The LHCb detector in its cavern. (CERN-PHOTO-201609-209-2)

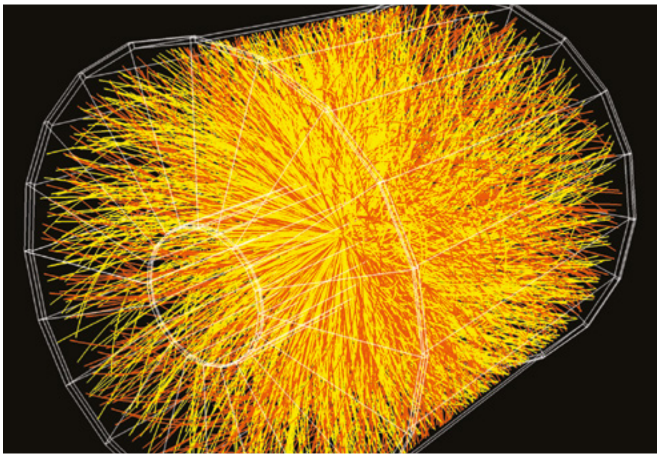
CLOUD advances climate science

Future global climate projections have been placed on more solid empirical ground, thanks to measurements of the production and growth rates of atmospheric aerosol particles published in high-profile journals in 2016 by CERN's Cosmics Leaving OUtdoor Droplets (CLOUD) experiment.

According to the Intergovernmental Panel on Climate Change (IPCC), the Earth's mean temperature is predicted to rise by between 1.5 and 4.5 °C when the amount of carbon dioxide in the atmosphere doubles as expected by around 2050. One of the main reasons for the large uncertainty in global temperature predictions is a poor understanding of aerosol particles in the atmosphere and their effects on clouds. To date, all global climate models use relatively simple parameterisations for aerosol production that are not based on experimental data.

By measuring aerosol formation under atmospheric conditions in a controlled laboratory environment, CLOUD has established the main processes responsible for new particle formation throughout the troposphere, which is the source of around half of all cloud seed particles. In an earlier paper published in 2016, the collaboration showed that particles can form purely from organic vapours produced naturally by the biosphere.
Also in 2016, CLOUD published the first-ever global aerosol model results based purely on laboratory measurements, which compared closely to atmospheric observations. The measured production rates of these subtle atmospheric processes can now be fed into global-circulation models to narrow the range of projected global temperatures.

CLOUD comprises an ultra-clean and controlled environment into which beams of particles from the Proton Synchrotron are injected to simulate the seeding of cloud droplets. (CERN-EX-1310264-03)



The outcome of a high-energy lead-lead collision recorded by the ALICE detector, in which a total of 3161 charged particles were detected. (ALICE-PHO-GEN-2016-001-3)

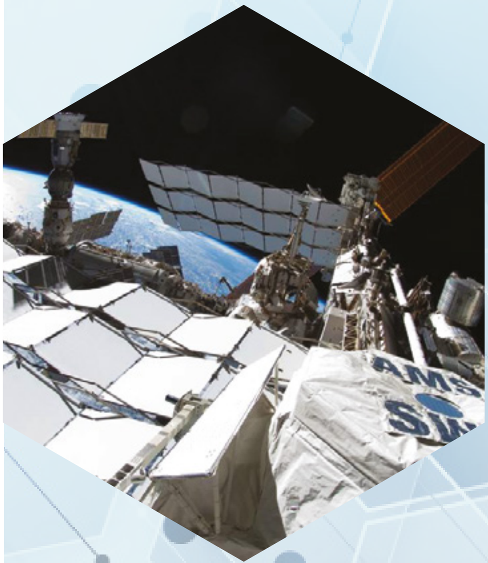
CERN's DIRAC experiment – which studies unstable hadrons produced using a beam from the Proton Synchrotron – also reported a new type of exotic "atom" made up of a pion and a kaon, which allows tests of quantum chromodynamics in the low-energy region. Shedding light on the murkier details of the strong force, two experiments at the SPS reported new results in 2016. The COMPASS facility switched to measurements of exclusive processes for generalised parton distributions, which are vital for understanding QCD contributions at the LHC, while the NA61/SHINE experiment took its first data in a programme designed to study particle production in neutrino targets.

ANTIMATTER ANTICS

Since CERN's production of the first antiatoms in 1995, a new era of tests has opened up to check if antimatter behaves the same as ordinary matter. If not, it would suggest that fundamental symmetries such as charge-parity-time (CPT) symmetry are violated and would point strongly to the existence of new physics. CERN's Antiproton Decelerator (AD) is host to five operational antimatter experiments, with another in the construction phase. In December, one of the experiments – BASE – announced that it had kept a shot of antiprotons trapped for more than one year, representing the longest-lived known anti-object in the universe. Storing antimatter for long periods, and keeping it cold, allows more precise measurements of its properties.

In 2016, the ALPHA experiment reached a goal that the antimatter community had been working towards for many years: the first optical spectroscopy of antihydrogen, opening the door to precision spectroscopy of antihydrogen and new tests of CPT symmetry. In parallel, the ASACUSA collaboration carried out the most precise measurement of the antiproton-to-electron mass ratio to date. Combined with measurements from ATRAP, BASE and ALPHA, this pushes limits on mass and charge differences between protons and antiprotons and between electrons and positrons to the level of sub-parts per billion. Preparations for tests of antimatter under gravity are equally advancing with the AEGIS and GBAR experiments, and all AD experiments will benefit from the new ELENA decelerator installed at the end of the year (see p. 47).

Results from space

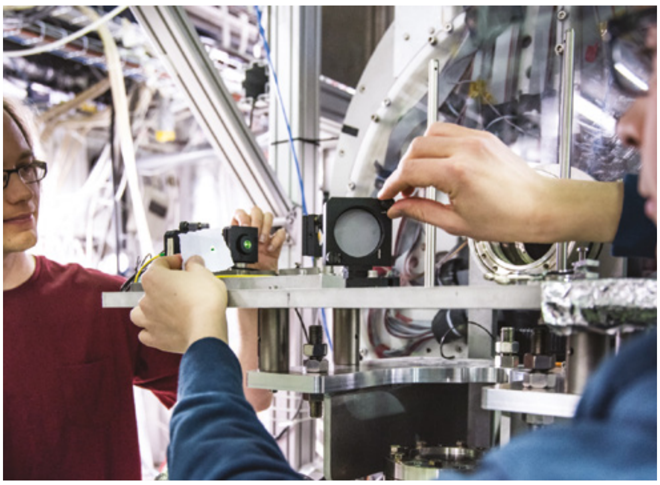


Located on board the International Space Station and operated from a control centre at CERN, the Alpha Magnetic Spectrometer experiment (AMS) released groundbreaking cosmic-ray results during 2016. AMS is a unique experiment in particle physics that is able to study cosmic rays free from atmospheric interactions to search for dark matter, antimatter and other exotic entities. 2016 marked its first five years of data since its launch, with the publication of several important papers. The latest AMS results are based on 17.6 million electrons and positrons and 350 000 antiprotons detected. In line with previous AMS measurements, the positron flux exhibits distinct differences from the electron flux that require accurate theoretical interpretation to determine whether the origin of these features is from dark matter collisions or new astrophysical sources. The latest AMS data also reveal that the proton, helium and lithium fluxes all deviate from traditional single-power-law dependence at a "rigidity" of about 300 GV, which is completely unexpected. The latest AMS measurement of the boron-to-carbon flux ratio also contains surprises, and expectations on AMS to clarify the nature of cosmic rays are high.

The Alpha Magnetic Spectrometer (AMS) is a state-of-the-art particle physics detector attached to the International Space Station.

Finding microscopic differences between antimatter and matter more generally could help explain why we see only matter on cosmological scales, whereas equal amounts of matter and antimatter should have been present at the moment of the Big Bang. Detecting CP violation is a key ingredient for this imbalance to occur, and the LHCb experiment looks specifically for new sources of this subtle asymmetry. During 2016, LHCb reported the first evidence of CP violation in baryons and also the world's most precise measurement of the unitarity triangle angle gamma, which characterises the amount of CP violation in the Standard Model. Ultra-precise searches for CP violation in the charm system were also carried out, but no clear signal has yet been seen. Further data from LHC Run 2 will be key to solving these fundamental puzzles.

The ALPHA experiment traps antihydrogen atoms in a magnetic trap and illuminates them with lasers to manipulate their electronic properties. (CERN-PHO-201603-070-11)



EXOTIC BEAMS

CERN doesn't just collide particles to see what matter's made of – it also generates a range of particle beams for experiments in fundamental nuclear physics, medical isotope production and materials science. The exotic-beam facility ISOLDE carried out 46 successful experiments in 2016, serving users spread mainly between nuclear structure studies (23%), decay studies (20%) and Coulomb excitation/scattering studies (23%). Nuclear astrophysics studies took up 7%, materials science 11% and biophysics and medicine dominated the remaining share. The main breakthrough of the year was the accomplishment of the HIE-ISOLDE energy upgrade, which means that the large variety of ISOLDE beams can now be accelerated to 5.5 MeV per nucleon.

2016 began with a measurement with cosmic implications: the production of a ^{7}Be sample at ISOLDE to be used at the n_TOF facility, which allowed researchers to study a vital reaction underpinning the "cosmological lithium problem". Based on astronomical observations, the universe contains much less lithium-7 than predicted by Big Bang Nucleosynthesis, the period immediately following the Big Bang during which the lightest elements were created. By studying a particular reaction relevant to lithium-7 production, n_TOF made direct measurements of the reaction rate that could help explain the missing cosmic lithium. In materials science, meanwhile, important results on the nature of doping in nitride semiconductors were obtained, as were data on the surface wetting of graphene. A new project served by proton beams from ISOLDE – CERN MEDICIS – also neared completion in 2016. MEDICIS will develop isotopes to be used as a diagnostic agent and for radiotherapy for the treatment of certain cancers, with start-up expected in 2017.

Future of physics with elusive neutrinos

Since the discovery almost 20 years ago that neutrinos can oscillate and therefore have mass, neutrinos remain one of the best hopes for discovering new physics. The CERN Neutrino Platform, inaugurated in 2014, is set up to act as a focus for the European neutrino community and undertakes R&D on detector technologies for use in accelerator-based neutrino projects outside Europe. Major progress was made during 2016 with the completion of the EHN1 hall extension in CERN's North Area, and preparation of the cryostats for the DUNE prototype liquid-argon time-projection chambers (both single- and double-phase variants). The refurbishment of the two ICARUS time-projection chambers and the construction of their new cryostats also reached completion, with the equipment ready for shipping to Fermilab in the US in 2017 to participate in the short-baseline neutrino experiment there. Other activities under way at the Neutrino Platform include the preparation of the Baby-MIND spectrometer that will form part of a neutrino experiment in Japan. To support these efforts, a neutrino group has been set up in the Experimental Physics department, and a task force for neutrino studies in the Theoretical Physics department.

A prototype detector prepared at CERN for the DUNE experiment in the US, which will be the target for neutrinos sent by Fermilab 1300 km away (CERN-PHOTO-201612-306-19)

A robotic sample changer at CERN's MEDICIS and ISOLDE facilities allows different isotopes to be produced. (OPEN-PHO-EXP-2016-013-3)

NATURE'S DARK SIDE

There could be aspects of the universe that we are blind to. In addition to direct searches for new particles at the LHC that might shed light on the dark matter in the universe at large, physicists have devised more subtle experiments to reveal the darker secrets of the vacuum.

In 2016, a new experiment at CERN's SPS called NA64 reported on a direct search for sub-GeV dark photons that would decay invisibly into dark matter particles and leave a clear signature of missing energy in the detector. No evidence for such decays was found, allowing NA64 to set new limits on the dark photon's properties, in particular concerning its ability to explain the long-standing discrepancy between the measured and predicted values for the anomalous magnetic moment of the muon.

Meanwhile the CAST experiment, in which a powerful magnet is aimed at the sun to detect hypothetical particles called axions, began a new three-year measurement programme in 2016. The experiment is searching for solar chameleons – candidates for dark energy – using a pixelated detector and a force sensor, and for dark matter axions using a resonant cavity.