



Physicists in the ATLAS control room applaud the first LHC proton collisions at the unprecedented energy of 13 TeV on 3 June 2015. (CERN-PHOTO-201506-128-7)

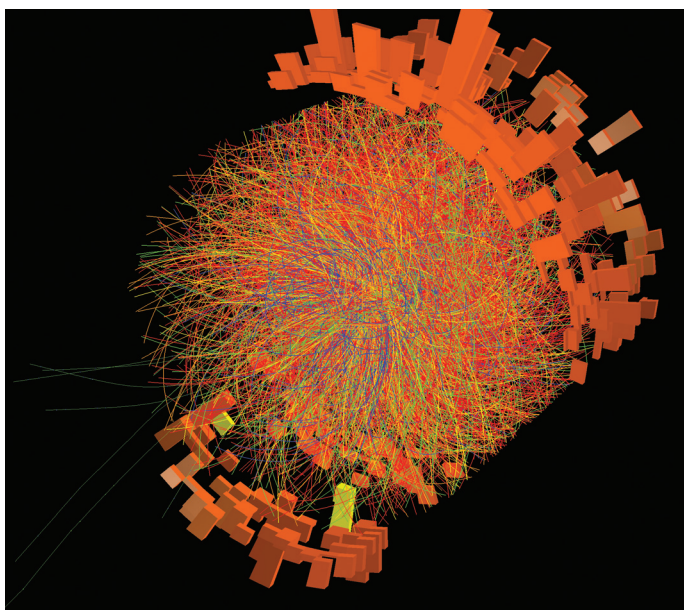
Physics and experiments

After two years of intense maintenance and consolidation and several months of preparation for restart, the Large Hadron Collider (LHC) was back in operation in 2015. On 3 June, the LHC started delivering physics data at the unprecedented energy of 13 TeV, almost double the collision energy of its first run. LHC Run 2 was under way.

ALICE rejuvenated

When the LHC resumed operation, it was with a rejuvenated ALICE experiment. During the LHC's first long shutdown (LS1), ALICE underwent an extensive facelift with the aim of improving the overall performance of the experiment. New modules were added to the Transition Radiation Detector, providing complete azimuthal coverage. Photon Spectrometer coverage was extended with the addition of a fourth module.

A new electromagnetic calorimeter was added to the existing one so as to provide azimuthal back-to-back coverage, and a new trigger detector was added to the detection systems. In anticipation of increased particle flux, the gas mixture in the Time Projection Chamber was changed, and the readout electronics of several detection systems were modified. With many other minor improvements, ALICE collected large and unique data sets from proton-proton collisions at 13 TeV and 5.02 TeV and from lead-lead collisions at 5.02 TeV. The total data collected, 7 petabytes, is already equivalent to all the data collected during the LHC's first run. This was made possible by the spectacular performance of the LHC, significantly surpassing the original design luminosity for ion operation, and heralding an exciting scientific programme ahead.



One of the first heavy-ion collisions with stable beams recorded by ALICE on 25 November 2015. (OPEN-PHO-EXP-2015-013-2)

Meanwhile, analysis of data from the LHC's first run continued apace. Drawing on comprehensive in-depth analyses, a standard model of heavy-ion collisions is taking shape. These measurements firmly establish that nuclear matter heated to the temperatures reached in lead-lead collisions at the LHC has all the dynamic and thermodynamic features of the most perfect liquid known and give us a glimpse of the potential of further high statistics measurements to pin down the fundamental properties of quark-gluon plasma with high precision.

But this is not the end of the story. The observation that many signatures attributed to the collective dynamics of a medium in lead-lead collisions were also present in lighter systems, such as proton-lead collisions and even proton-proton collisions, triggered a change of focus towards a comprehensive understanding of hadronic collisions in small and large systems. Despite the fact that one feature of lead-lead collisions, the quenching of emerging particle jets by the dense and hot medium, does not seem to happen in proton-lead collisions, the question is raised of whether the fundamental mechanism giving rise to collective dynamics in lead-lead collisions is present in lighter hadronic collisions, or whether droplets of quark-gluon plasma are formed in such collisions. Answering such questions and establishing what the fundamental mechanism is have become the driving motivations guiding ALICE's data-taking and analysis in the second LHC run.

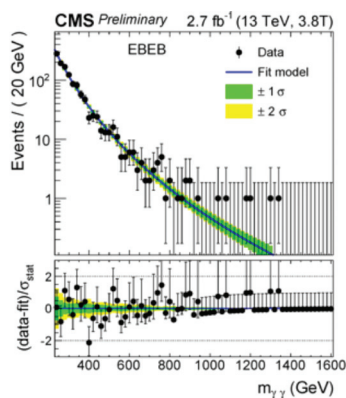
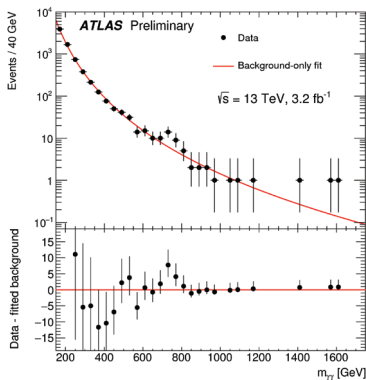
ALICE's versatility has been demonstrated in measurements leading to new and unique results. For example, a high-precision measurement, improving on previous measurements by more than one order of magnitude, has been performed on the mass difference between matter and antimatter for the deuteron and ^3He . This provides an important test of nature's most fundamental symmetries. In another example, a detailed analysis of the spectrum of J/ψ particles offers the promise of new perspectives in the study of quark-gluon plasma.

In 2015, the R&D phase for the approved ALICE upgrade programme, scheduled to be installed following the end of LHC Run 2, was drawing to a close. Prototyping is now under way and series production is scheduled to start in 2016.

ATLAS – a five-fold focus

The focus for ATLAS during 2015 was five-fold: recommissioning the detector as well as the new software and analysis model developed during the shutdown, accumulating the maximum amount of good-quality data at 13 TeV proton-proton (pp) collision energy, prompt analyses for the purpose of new physics searches and initial Standard Model measurements, continuing the completion of Run 1 analyses, and preparation of the scoping document for the Phase 2 upgrade of the ATLAS detector. That document was favourably received by the LHC Resources Review Board, successfully completing the first step of the Phase 2 upgrade approval process and giving the green light to move on to detailed Technical Design Reports (TDRs).

The year began with an intense phase of trigger and detector commissioning using cosmic-ray and pp collision data. The first data in stable-beam conditions were recorded on 3 June. More than 200 million pp collision events were taken with low-intensity beams for the alignment and detailed studies of the tracking systems, in particular the new innermost pixel layer, the Insertable B-layer (IBL). These data were used for the re-observation of the so-called ridge effect at 13 TeV, a peculiar long-range correlation pattern that could be shown by ATLAS to be due to single-particle modulation with similar underlying physics, as in proton-lead collisions. In the summer, ATLAS presented early 13-TeV measurements of soft-QCD processes and W, Z and top production. Initial searches for new strongly interacting high-mass phenomena using the first 100 pb^{-1} of data did not show a signal. ATLAS also prepared a broad set of detector performance results showing a good understanding of the early data.



Bump hunting

In particle physics, new particle discoveries can sometimes be characterised by bumps appearing on regular distributions of known physics. For example, known physics may account for a distribution of events containing photon pairs, descending smoothly with a quantity physicists call invariant mass – a measure of the total energy and momentum of the particle that produced two photons. If a new particle is produced at a particular mass, and it too produces photons, this new source of photon pairs will produce a bump on the distribution – an excess of photon pairs compared to what would be expected from known physics. This was one of the signals contributing to the discovery of the Higgs boson in 2012.

As 2015 drew to a close, a small bump at around 750 GeV was seen by both the ATLAS and CMS experiments, leading to much speculation as to what it might be. While it may well be due to statistical fluctuations, all eyes will be on ATLAS and CMS when Run 2 resumes in 2016.

Plots from the ATLAS and CMS experiments showing a small bump in the data at around 750 GeV.

In a fast turnaround, ATLAS presented numerous analyses using the full sample of up to 3.6 fb^{-1} of 13 TeV pp data at the 2015 end-of-year seminar and the subsequent winter conferences. Among these were initial measurements of inclusive Higgs boson production via its decays to photon and Z-boson pairs, further measurements of top-quark production, including the less abundant electroweak (single top) channel and the rare top-antitop production associated with a W or Z boson.

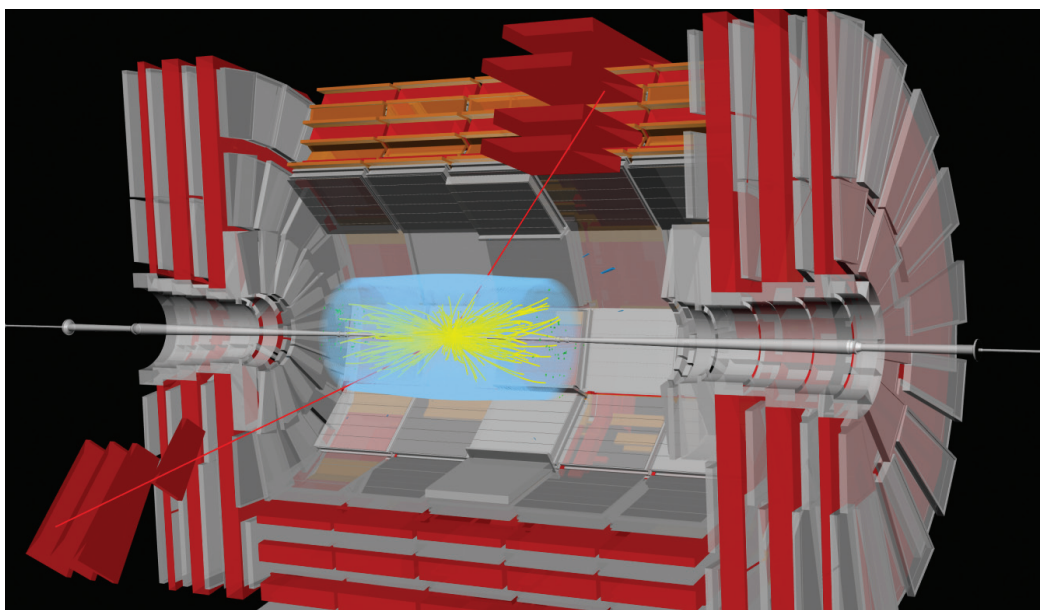
Primary emphasis was put on searches for new phenomena, resonant or not, involving events with highly energetic jets, leptons, photons, W, Z or Higgs bosons, missing transverse momentum and combinations of these. The majority of these searches did not exhibit deviations from the Standard Model. An eye-catching exception was an unexpected bump at around 750 GeV seen in the diphoton mass spectrum. The probability of such an effect occurring in the absence of a signal is equivalent to about two standard deviations. A potential signal is not excluded by Run 1 searches although there is tension. However, no resonant signal was seen by ATLAS in the photon plus Z mass spectrum in the 13-TeV data. The upcoming restart of the LHC is expected to clarify the interpretation of these findings.

ATLAS has continued to publish analyses based on Run 1 data. A total of 525 papers will have been published by April 2016, with 122 of those released during 2015. Among these were papers on CP-violation and rare decay measurements of B

mesons. Comprehensive ATLAS papers discuss W and Z boson pair production and measurements of top-quark production and decay properties. ATLAS published the complete suite of relevant Run 1 Higgs mass, production and decay property measurements in 2015. ATLAS and CMS joined forces by combining their Higgs boson mass and coupling measurements, thereby establishing the observation of the decay into a pair of tau-leptons. The Run 1 search programme was completed in 2015, including detailed summary papers. A highlight of the heavy-ion collision programme for ATLAS was a new analysis of the dijet asymmetries in lead-lead, proton-lead and proton-proton collisions, exhibiting similar properties for peripheral lead-lead and proton-proton collisions, but large modifications in central lead-lead collisions.

CMS – starting Run 2 with gusto

The CMS collaboration had a busy 2015. In the first quarter, work scheduled for LS1 was successfully completed, and intense preparation for Run 2 began. Analyses with Run 1 data were concluded and published, early installations of the Phase 1 upgrades were carried out, and an in-depth study for the Phase 2 upgrades was conducted and published in a technical proposal. A scoping document set out studies of the proposed baseline upgrades, accompanied by an analysis of cost-benefit versus loss in the physics potential of various downgrades, and was highly appreciated by reviewing committees, opening the door to further progress.



A collision event with the largest-mass muon pair so far observed by the CMS detector in proton-collision data collected in 2015. The mass of the di-muon system is 2.4 TeV. (CMS-PHO-EVENTS-2015-005-5)

With beams back in the LHC, CMS set about 13-TeV data-taking with gusto. The first results and even a first publication were presented at conferences in July. The publication concerned the number of charged hadrons produced in proton collisions as a function of energy. This is one of the first measurements performed at the start of exploration of a new energy regime because it allows researchers to check whether the theoretical models used in simulations are accurate, as proved to be the case.

Another important measurement when exploring a new energy regime is the rediscovery of known particles. CMS measured pairs of muons emerging from the collisions, revealing a spectrum that clearly showed peaks corresponding to particles ranging from the omega meson to the Z boson. The particles in this spectrum were originally discovered over several decades but it took CMS just weeks to observe them all at 13 TeV, a clear demonstration of the readiness of CMS for new physics at this energy.

As the year progressed, CMS pursued a broad range of analyses with 13-TeV data, and in December presented a large number of searches for new physics. Results included a small excess above background in the two-photon channel near a mass of 750 GeV, an effect also seen by ATLAS. In both cases, the statistical significance is small, but the fact that both experiments see the same thing is intriguing. More data is needed to determine whether this excess is just a statistical fluctuation or a sign of new physics.

Other 2015 highlights include the continuing search for dark matter, with analyses placing new limits on the direct production of supersymmetric particles. Searches for events containing bottom quarks that could arise from dark matter produced in association with bottom or top quark pairs were carried out, along with searches for non-standard decays of the Higgs boson and for exotic Higgs bosons. So far, all avenues have drawn

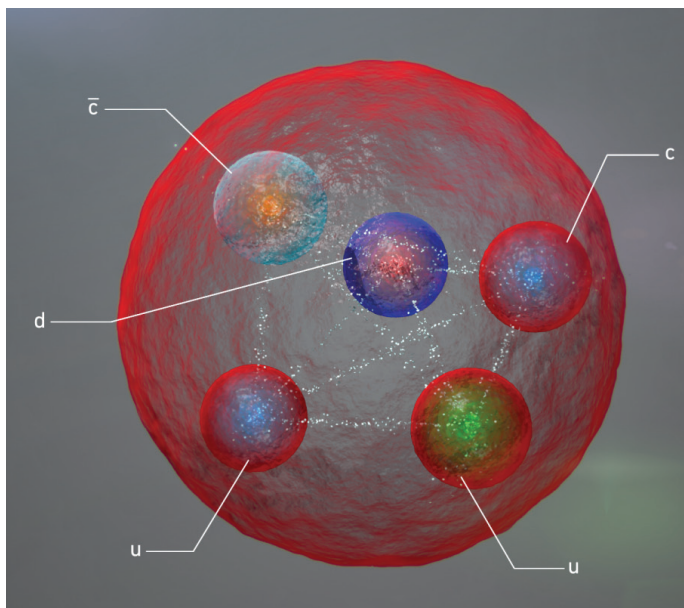
a blank, though the limits on supersymmetry are tightening. While Run 2 was the focus of attention in 2015, CMS also wrapped up its analysis of Run 1 data, with more than 120 new results presented at conference and published. Many results concentrated on the properties of the Higgs boson. Others concerned high-precision measurements to probe the Standard Model ever more precisely. These included measurements of the two-photon production of W-boson pairs, production rates for particle jets at 2.76 TeV compared to 8 TeV, production of two photons along with jets, and electroweak production of a W boson with two jets.

Discovered over two decades ago, the top quark continues to play a vital role in measurements and searches. New CMS results include measurements of top-antitop production rates in the fully hadronic sample and a measurement of the top-antitop+bottom-antibottom process in the lepton+jets channel. In addition, searches for signs of new physics continue, most recently in the process $t \rightarrow cH$, where the Higgs boson transforms to photons.

Significant heavy-ion results from Run 1 include upsilon polarisation as a function of charged-particle multiplicity in proton-proton collisions, Z-boson production, jet-fragmentation functions in proton-lead collisions, and nuclear modification of upsilon states in lead-lead collisions.

LHCb – good things come in fives

The clear highlight of 2015 for the LHCb experiment was the discovery of a class of particles known as pentaquarks. These particles aggregate quarks in a pattern that had not been observed before. Studying their properties may allow us to understand better how ordinary matter, the protons and neutrons from which we are all made, is constituted.



One possible arrangement of quarks in a pentaquark particle. The five quarks are tightly bound. Another possible arrangement has the quarks assembled into a meson (one quark and one antiquark) and a baryon (three quarks) weakly bound together. LHCb announced the discovery of pentaquarks in 2015. (OPEN-PHO-EXP-2015-009-3)

Our understanding of the structure of matter was revolutionised in 1964 when American physicist Murray Gell-Mann proposed that a category of particles known as baryons, which includes protons and neutrons, are comprised of three fractionally charged objects called quarks, and that another category, mesons, are formed of quark-antiquark pairs. Gell-Mann was awarded the Nobel Prize in Physics for this work in 1969. This quark model also allows for the existence of other quark composite states, such as pentaquarks, composed of four quarks and an antiquark. Until now, however, no conclusive evidence for pentaquarks had been seen.

Earlier experiments that searched for pentaquarks proved inconclusive. Where LHCb differs is that it was able to look for pentaquarks from many perspectives, with all pointing to the same conclusion. It's as if previous searches were looking for silhouettes in the dark, whereas LHCb conducted the search with the lights on, and from all angles.

Other results from Run 1 data include the measurement of one of the key parameters describing the difference between matter and antimatter. These parameters are encapsulated in the so-called unitarity triangle, which is characterised by the angles alpha, beta and gamma. A new LHCb measurement provided the world's best measurement of the least-well known angle, gamma, marking an important step on the way to understanding matter-antimatter asymmetry. In 2015, LHCb also published a combined analysis with CMS on an extremely rare process: the decay of the B^0_s particle into two muons. The Standard Model predicts that this process should happen about four times out of a billion decays, but it had never been seen before. Studying such decays could open a window to theories beyond the Standard Model, such as supersymmetry.

LHCb made a successful start to Run 2, collecting data with high efficiency. Most notably, a revolutionary approach to the data-acquisition chain enabled the first Run 2 physics results to

be produced very quickly. Results on known physics, such as J/ψ particles, are an essential start to running at a new energy, and were presented at conference within a couple of weeks of the start of data-taking. In 2015, LHCb also collected data from lead-ion collisions for the first time.

Looking ahead, LHCb physicists are working towards an upgrade to be installed during the LHC's second long shutdown, starting in 2019. This is an ambitious project that involves entirely removing the hardware trigger so as to read out the detector at the crossing-rate of the LHC, making all trigger decisions in a software CPU farm. All readout electronics will be renewed, along with many subdetector systems.

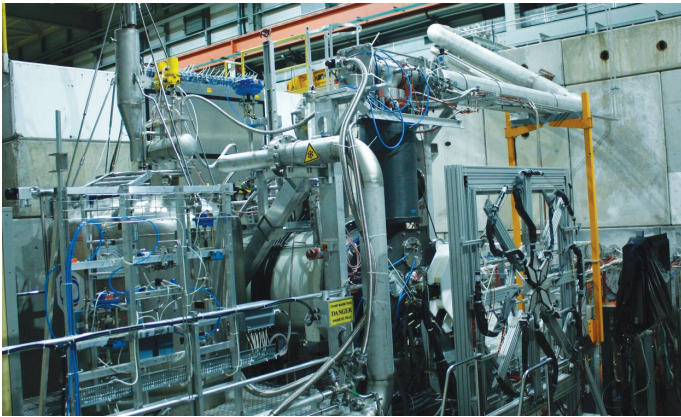
Last but not least, LHCb turned 20 in 2015 and marked the occasion with a festival of physics and milestones from the history of the collaboration. LHCb officially came into existence in August 1995 when a letter of intent was submitted for the world's first dedicated b-physics experiment at a hadron collider.

LHCf – moving forward

The LHCf experiment had a busy year in 2015. LHCf looks at neutral particles emitted at very low angles to LHC collisions. Studying these so-called forward interactions helps scientists understand what happens when high-energy cosmic rays collide with the atmosphere. In 2015, LHCf collected its first 13-TeV data, recording some 40 million events in 30 hours of data-taking. While these data were being analysed, LHCf published papers based on 7-TeV data. These results showed some discrepancies with models used to interpret cosmic-ray data, and so provided input for refining the models. LHCf also started a joint analysis of proton-lead data with the ATLAS experiment, demonstrating the potential of combining data from the two experiments.

MoEDAL – towards the discovery frontier

MoEDAL is a pioneering experiment designed to search for



A view of the COMPASS experiment in its 2015 configuration. (OPEN-PHO-EXP-2016-005-1)



A scene from the experiment's control room as NA62 commissioning got under way. (OPEN-PHO-EXP-2016-004-1)

highly ionising particle (HIP) messengers of new physics. Its innovative detector, deployed on the LHC ring near the LHCb experiment, has a dual nature tuned to discovery physics. First, it acts like a giant camera, comprised of nuclear track detectors, sensitive only to new physics. Second, it is uniquely able to trap HIPs, for example the magnetic monopole, for further study. The installation of the full detector was completed early in 2015 and it took data for the first time in spring 2015. MoEDAL's first physics paper will be published in spring 2016.

TOTEM – a total measurement

After substantial upgrades, including inserting additional so-called Roman pot detectors that allow measurements very close to the beam, the TOTEM collaboration began Run 2 with a much-improved apparatus. TOTEM measures the total cross-section for pp collisions with unprecedented precision, and is a unique tool for exploring proton structure. In 2015, TOTEM published results showing how the cross-section for pp collisions varies with energy, including previously unseen features. These measurements provide vital reference points for the larger LHC experiments, and are important in interpreting cosmic-ray showers. In Run 2, TOTEM is hunting for exotic particles such as the hypothesised glueballs, formed from the gluons that hold other particles like protons and neutrons together. Thanks to an agreement with CMS, allowing the experiment to combine data with its larger neighbour, TOTEM begins Run 2 with increased sensitivity to new physics.

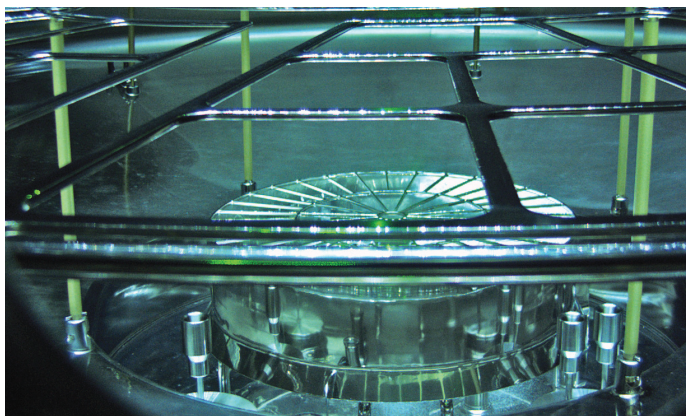
Experiments at the SPS

Moving upstream from the LHC we find the Super Proton Synchrotron, SPS, which in addition to providing beams for the LHC is host to four active experiments. These are designated NA58, NA61, NA62 and NA63, where NA stands for North Area, their location, and the number is simply their place in the series of North Area experiments that began in the 1970s with NA1.

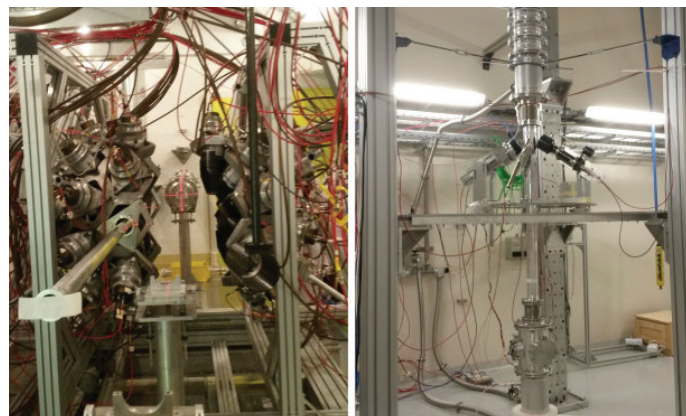
After a successful 2014 pilot run, the COMPASS experiment (NA58) embarked in 2015 on the study of interactions between a 190-GeV pion beam and a transversely polarised ammonia target. Measuring how the polarisation of the protons in the target affects the production of muon pairs gives COMPASS researchers a complementary approach to elucidating proton structure compared to previous COMPASS experiments. In particular, it allows the orbital angular momentum in the proton to be probed: a very eagerly awaited result. To perform this measurement, many COMPASS spectrometer elements were upgraded: the superconducting magnet of the polarised target was completely rebuilt, the tracking system was reinforced and a new data-acquisition system was successfully implemented.

The SPS Heavy Ion and Neutrino Experiment (NA61/SHINE) studies the production of hadrons – particles taking part in the strong interaction that keeps atomic nuclei from falling apart. One of the experiment's goals is to identify the critical point at which ordinary matter transforms into quark-gluon plasma: matter as it would have been just after the birth of the universe. The technique they use is to vary the beam particles in order to explore a range of collision temperatures and densities; the salient parameters in pinpointing the critical point. In 2015, milestones were reached as argon beams were delivered by the SPS for the first time in February, followed by lead ions in November.

Commissioning of the NA62 experiment got under way in earnest in 2015. NA62 studies rare decays of particles called kaons. It will detect just 40 decay candidates per year if the Standard Model prediction is correct. This will enable scientists to investigate the likelihood that top quarks decay to down quarks. Understanding such relations between quarks is a powerful way to check Standard Model consistency. In 2015, good commissioning data were recorded from all NA62's subsystems. The detector recorded some 20 billion events: a clear demonstration of its ability to work at high intensity. A key



Inside the lower section of the CLOUD apparatus, illuminated by UV light, during an experimental run at the PS. (OPEN-PHO-EXP-2016-003-1)



The horizontal neutron beam line in EAR1 (left) and the vertical neutron beam line in the newly constructed EAR2. (OPEN-PHO-EXP-2016-006-3)

subsystem, the Gigatracker, was successfully demonstrated and the experiment's trigger, which decides which collisions to record and which to reject, was commissioned.

NA63 directs beams of electrons and positrons onto crystalline targets to study processes that occur in the extremely strong electromagnetic fields they experience there. These fields can lead to the creation of new particles from the vacuum in a process analogous to those at work in neutron stars and black holes, and could help in understanding mechanisms that give rise to the highest energy cosmic rays. In 2015, NA63 also examined how photons are emitted by electrons and positrons passing through high fields: work that has implications ranging from new techniques for lasers to understanding Hawking radiation from black holes, which has yet to be observed.

Experiments at the PS

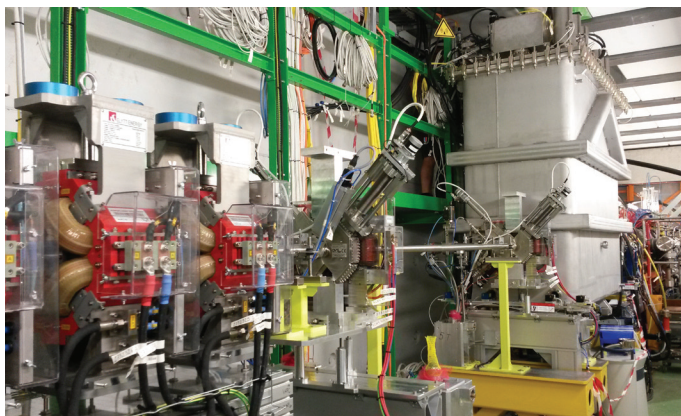
Further upstream is the veteran PS accelerator, in operation since 1959 and still the linchpin of CERN's accelerator chain. In 2015, the PS provided beams to three experiments and facilities.

The CLOUD experiment is tackling an important societal issue of our day: the science of aerosol formation in the atmosphere and its impact on clouds and climate. A PS beam allows CLOUD to study whether aerosol formation is enhanced by galactic cosmic rays. In 2015, CLOUD extended its investigations of aerosol particle nucleation and growth to include two of the most abundant biogenic vapours in the atmosphere: alpha-pinene and delta-3 carene. Sulphuric acid, ammonia and nitrogen oxides were included in the mix to recreate the complex conditions found at the Hyytiälä Forestry Field Station in Finland to reveal which vapours control aerosol particle nucleation and growth and how these processes are affected by natural radioactivity and galactic cosmic rays. Analysis is under way, and the first publications are expected in 2016.

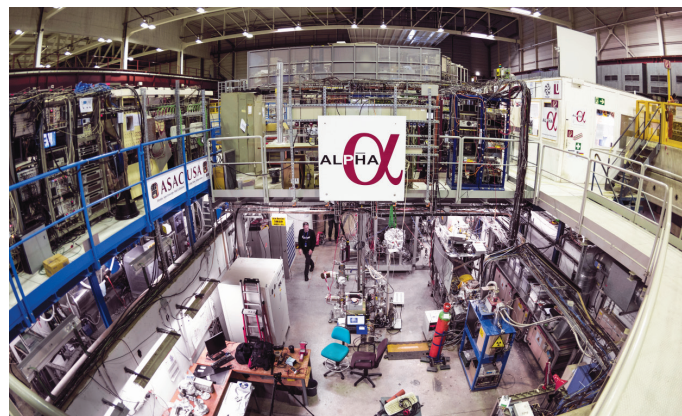
DIRAC, the Dimeson Relativistic Atom Complex, is an experiment to help physicists gain a deeper insight into the strong force by measuring the lifetimes of exotic short-lived atoms made up of pairs of particles from the meson family. In 2015, DIRAC made the first observation of atoms made of pions and kaons, π^+K^- and π^-K^+ atoms. These are made through the interaction of protons from the PS with targets of nickel and platinum. Some of them rapidly break up in the target, leaving the constituent pion and kaon to go their separate ways. Measurement of the lifetime and other properties of these atoms can then be compared to theoretical predictions with high precision, bringing greater clarity to our understanding of the strong interaction.

The neutron time-of-flight facility, n_TOF, provides pulsed beams of neutrons produced by the interactions of protons from the PS with a lead target. The neutrons are collimated and guided to two experimental areas, EAR1 and EAR2. EAR1 is 185 metres from the target horizontally and has been taking data since 2001. EAR2 is situated vertically at about 20 metres and received its first beam in 2014. Both areas work simultaneously. The time-of-flight technique allows neutron-induced reactions to be studied as a function of neutron energy, with implications for stellar nucleosynthesis and nuclear technology, for example in the elimination of nuclear waste.

The 2015 EAR1 physics programme included measurements of gamma rays accompanying neutron capture by a number of nuclei. In addition, a neutron-induced fission measurement was performed on the nucleus neptunium-237. Meanwhile at EAR2, beam-line commissioning was completed and followed by neutron capture measurements on the radioactive isotopes thulium-171 and promethium-147. Neutron-induced alpha emission cross-sections were measured on sulphur-33 and beryllium-7. The last of these could help understand why measurements of lithium abundance are at odds with the predictions of Big Bang models. A new spectrometer, STEFF



The ISOLDE beam line that supplies the Miniball array. The first HIE-ISOLDE cryomodule can be seen in the background in its light-grey cryostat. (OPEN-PHO-ACCEL-2016-007-1)



Inside the Antiproton Decelerator experimental hall. (CERN-PHOTO-201601-005-11)

(Spectrometer for Exotic Fission Fragment), was installed and took its first data, making both n_TOF experimental areas fully operational.

ISOLDE – exotic beams

CERN's exotic beam facility, ISOLDE, carried out 35 successful experiments in 2015. Notable among these was the first extraction of very difficult, refractory, boron beams through the ionised molecule, BF_2^+ . A refractory material, such as boron, is one that retains its strength in extreme conditions and so is hard to ionise. This new beam will allow scientists to study the halo nucleus ^8B . Halo nuclei have a dense core of protons and neutrons, with others in a loose halo surrounding the core. Loosely bound systems such as these are important, since they allow the boundary between bound and unbound systems to be explored.

Five successful experiments were carried out at the ISOLDE decay station ranging from the nucleus ^{20}Mg at the proton drip line, so called because it is so far from stability that it literally drips protons, to the very neutron-rich doubly magic ^{132}Sn . In nuclear models, protons and neutrons are arranged in shells, and when a nucleus contains a certain number of protons or neutrons, the shells become full and are said to be closed. A nucleus with a closed shell is said to be magic, and if both proton and neutron shells are closed, it is doubly magic. Stable doubly magic nuclei have particular, easily recognisable, properties: they are spherical and difficult to excite. An important current question in nuclear theory is whether magic numbers established for stable nuclei remain magic for very unstable ones. This ISOLDE result sheds light on this question, and is very challenging for nuclear theory.

Combining data from the ISOLDE decay station with mass measurements from the ISOLTRAP detector, the heavier mass border of the island of deformed nuclei containing around 20

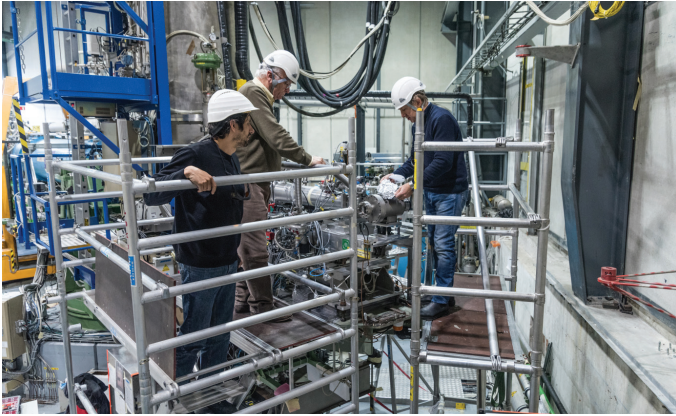
neutrons, such as ^{34}Mg , should soon be revealed. Measurements such as these are important for testing nuclear models and thereby understanding the physics of nuclei. Other important breakthroughs include the determination of the mean square radii of mercury and gold isotopes obtained by pushing the sensitivity limits by combining state-of-the-art techniques for production, separation and detection. These measurements confirm spectacular changes of deformation in isotopes with 104 neutrons.

The High-Intensity and Energy ISOLDE project (HIE-ISOLDE) delivered its first post-accelerated beams in 2015 (see p. 24). Beams of exotic zinc with atomic numbers 74 and 76 were accelerated to 4 MeV per nucleon for the first time on 22 October. This marked the beginning of a new era at ISOLDE.

Experiments on antimatter

CERN's Antiproton Decelerator (AD) is a unique facility, delivering beams of low-energy antiprotons to a range of experiments mainly concerned with the study of antimatter. Since the hydrogen atom is among the best-understood systems in physics, one of the key aims of the AD experimental programme is to make precise measurements of antihydrogen atoms. Instead of being made up of a proton and an electron like hydrogen atoms, these are made up of their antiparticle equivalents, an antiproton and a positron. Measuring the properties of antihydrogen with similar precision to that of hydrogen will provide a powerful test of the symmetries linking matter and antimatter, and perhaps help explain why we live in a universe of matter, even though matter and antimatter would have been produced in equal amounts at the Big Bang.

In 2015, the ASACUSA experiment published results from experiments with an atomic hydrogen beam that show their apparatus is able to make spectroscopic measurements of atoms in flight. The next step will be to repeat the experiment with an antihydrogen beam.



Members of the CAST collaboration in front of the new KWISP detector. Installed on the axion helioscope, the KWISP will extend CAST's search to include the dark-energy candidates, chameleons. (CERN-PHOTO-201602-049-22)

While ASACUSA compares atoms with antiatoms, the BASE experiment makes comparisons between particles of matter and antimatter with the same objective in mind: trying to identify any differences in the properties of matter and antimatter. In 2015, BASE compared the charge-to-mass ratios of protons and antiprotons, and found there to be no difference at the level of parts per trillion.

ALPHA, ATRAP and AEGIS worked steadily towards their next goals: interaction of lasers with trapped antihydrogen atoms in the case of ALPHA and ATRAP, and pulsed production of antihydrogen atoms via pulsed production and laser-excitation of positronium in the case of AEGIS. Preparation of the AD for the installation of GBAR was completed, with the first equipment due to be in place in early 2016.

Astroparticle physics

There's more to particle physics than research with high-energy beams from accelerators. The low-energy frontier can also teach us much, as can particles coming from space. Two such experiments at CERN are on the hunt for new physics.

The OSQAR experiment explores the low-energy frontier in the quest for hypothetical particles that could make up the universe's mysterious dark matter and energy. Theories predict that such particles could be produced from a beam of light in a high magnetic field, so OSQAR shines a laser into an LHC dipole magnet at CERN's magnet test facility. In 2015, OSQAR extended its search to include chameleons, mysterious new dark-energy candidates that change mass according to the density of their surroundings. If chameleons exist, they should appear through the conversion of photons in a transverse magnetic field. No signature was detected, and the ongoing analysis should set new exclusion limits in the search for chameleons. For now, however, dark energy remains as elusive as ever.

The veteran CAST experiment has spent 14 years observing the sun with the goal of detecting axions: particles hypothesised to

make up the universe's dark matter, which could be copiously produced in the sun's core. Solar axions entering the CAST detector would be converted into X-rays, which can be easily measured. So far, CAST has not observed any axions coming from the sun, and has extended its net to search for relic axions left over from the Big Bang. CAST is also installing two sensors that will allow it to be more sensitive to solar chameleons, the dark-energy candidates with variable effective mass, whose production and detection mechanisms are similar to those of axions. One of CAST's detection techniques uses a sensitive force sensor, unique in the field of astroparticle physics.

The CERN Neutrino Platform

Inaugurated at the end of 2014, the CERN Neutrino Platform provides a focal point for Europe's contribution to global neutrino research. It includes an R&D facility at CERN allowing a global community of neutrino experts to develop and prototype the next generation of neutrino detectors.

Understanding the elusive neutrino is a worldwide priority for particle physics. Neutrino research at particle accelerators is complementary to studies made in cosmology, and future measurements could cast light on outstanding questions concerning, for example, the nature of dark matter and the matter/antimatter imbalance in the universe. Experiments at accelerators will also be able to observe neutrinos from supernovae.

The CERN Neutrino Platform marks a new direction in CERN's neutrino research. In the 1970s, neutrino beams at the Laboratory allowed the discovery of neutral currents with the Gargamelle bubble chamber. The most recent neutrino beam produced at CERN went through the Earth to the INFN's Gran Sasso National Laboratory in Italy from July 2006 to December 2012.

In December 2014, the CERN Neutrino Platform took delivery of the ICARUS detector, shipped from Gran Sasso, where it studied the neutrino beam from CERN. ICARUS is now being refurbished, and in 2017, it will be shipped to Fermilab in the US where it will become part of a dedicated neutrino programme.

Detectors for a linear collider

The CERN Linear Collider Detector (LCD) project brings together institutes from around the world to study physics and detector issues for a potential future linear electron-positron collider, such as CLIC (see p. 27). Its activities are divided between three collaborations: CLIC detector and physics (CLICdp), CALICE, which focuses on energy-measuring calorimeters, and FCAL, which looks at detectors in the forward regions, close to the beam pipe.

In 2015, physics studies looked at Higgs and top quark physics, as well as simulating physics beyond the Standard Model at CLIC energies. Detector optimisation and engineering studies led to a new CLIC detector model with enhanced physics coverage in the endcaps. Software tools for event simulation and reconstruction were significantly upgraded and now include

a flexible detector description and new track reconstruction software for a full silicon tracker. Successful beam tests were carried out with various CLIC vertex detector assemblies, as well as with CALICE and FCAL detectors. Meanwhile, the CALICE collaboration carried out laboratory tests of scintillator tiles read out by silicon photomultipliers, and published results of test-beam campaigns with a tungsten-scintillator calorimeter prototype. While the focus of this work is on a potential detector for CLIC, there is considerable synergy with other future options including the International Linear Collider and the Future Circular Collider (FCC) study (see p. 27).

R&D for a bright future

CERN's accelerators are host to a number of R&D projects preparing particle detection technologies for the future. The veteran among these is RD18, the Crystal Clear Collaboration, which has been investigating innovative crystal detectors for use in electromagnetic calorimetry for particle physics, medical and industrial applications since 1991. RD39 and RD50 develop silicon tracking devices that can withstand the harsh environment of hadron colliders, while RD42 looks at industrial diamond-based detectors for similar applications. RD53 is developing readout electronics for such detectors. RD51 pushes the limits of gas-filled detectors, while RD52 is developing calorimetry for high-quality energy measurements. Together, these collaborations cover the needs for future collider detectors.

Two further initiatives in the R&D phase blur the boundary between R&D and experiment. UA9 studies how bent crystals could be put to work in future colliders to channel the diffuse halo of particles accompanying the beam away from sensitive equipment, leaving tight needle-like beams to interact at the collision points. In the LHC, this process of collimation is done by tungsten jaws that mop up the halo. SHiP, the Search for Hidden Particles, is a proposed fixed-target experiment at the SPS accelerator to look for particles predicted by models of physics beyond the Standard Model. SHiP has been encouraged to perform a comprehensive design study over the next three years, with R&D to demonstrate the feasibility of the experiment.

In theory

In 2015, roughly half of the research effort of the CERN Theory group was devoted to the Standard Model or physics beyond the Standard Model. Standard Model particle physics includes research directly relevant to the LHC, in particular QCD and Higgs physics. Physics beyond the Standard Model includes research on building models of extensions to the Standard Model, dark matter, possible signatures of new physics at the LHC, and more.

The announcement on 15 December of a possible bump in the two-photon distribution in LHC data at 13 TeV generated great excitement in the theoretical physics community. CERN's Theory group actively participated in the ensuing discussions and studies on the theoretical interpretation of the data (see p.14).

Apart from particle physics phenomenology, there was intense research on astroparticle physics and cosmology, heavy-ion physics, lattice field theory, formal field theory, gravity and string theory. Projects often overlapped between fields, such as dark matter being possibly relevant both for cosmology and collider physics, or black-hole physics being holographically related to heavy-ion collisions. Another example is conformal field theory, which links together particle physics, black holes and condensed matter physics. Moreover, novel techniques to compute scattering amplitudes, as a spin-off from insights in mathematical physics, were employed to perform computations directly relevant for collider physics of a complexity never managed before. All in all, members of the group published about one paper per day on average.

CERN's Theory group comprises 18 research staff members and about 40 fellows at any given time. It also conducts a large visitor programme, which involves about a dozen scientific associates, and around 800 short-term visitors. The unparalleled high flux of visitors is an important aspect of the group's role as a world-leading centre for scientific exchanges.

Theory Institutes form an important part of the visitor programme: quick-to-setup, informal workshops that last for up to a few weeks, they help to optimise resources by bringing together visiting scientists with common interests and by sharing resources with the international community. In 2015, there were three such Institutes, covering Understanding the early Universe, Neutral Naturalness and Duality Symmetries in String and M-Theories.

Members of the Theory group attended many international conferences and workshops. They were also involved in the work of the Particle Data Group and in several teaching activities at CERN, including the Academic Training, Summer Student and High School Teacher programmes, as well as the European and Latin American Schools of High-Energy Physics. As it does every year, the Theory group hosted the annual CERN Winter School on Supergravity, Strings and Gauge Theory, as well a doctoral school on String Theory. A particularly important ongoing activity is the LHC Physics Centre at CERN (LPCC), which organises workshops, lectures and working groups. In November, the group held its annual TH retreat, offering members a comprehensive overview of all the ongoing research activities. Its purpose was to facilitate the integration of newcomers and generally exchange ideas in a stimulating environment. The programme provides a good snapshot of the group's work in 2015. (see <https://indico.cern.ch/event/433779/other-view?view=standard>).

In 2016, there will be a major change for CERN Theory as it regains the status of a department, recognising the leading role that theory plays as a reference centre in all areas of theoretical particle physics.