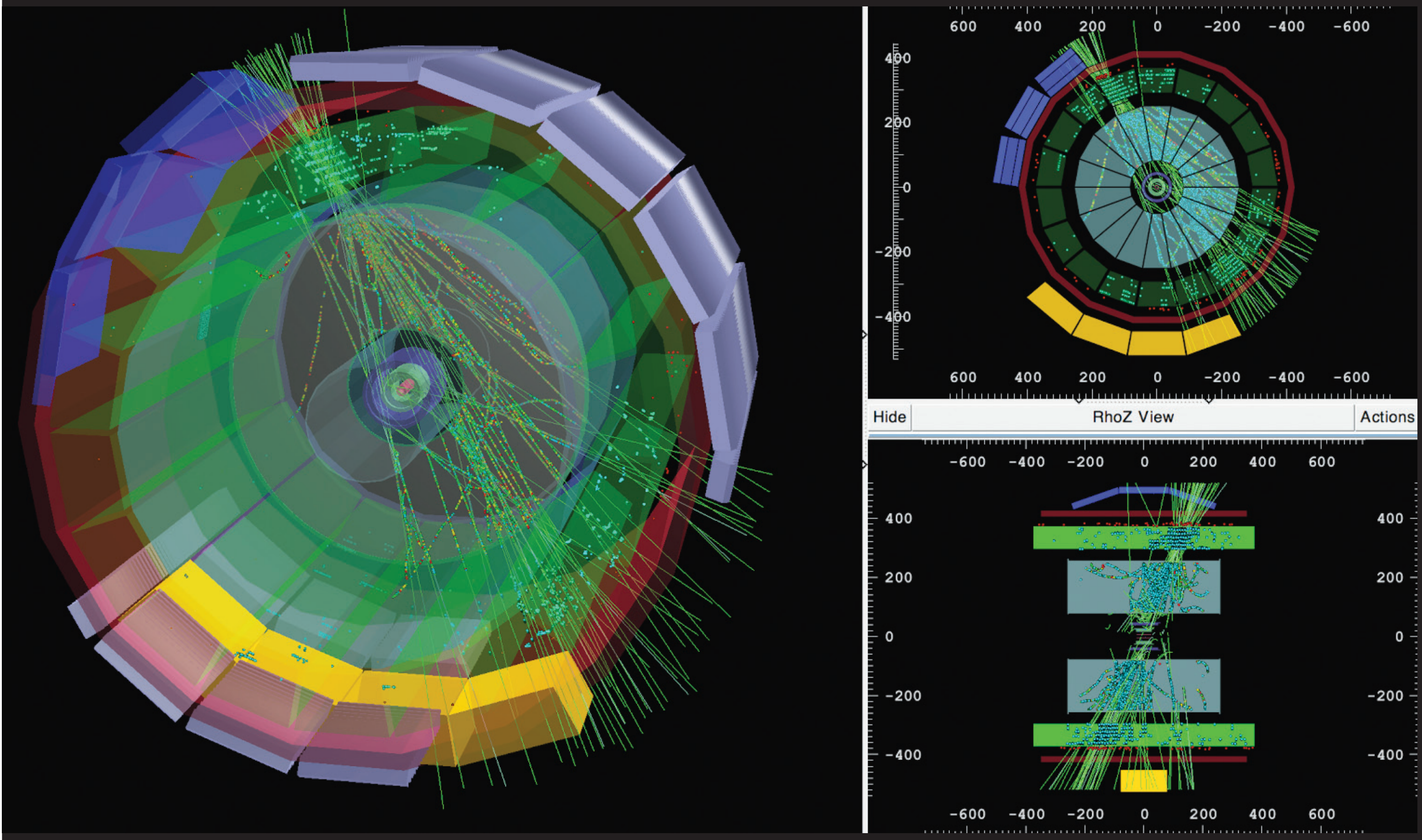


An event display from the completed ALICE detector with the components installed during LS1, showing a shower of particles produced by a high-energy cosmic muon. (ALICE Collaboration)

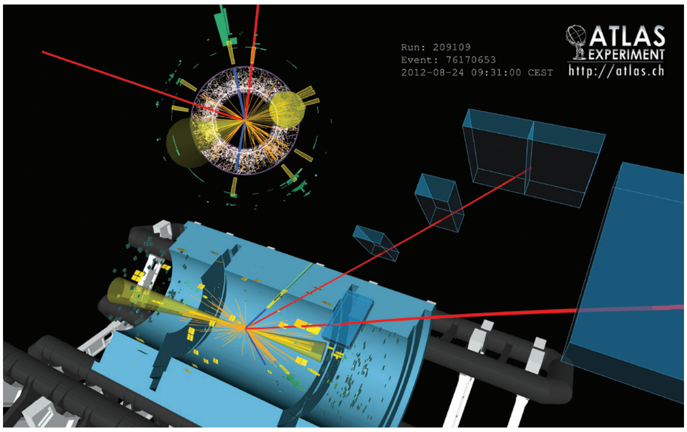
Physics and Experiments

For most of the experiments at CERN, 2014 was dominated by the final stages of the long shutdown and preparations for the gradual restart of the accelerator complex during the autumn, with beams returning to all but the LHC. While some teams worked hard on refurbishment and upgrades, others continued to analyse data from previous runs. In particular, the LHC collaborations still had much to harvest and were able to present many final results from Run 1.

ALICE: the hottest matter

By making precision measurements, the ALICE collaboration aims to answer the fundamental question of what consequences the quark structure of matter has on the behaviour of matter at extreme conditions of temperature similar to those that prevailed in the early Universe. ALICE had already established that matter created in heavy-ion collisions at the LHC has all of the features of a ‘perfect’ liquid. New insights from detailed analyses in 2014 of the full data set from Run 1 have helped to consolidate this picture. The equations of hydrodynamics describe well the way that the collisions evolve through a phase of freely moving fundamental constituents — ‘partons’ — to matter consisting of familiar hadrons. The measured final hadronic state is consistent with a statistical model in which the hadrons emerge from a hot ‘bath’ with a temperature of 155 MeV, although some features remain unexplained.

But what does the partonic phase — the phase known as quark-gluon plasma (QGP) — consist of? To test the possibility that



Display of a candidate event for the decay of a Higgs boson into two electrons and two muons, accompanied by two energetic jets of particles in the forward directions. (ATLAS Collaboration)

hadrons could be produced by the coalescence of quarks in the QGP, ALICE compared the spectra of protons (made of three quarks) and phi-mesons (which have the same mass, but consist only of a quark–antiquark pair). The coalescence model does not predict the observed results and leaves open the question about the composition of the QGP. However, the observation that the J/psi — a charm quark and its antiquark bound together — can be regenerated in the QGP supports the idea that unconfined charm quarks exist within this phase of matter. To gain a deeper insight, ALICE is exploiting the production of jets of particles, which have the potential to reveal what happens within the QGP at a higher resolution. The analysis of data taken in Run 1 offers the promise of future precision measurements in Run 2 and beyond, to answer the question about the makeup of QGP.

The main emphasis of the data analysis in 2014, however, was to investigate whether a droplet of QGP can be created in small systems. The question was triggered by a surprising observation in proton–lead collisions in which many particles are produced. These high-multiplicity proton–lead collisions share with lead–lead collisions most of the features attributed to the collective dynamics of the QGP. Similarly, a feature called the ‘ridge structure’, which is interpreted in lead–lead collisions as a signature of collective behaviour, has been observed unexpectedly in high-multiplicity proton–proton collisions. There is so far no unique interpretation of this observation.

In studies of central proton–lead collisions — where there is the most overlap between the proton and the lead nucleus — ALICE has measured a set of observables that are described well by the collective dynamics of a system in equilibrium. In particular, the composition of the final hadronic state (given by the production rate of the different hadrons) follows the expectation of the statistical model. The measured values of the radial and elliptic flow of identified hadrons with low transverse momentum, together with the size of the hadronic system at ‘freeze out’ (the stage where the hadrons cease to interact), follow the expectations for a system that is expanding collectively. Further measurements showed that the signals for collective behaviour observed in proton–proton and proton–lead collisions evolve gradually with the multiplicity, and approach the values measured in lead–lead collisions. These observations have been possible thanks to the development by ALICE of a new method to determine centrality in proton–nucleus collisions.

A puzzle remains, however: why are the features of jet ‘quenching’ that have been universally observed in heavy-ion collisions not observed in central proton–lead collisions?

The ALICE experiment also underwent an intensive programme of consolidation and improvement during LS1, which allowed the completion of several detector systems as well as preparations for the anticipated increase in LHC luminosity in Run 2.

The five super-modules of the transition-radiation detector that were missing in Run 1, were produced and installed. The coverage of the calorimeter system was increased through the installation of a new dijet calorimeter, back to back with the existing electromagnetic calorimeter, and an extra module was added to the photon spectrometer. A new component, the ALICE diffractive detector, was also installed. This consists of two double layers of shower counters placed far from the interaction region, at 16 m from the collision point in the ALICE cavern and at 19 m in the opposite direction in the LHC tunnel. The gas mixture of 90% neon and 10% carbon dioxide in the ALICE time-projection chamber was changed, with argon replacing neon. This will allow a more stable response at high particle-fluxes without significant degradation in the resolution of the momentum measurement at low values of transverse momentum.

Working together

Combining different analyses leads to higher precision in measurements, and the year 2014 saw the different experiments at the LHC get together in some key areas of physics. In this way, collaborative hard work by ATLAS and CMS to combine analyses resulted in the best precision so far for the mass of the Higgs boson.

Another highlight was the combination of measurements by CMS and LHCb of the decays to muons of two neutral B mesons, $B^0_s \to \mu\mu$ and $B^0 \to \mu\mu$. (These related particles consist of a b quark bound with an s quark, in B^0_s, or a d quark, in B^0.) This is a golden channel in the search for new physics, as both decays are heavily suppressed in the Standard Model; the hunt for small deviations from predictions continues.

The strengths of the CMS and TOTEM experiments were combined in a joint analysis of charged particles produced in proton–proton collisions and set a milestone for future common measurements.

The readout electronics of all of the detector systems was adapted to work at an increased speed. Together with a complete upgrade of the data-acquisition and high-level trigger computer clusters, this will allow ALICE to exploit fully lead–lead collisions at a rate as high as 10 kHz in Run 2.

For the longer term, and particularly the HL-LHC project (see p. 19), a vigorous upgrade programme has begun. This will dramatically enhance the performance of the ALICE detector systems in the charm and beauty sectors and also cope with the future high luminosities that will require readout rates of up to 50 kHz for lead–lead collisions. In 2014, the LHC Committee approved two Technical Design Reports, one for a new internal tracking system and one for new electronics. Other reports for a new muon forward-tracker, for the upgrade of the time-projection chamber and for a new online/offline computing system were prepared for approval in 2015.

ATLAS: many results

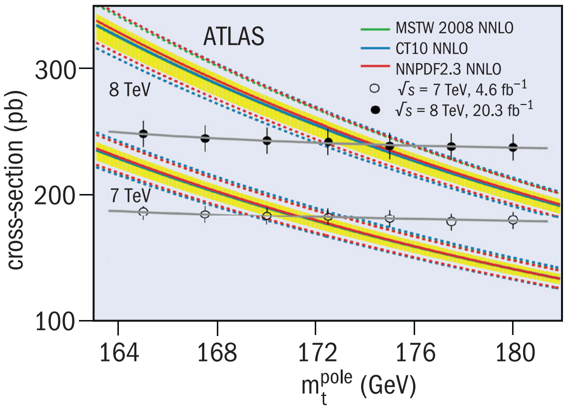
The main theme for ATLAS was to extract the maximum possible information from the large data sets from Run 1, before Run 2 takes over in 2015. After establishing the main properties of the Higgs boson and observing its bosonic and fermionic couplings in 2013, further insights came from a new set of measurements of the two high-resolution decay channels to two photons and to four charged leptons (see figure opposite). As well as providing more precise results on the Higgs boson's mass and its couplings, these measurements shed light on the various mechanisms that produce the boson in proton–proton collisions. ATLAS also firmly established the existence of the decay of the Higgs boson to two W bosons and measured the corresponding signal strength with a precision of about 20% — an important step towards gaining a complete picture of the Higgs boson's properties. No deviations from the predictions of the Standard Model have appeared so far in these investigations.

Extensive investigations of the Standard Model continued in 2014 with many new results, including the most precise measurements to date of the production rate of top quarks, with an uncertainty of around only 4%. These results agree well with theoretical predictions and can be used both to determine the mass of the top quark to good precision (see figure p. 24) and to limit the room for additional production of top quarks through processes linked to physics beyond the Standard Model, such as supersymmetry.

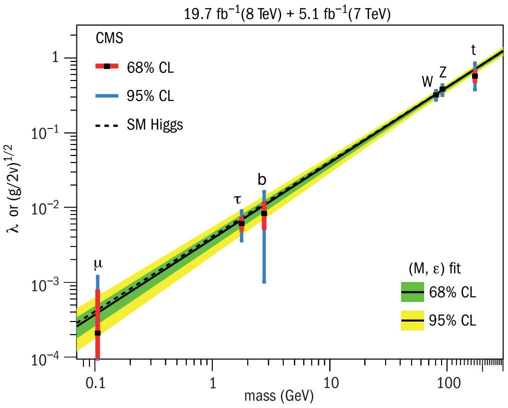
Measuring the couplings of the W and Z bosons to each other is an important test of the underlying electroweak model, which may reveal contributions from anomalous couplings and therefore point to new physics. The corresponding processes are, however, extremely rare and their observation has become possible only recently with the large centre-of-mass energy and luminosity provided by the LHC. ATLAS has extracted the purely electroweak contribution to the production of a Z boson and two jets of particles, which includes the process of weak-boson fusion, $WW \to Z$. The results are in good agreement with the Standard Model.

The many other results from ATLAS in 2014 included the rate for producing W bosons in conjunction with jets, and a very precise determination of the total probability for proton–proton interactions at the energy of Run 1, using the ALFA detectors in ATLAS. There were also new results on the collisions of protons and lead ions, using the production of jets to shed light on the geometry of such proton–nucleus collisions.

Searches for new particles or phenomena continued unabated. ATLAS took the search for supersymmetry into new areas by looking for events with two or three leptons together with missing energy, which could signify an undetected supersymmetric particle. The search found no significant excess beyond the expectations of the Standard Model in either case. This null result



Measurements by ATLAS of the top-pair production probability (the cross-section) at centre-of-mass energies of 7 and 8 TeV, compared to theoretical predictions from quantum chromodynamics as a function of the top-quark mass.



Measurement by CMS showing how the coupling of other particles to the Higgs boson increases with the mass of the particles.

can be used to narrow down the region where supersymmetry might exist in nature. Many more searches looked for new particles in a variety of scenarios, but no hints of new physics were found, thereby severely constraining models that predict exotic particles and phenomena.

The year also saw the completion of the intensive programme of detector maintenance, consolidation and upgrades that ATLAS underwent during LS1, with full-scale commissioning for Run 2 starting towards the end of the year. The Insertable B-Layer was installed inside the pixel detector to enhance its capability to identify and ‘tag’ heavy quarks in dense jets of particles. A series of commissioning weeks throughout the year sought to reintegrate all of the components of ATLAS and to begin rehearsing data taking at a rate of 100 kHz at the level of the first trigger, compared with 75 kHz in Run 1. This trigger now has new capabilities, notably the possibility to select events at this early stage according to their topology, rather than just to count objects. There have also been major improvements in the offline software, increasing the speed of event reconstruction by a factor of three, in preparation for a full exploitation of the LHC’s enhanced performance after LS1.

CMS: high precision

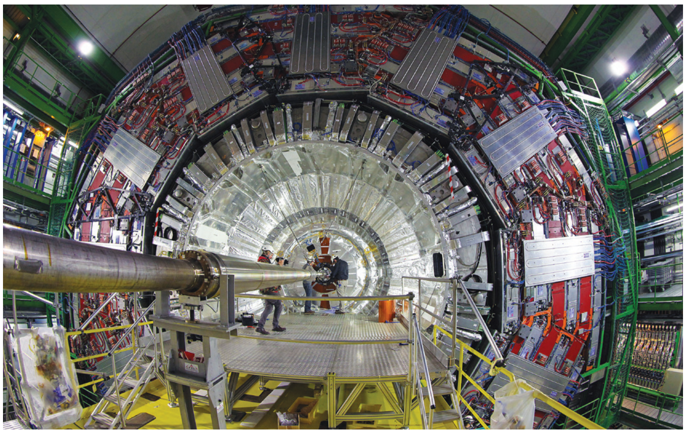
Intense scrutiny of the Higgs boson is one of the highest priorities for the physics programme and 2014 saw remarkable progress not only in finalizing the analyses for Run 1 but also in combining them to reach higher precision. Following the publication of results on the Higgs boson’s dominant decay channels, such as the two-photon channel, the addition of decays into tau leptons and into b quarks was a major accomplishment, leading to strong evidence for fermionic decays. Another highlight was CMS’s new bound on the Higgs boson’s decay width, which improved by more than two orders of magnitude on the previous measurement. Other studies nicely confirmed the Standard Model’s expectation that the coupling strength of the Higgs boson to other particles should increase with the mass of the particles (see figure above right).

The first combined results on the Higgs boson published by CMS incorporated all of the main channels analysed with the full data set from Run 1. Combining the search for Higgs bosons produced in association with top quarks with other analyses revealed an interesting deviation of about 2 sigma (σ) from the expectations of the Standard Model — a result that offers good prospects for gains in sensitivity in the future. CMS also extended the search for Higgs bosons all the way up to the scale of tera-electron-volts. Through combinations of all of the searches, CMS is interpreting the data at these high masses in the context of models with new physics and setting limits on potential discoveries.

While ‘standard’ searches for supersymmetric particles and, for example, dark matter are intensively pursued, other searches often employ the Higgs boson as a ‘scout’ for signs of new physics. This technique allowed CMS to set several exclusion limits, but produced no evidence for dark matter or other new particles. Nevertheless, several new analyses are under way to investigate remaining unexplored corners.

High-precision measurements in the physics of the Standard Model led to exceptional results. Here the top quark, the heaviest elementary particle, continued to be the main focus of attention. The historic combination of results from the LHC and from Fermilab’s Tevatron announced in March provided a world average for the mass of the top-quark, but this was soon superseded by a new measurement by CMS, which on its own had even higher precision. CMS also released many results for heavy-ion physics — some unique in the field — and presented the highlights at the major Quark Matter 2014 conference.

To prepare for the new data to come in Run 2, CMS performed two intense campaigns. The Computing, Software and Analysis exercise, CSA14, generated valuable feedback to the teams



CMS ready to close, showing the beam-pipe and the extensive new environmental seal. (CMS Collaboration)

working on computing, software, validation and physics analysis. The second exercise, PHYS14, successfully targeted the readiness of high-priority analyses for the first inverse femtobarn of Run 2 data.

A big effort on the CMS Upgrade Project made substantial progress towards the Technical Proposal. This work demonstrated the need for Phase 2 of the upgrade, by fully simulating the detector for Phase 1 (including assumptions on how it will age), evaluating the expected performance of the Phase 2 detector, and expanding the physics goals to exploit fully the potential of the HL-LHC project (see p. 19).

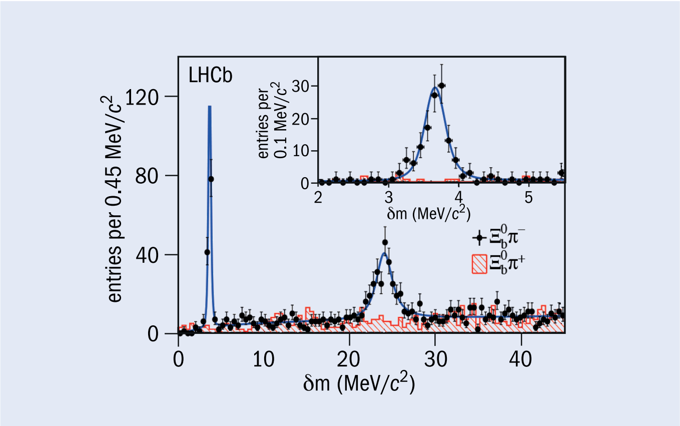
The main objectives of the LS1 programme were also completed in 2014, some even ahead of schedule, allowing time to resolve problems that surfaced during the shutdown. Challenges arose from unforeseen failures in the pixel detector and in the pre-shower detector of the electromagnetic calorimeter, but were successfully overcome. Particularly important objectives included: the installation of an extensive new environmental seal to enable the tracker to operate at a much lower temperature than in Run 1, and so prolong its lifetime in the increasing beam intensities of Run 2; the installation of the beam-pipe for Phase 1 of the upgrade; and the installation and commissioning of muon chambers to complete the original design. The replacement of the photon-detectors in the outer layer of the hadron calorimeter was successfully completed, together with major improvements in common systems and infrastructure. There were also major upgrades for the trigger and data-acquisition systems to guarantee the highest benefit from the unprecedented high-energy, high-intensity data taking anticipated in Run 2, with final preparations taking place in various campaigns and extended runs with cosmic rays.

B for beauty

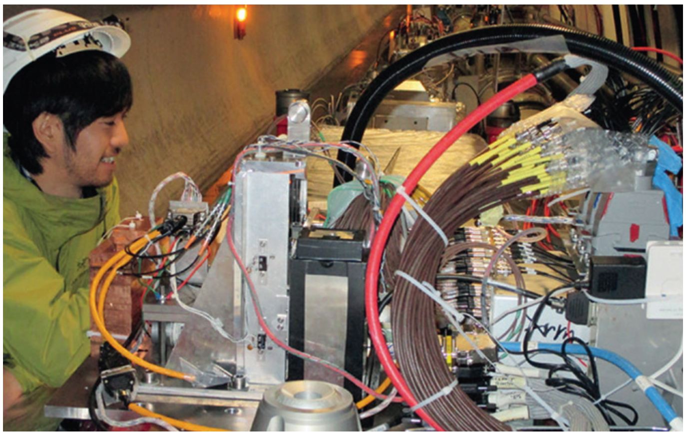
The LHCb experiment makes precise studies of particles containing beauty (b) or charm (c) quarks. It focuses on rare decays and on CP violation — a difference in behaviour between particles and their antiparticles. These are phenomena that are sensitive to new physics through quantum effects. Throughout 2014, the LHCb collaboration continued to analyse the data collected in Run 1, making great progress on benchmark measurements.

One of the most eagerly awaited measurements concerned the complete analysis for Run 1 of φ_s, the CP-violating phase-angle related to the interference between the decay and 'mixing' of the B^0_s meson with its antiparticle. This is an interesting place to search for new physics because the prediction of the Standard Model for φ_s is extremely small and precise, but new physics could enhance its value. The result $\varphi_s = -0.010 \pm 0.039$ radians is the most precise to date and is in very good agreement with the Standard Model. Another notable result is LHCb's precise measurement of the weak phase γ — one of the angles of the Cabibbo-Kobayashi-Maskawa triangle that links the interactions of the six quarks of the Standard Model. For the first time a single experiment has achieved a precision of better than 10°.

Another interesting result concerns the ratio R_K of the probabilities that a B^+ meson decays to $K^+\mu^+\mu^-$ or to $K^+e^+e^-$. These very rare decays occur just twice in 10 million events (2×10^{-7}); they are driven by transitions between b and s quarks ($b \rightarrow s$) that are highly sensitive to the effects of particles that exist only in extensions to the Standard Model. In the Standard Model this ratio is expected to be very close to 1 thanks to 'lepton universality', according to which electrons (e) and muons (μ) behave in an identical manner. LHCb measured R_K to be different from 1 with a significance of 2.6 σ, which, if confirmed, may be a sign of non-universal lepton interactions. Another $b \rightarrow s$ process, the decay $B \rightarrow K^{*0}\mu^+\mu^-$, also exhibits a significant discrepancy in one angular observable (referred to as P_5') compared to predictions from the Standard



LHCb's evidence for two new particles, Ξ'^{-}_{b} (the first peak) and Ξ^{*-}_{b} (the second peak), seen through their decay to $\Xi^0_b\,\pi^-$. δm is the difference between the mass of the $\Xi^0_b\,\pi^-$ pair and the sum of the individual masses of the Ξ^0_b and π^-.



LHCf's Arm1 detector. (T Sako)

Model, provoking considerable discussion in the particle-physics community.

The large samples of decays allow detailed studies of particles produced in different decay channels. LHCb has, for example, published results that for the first time unambiguously demonstrate that certain hadrons, in this case the Z(4430), have an exotic nature that cannot be accommodated in the simplest form of the quark model. The collaboration has also shown that a $\overline{D}^0K^-$ structure with a mass of 2860 MeV is composed of two resonance states, one with spin 1 and the other with spin 3. This is the first time that a spin-3 particle involving heavier quarks has been observed and should lead to new insights into the spectroscopy of hadrons. Another interesting result is the discovery of two new particles, the Ξ'^{-}_{b} and Ξ^{*-}_{b}. Predicted to exist by the quark model, they are both baryons containing three quarks, in this case, b, s and d. By observing these particles and measuring their properties with great accuracy, LHCb is making a stringent test of models of low-energy quantum chromodynamics (QCD).

The programme to measure benchmark processes is facilitated by the excellent calibration of the luminosity that the experiment has achieved. The relative precision is 1.12%, which is the best obtained at the LHC, and the most precise luminosity measurement achieved so far at a hadron collider operating with bunched beams. In early 2013, LHCb successfully collected data in the run with lead ions, making the first observation of the production of Z bosons in proton–lead collisions, at a centre-of-mass energy per proton–nucleon pair of 5 TeV.

The approved upgrade for LHCb, to be installed during the second long shutdown of the LHC, will increase the experiment's data-taking capacity by an order of magnitude. During 2014, the collaboration approved the choice of technology for the three tracking stations behind the magnet, giving the go-ahead for the construction of a full fibre-tracker.

F for forward

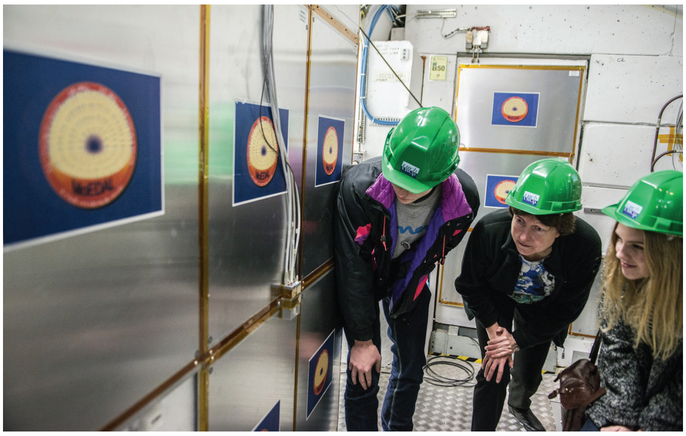
The Large Hadron Collider forward (LHCf) experiment measures neutral particles emitted at around 0° to the collisions in the LHC. These 'forward' interactions are important for the understanding of what happens when high-energy cosmic rays collide with the atmosphere. The collaboration published results on neutral pions obtained during proton–lead running in 2014. They also completed the upgrade to radiation-hard detectors. The new detectors were tested at the SPS in October before installation in the LHC tunnel, 140 m on either side of the interaction point in ATLAS. The two collaborations — LHCf and ATLAS — have started discussions on common data taking and analysis to study forward particle-production.

M for monopoles

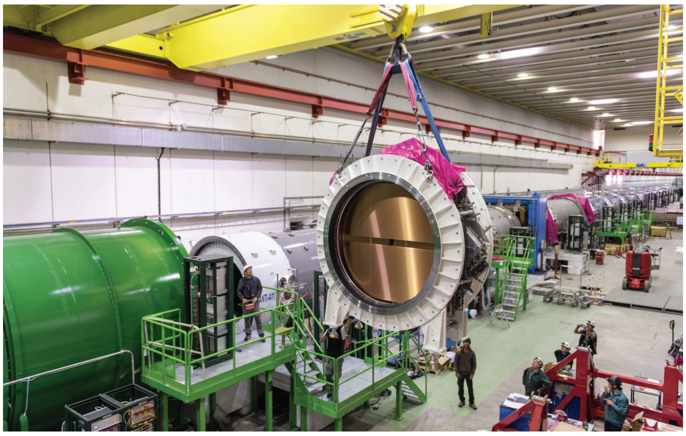
MoEDAL, the Monopole and Exotics Detector At the LHC, is designed to search for highly ionizing particles that are manifestations of new physics, such as magnetic monopoles and massive long-lived charged particles. The collaboration made substantial progress in 2014, including the publication of a paper describing MoEDAL's physics programme, which includes more than 30 discovery scenarios. The innovative MoEDAL detector was installed for the first time in the winter of 2014 for data taking in 2015. This largely passive device consists of an array (100 m^2) of plastic nuclear track detectors, which acts like a giant camera sensitive only to new physics. In addition, MoEDAL's 1-tonne Trapping Array is able to capture the high-ionizing particles associated with physics beyond the Standard Model. The radiation environment is monitored by a state-of-the-art real-time TimePix array of pixel detectors.

T for total

The TOTEM experiment, which cohabits with CMS at Point 5 on the LHC, is optimized to make precise measurements of particles that emerge from collisions close to and along the direction of the



Teacher Becky Parker, centre, at Point 8 with two members of the MoEDAL team from Simon Langton Grammar School for Boys, which joined the collaboration in 2014. (CERN-GE-1311279 – 11)



The final straw-tracker module, weighing close to 5000 kg, is lowered into position in NA62. (CERN-PHOTO-201409-176 – 4)

LHC beams. In 2014, the analysis of data collected during special runs in 2012 found surprising evidence for non-exponential behaviour in elastic proton–proton scattering at a centre-of-mass energy of 8 TeV. Previous measurements were not able to show such an effect.

In preparation for Run 2, TOTEM completed the consolidation and upgrade of the Roman Pots — devices that allow detectors to be brought very close to the beam. This included the addition of new cylindrical Roman Pots dedicated to high-precision timing detectors for high-luminosity running. The collaboration also produced a detailed upgrade proposal and Technical Design Report (TDR) for timing measurements, and has written a common TDR with CMS. The documents, endorsed by the LHC Committee, describe the consolidations and upgrades in view of the updated physics goals for Run 2.

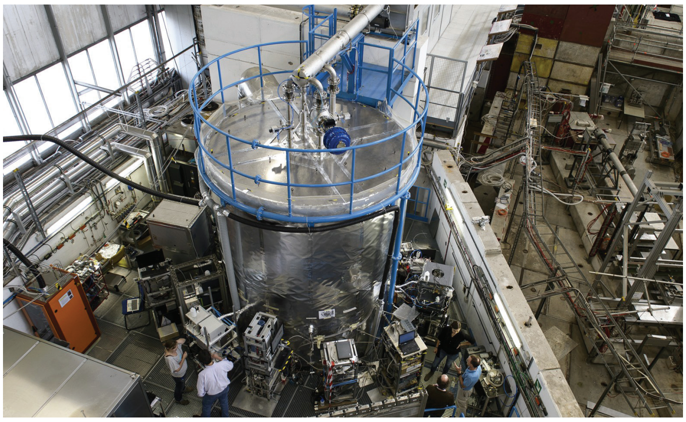
Beams from the SPS

In October, the SPS began once again to deliver protons to experiments in the North Area (NA) at CERN's Prévessin site. The COMPASS experiment (NA58) completed preparations for data taking in 2015, when the collaboration will study what happens when a 190 GeV beam of pions interacts in a transversely polarized ammonia target. The goal is to measure for the first time how the polarization of the protons in the target affects the production of pairs of muons in the reaction $\pi^- p \rightarrow \mu^+\mu^- X$. The complex modifications to the beamline involved moving the world's largest target of polarized protons and its superconducting magnets by 2 m in order to make room for a thick absorber consisting of tungsten, alumina and concrete. This stops all particles except muons (and neutrinos), but it also generates many low-energy particles, making reconstruction of the events more difficult. The two-month pilot run in 2014 allowed commissioning of the new setup, but without the target being polarized yet.

The NA61/SHINE experiment uses beam from the SPS to investigate under what conditions and how the quarks and gluons that are normally confined inside hadrons can form quark–gluon plasma — a medium in which they move freely. In 2014, the collaboration released its first results from scans through SPS energies of proton–proton and beryllium–beryllium collisions. Surprisingly, the proton–proton collisions show changes with energy similar to those that were associated with the onset of deconfinement in lead–lead collisions in NA49, an earlier experiment at the SPS. On the other hand, results from both proton–proton and beryllium–beryllium collisions showed no signs of the hypothesized 'critical point', beyond which the confined and deconfined phases of matter would transform between each other seamlessly.

With the return of beam to the SPS, NA61/SHINE was able to commission various upgrades to the beamline, the detectors and the analysis software, which had been undertaken during LS1. In addition, CERN's Research Board approved an extension of NA61/SHINE's physics programme to include measurements of hadron production to provide data for the modelling of neutrino beams in ongoing and future experiments at Fermilab.

The new NA62 detector took its first beam from the SPS in October. In early September, the last of the four 'straw-tracker' chambers had been lowered into position in the experiment. Each of these chambers consists of 16 layers of highly fragile, gas-filled tubes — straws — which detect charged particles as they pass through. The NA62 straw tracker is the first of its size to be placed directly into the vacuum tank of an experiment, allowing the direction and momentum of charged particles to be measured with high precision. The experiment's main aim is to explore distances as small as 10^{-21} m, using very rare decays of kaons.



The CLOUD experiment. (CERN-EX-1310264 – 02)

The new EAR2 building for the n_TOF neutron source. (OPEN-PHO-CIVIL-2015-002 – 1)

The NA63 experiment studies quantum effects in interactions with strong electromagnetic fields that occur when high-energy particles pass through thin amorphous and crystalline targets. In 2014, members of NA63, together with physicists from the CLIC study (see p. 20), published calculations for the phenomenon of ‘beamstrahlung’, based on comparisons with data from NA63. Beamstrahlung is a limiting factor in studies for next-generation electron–positron colliders, such as CLIC. It occurs when particles in one high-energy bunch ‘see’ a strong electric field from the opposing bunch, leading to the emission of intense radiation. The strength of these fields may lead to undesirable effects such as the loss of beam polarization and/or more diffuse beams. Conversely, as other members of NA63 have shown, the polarization effects of the extremely strong fields may allow a test of the phenomenon known as vacuum birefringence.

Beams from the PS

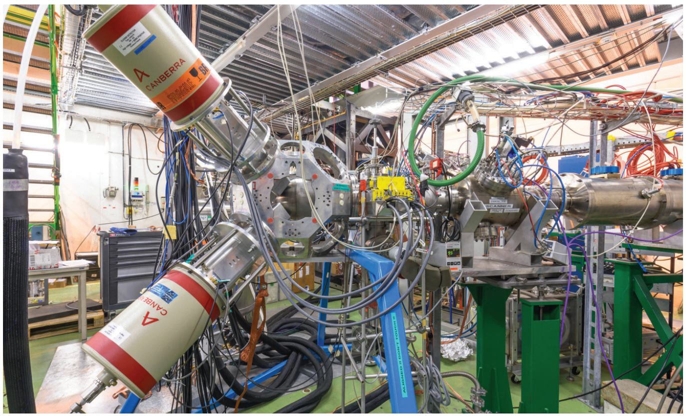
The CLOUD experiment is tackling one of the most challenging problems in atmospheric science — understanding how new aerosol particles are formed in the atmosphere and the effect that these particles have on climate. In particular, using a beam from the PS, CLOUD is studying whether the formation of aerosol particles is enhanced by ionization from galactic cosmic rays. In experimental studies published in *Science* in May, CLOUD showed that oxidized biogenic vapours form new particles with sulphuric acid and that this process can explain a large fraction of particle formation observed in the lower atmosphere. The CLOUD team also reported on global modelling studies that establish that trees play a fundamental role in forming new particles in the atmosphere, familiar as ‘blue haze’ when viewing distant mountains.

The DIRAC experiment, which ran at the PS during 2007–2012, has measured the lifetimes of unusual ‘atoms’ — $\pi^+\pi^-$ and πK — to check the low-energy predictions of QCD for light quarks. These lifetimes may be expressed as a known linear function of two scattering ‘lengths’, which characterize the interaction. Through continuing analysis in 2014, the DIRAC collaboration made the first measurement of the lifetime of the πK atom. Further analysis also revealed the first observation of long-lived $\pi^+\pi^-$ atoms, with a significance larger than 7σ. This gives access to an additional linear function of scattering lengths, and hence to a measurement of individual scattering lengths.

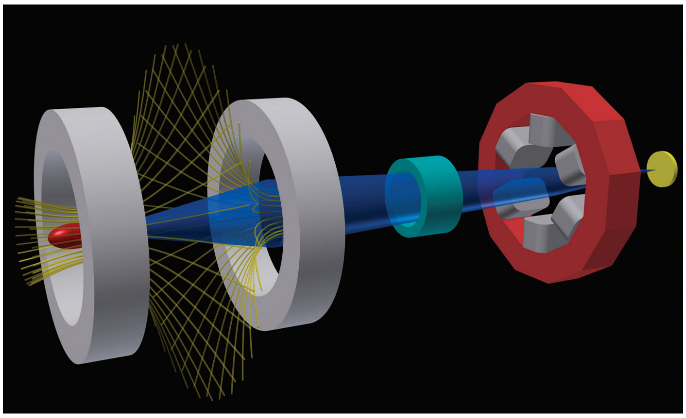
The neutron time-of-flight facility, n_TOF, provides pulsed beams of neutrons produced by the interactions of protons from the PS with a lead target. The neutrons are collimated and guided through evacuated beam tubes to two experimental areas, EAR1 and EAR2. EAR1 is located horizontally at approximately 185 m from the target, while EAR2 is situated vertically at about 20 m. The newly constructed second area, EAR2, received its first neutron beam on 25 July. The beam here complements and runs in parallel with the existing area, EAR1. The physics programme in EAR1 included measurements of neutron-capture on germanium-73 and on the radioactive thulium-171. EAR2 saw the first part of the commissioning of the new beam line, as well as a real experiment, at the end of the year, on the fission cross-section of plutonium-240. This cross-section was measured in the past in EAR1, during an experimental campaign spanning more than 2 years, where the high activity of the samples had a negative impact on the operation of the detectors and the data analysis. In EAR2, the measurement was successfully completed after 6 weeks, thanks to the higher neutron flux and the much higher neutron rate, which allowed the cross-section to be measured in the sub-threshold region as well. This clearly demonstrated the feasibility of fission experiments in EAR2.

ISOLDE reawakens

The ISOLDE Radioactive Ion Beam Facility is dedicated to the production and acceleration of radioactive nuclei. Teams took advantage of the long shutdown to upgrade existing apparatus, such as ISOLTRAP, and to build and commission two new



The ISOLDE Decay Station (IDS) is one of two new permanent experimental stations at the ISOLDE facility. It will allow physicists to study beta decay and to measure the lifetime of excited states. (CERN-PHOTO-201410-212 – 5)



ASACUSA's cusp-trap scheme. Left to right: the cusp trap to produce antihydrogen atoms, a microwave cavity (green) to induce hyperfine transitions, a sextupole magnet (red and grey) and an antihydrogen detector (gold). (Stefan Meyer Institut)

permanent set-ups, the ISOLDE Decay Station (IDS) and the Versatile Ion-polarized Technique on-line (VITO), which even took data. New ISOLDE groups also brought new travelling set-ups. These included neutron detectors used in an experiment led by groups from Caen and Madrid to study neutron–neutron correlation in lithium-11, and TATRA, the Bratislava group's tape-station used for the measurement of the decays of neutron-deficient mercury.

Following the restart of the PS Booster, which delivers protons to ISOLDE, 26 experiments and 3 test runs were scheduled between the end of July and mid-December. A fantastic atmosphere greeted the very first experimental run on 1 August. Samples of lanthanide elements were collected and shipped to other laboratories: terbium-149 and terbium-155 to the Paul Scherrer Institute in Switzerland, and neodymium-140 to the Risø campus of the Danish Technical University. The aim was to identify chemical elements with suitable isotopes for medical diagnosis and therapy.

The state-of-the-art capabilities of different devices at ISOLDE and their complementarity allowed the determination of the ground-state properties of a long series of isotopes of astatine — the rarest element on Earth — with production rates and half-lives extending over eight orders of magnitude. This successful experiment combined the synergies of three devices: the lasers of the Resonance Ionization Laser Ion Source, the Windmill set-up equipped with silicon and germanium detectors, and the ISOLTRAP Multi-Reflection Time-of-Flight mass spectrometer.

The High Intensity and Energy ISOLDE (HIE-ISOLDE) project progressed well during 2014 (see p. 19). Worldwide interest in the facility continued to grow, with everyone looking forward to its start-up with post-accelerated beams in 2015.

An exciting year came to a close with the annual ISOLDE workshop and users meeting, which took place on 15–17 December, with a golden jubilee session on 17 December, 50 years after the approval of ISOLDE in Council in 1964. The session was opened by Torleif Ericson, who was chair of the Nuclear Physics Experiments Committee at that time. Presentations followed from all of the former group leaders, who described the breakthroughs and highlights at the facility during their leadership.

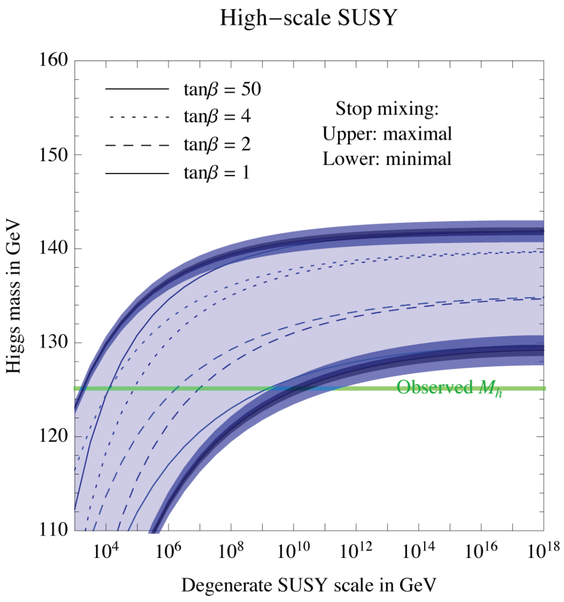
Focus on antimatter

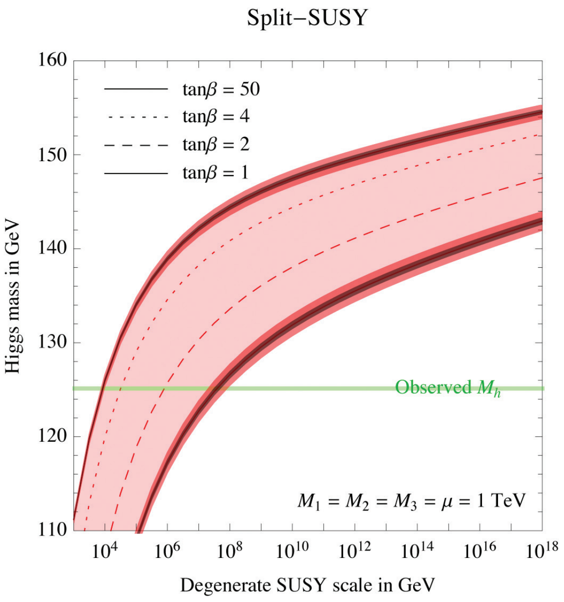
The AD produces low-energy antiprotons for a range of studies, including the synthesis of antihydrogen. The antiprotons originate when protons from the PS strike a target, so the experiments at the AD saw beam again in October, following work on installation and upgrades during LS1.

In continuing studies of data collected before LS1, the ALPHA collaboration published a new precise measurement of the charge of antihydrogen, finding it to be compatible with zero to eight decimal places. The ASACUSA collaboration, which has high-precision microwave spectroscopy of antihydrogen in its sights, also published results from data collected in 2012, which demonstrated the first ever production of a beam of antihydrogen.

The arrival of beams during the autumn enabled the commissioning of ALPHA-2, a modified apparatus with improved access for lasers to probe trapped antihydrogen atoms. Elsewhere in the AD hall, the ATRAP collaboration completed the installation of a second-generation antihydrogen trap to allow laser access. The ASACUSA experiment also commissioned a completely new set-up, which includes a new superconducting 'double-cusp' magnet, a new tracking detector and a new final antihydrogen detector.

LS1 also saw the installation of a brand-new beamline for BASE, a new experiment that aims to take ultra-high-precision measurements of the antiproton's magnetic moment. The





collaboration installed and commissioned all of the apparatus, took data with single antiprotons and implemented an antiproton reservoir.

Both the AEgIS and GBAR experiments are designed specifically to measure the gravitational interaction of antimatter. The AEgIS collaboration completed installation of the apparatus and commissioned it with antiprotons and positrons, in readiness for operation in 2015. Meanwhile studies continued for the GBAR experiment, which will take place at the future ELENA facility at the AD (see p. 18). The team made good progress on a demonstrator at Saclay, advancing on all fronts towards the technical implementation of the apparatus at CERN from 2016 onwards.

Astroparticle physics

There was no LS1 for two experiments at CERN that search for hypothesized particles that could form dark matter, making use of LHC dipole magnets. The CAST experiment tracks the Sun in search for solar-produced axions and other dark-matter candidates. In 2014, following the commissioning of a second X-ray optics that further improves its performance for detecting solar axions, it continued to operate with vacuum in the tubes of its LHC magnet. The silicon detector working in the sub-kiloelectronvolt range has been replaced by an InGrid pixel detector at the focal plane of one of the X-ray telescopes. This should improve on the current sensitivity of CAST in the dark-energy sector.

OSQAR — a ‘light shining through a wall’ experiment — probes the possibility of quantum oscillations between optical photons and dark-matter candidates, such as axions or axion-like particles (ALPs), in the 9 T transverse magnetic field produced by two spare LHC dipoles. In 2014, the experiment ran with an outstanding sensitivity, using an 18.5 W continuous-wave laser emitting in the green region (532 nm), but detected no regenerated photon after the ‘wall’. This pushes the limit on the possible existence of axions and ALPs down to an unprecedented level for a laboratory experiment of this kind.

Detectors for a linear collider

The Linear Collider Detector project at CERN encompasses physics and detector studies for a future high-energy linear electron–positron collider. The work is carried out together with study groups from around the globe. In particular, CERN hosts the CLIC Detector and Physics (CLICdp) collaboration, which studies the physics potential of the CLIC concept (see p. 20), in addition to designing a suitable detector. During 2014, its second year of existence, five institutes joined CLICdp, bringing the total to 25 participating institutes and over 130 members. As CLIC and the International Linear Collider design have many challenges in common, CLICdp collaborates with groups developing the ILD and SiD detector concepts.

In 2014, simulation and engineering work focused on consolidating the two detector designs featured in the CLIC Conceptual Design Report into one optimized model. This required choosing parameters such as dimensions and granularities for the tracker and calorimeters, and identifying suitable technologies. The scenario for constructing CLIC in stages was also reviewed with the aim of defining better the lowest energy stage. At this energy the production of single Higgs bosons and pairs of top quarks are both of interest, but the physics potential of each of them depends on the exact centre-of-mass energy. A compromise to enable precise top and Higgs physics is being studied and will conclude in 2015.

Physics simulation studies continued to benchmark the expected performance of the detectors and reconstruction algorithms, as well as the potential for measuring the Higgs boson’s properties. Preparation of a comprehensive report on Higgs physics at CLIC is underway, for publication in 2015.

The hierarchy problem in particle physics relates to the enormous difference between the measured masses of the Higgs boson, for example, and basic predictions of quantum field theory. One familiar approach to mitigate this discrepancy is to incorporate supersymmetry (SUSY). The figures, opposite page, shows predictions for the mass of the Higgs boson as a function of the energy at which SUSY breaks down, for two possible scenarios: high-scale SUSY and split SUSY. The interesting result is the upper bound on the scale for SUSY. This means that the simple idea of a theory in which SUSY breaks at the so-called Planck scale around 10^{19} GeV, with nothing new at lower energies, is not compatible with the mass of the Higgs boson measured at CERN. (From http://arxiv.org/abs/1407.4081)

With the return of beams as LS1 neared its end, detector testing was again possible at the PS and the SPS. Prototype pixel-detector assemblies comprising Timepix3 and CLICpix chips coupled to thin sensors were assessed and showed promising results. With support from CLICdp, the CALICE collaboration tested a combined electromagnetic and hadronic calorimeter stack; the FCAL collaboration made the first demonstration of multi-plane operation of the forward calorimeter; and lab-based engineering studies verified the air-flow cooling of the vertex detector, using a full-scale 3D model and the CERN Fire Brigade's smoke machine.

In theory

In 2014, the CERN Theory Unit (PH-TH) continued to play a leading role as a reference centre in all areas of theoretical particle physics. Its research covered a broad spectrum, ranging from Standard Model physics directly related to the LHC, to formal aspects of quantum field theory and string theory.

A large effort was devoted to the consequences of the discovery of the Higgs boson, including possible implications for what is known as the hierarchy problem (see figure on opposite page for an example). A major part of this research dealt with particle-physics phenomenology beyond the Standard Model (such as extensions based on supersymmetry or more than four dimensions), astroparticle physics and cosmology and heavy-ion physics, as well as lattice field theory and mathematical physics. Roughly half of the effort was devoted to the particle physics of the Standard Model or beyond the Standard Model. Projects often overlapped between fields, such as dark matter being possibly relevant both for cosmology and for collider physics, or black-hole physics being holographically related to heavy-ion collisions. Members of the group published about one paper a day on average.

The group comprises 18 staff-members and more than 35 fellows at a given moment. In addition, it hosts 10–15 paid scientific associates and each year welcomes around 800 short-term visitors, paid and unpaid. The total head count exceeds 120 during the busy summer months. The high turnover is an important aspect of the group's role as a world-leading centre for scientific exchanges.

An important contribution towards fostering international collaboration and exchanging ideas are the 'Theory Institutes' — informal workshops that last for up to a few weeks. The aim is to optimize resources by putting together visiting scientists with common interests and by sharing resources with the international community. In 2014 there were four such events on 'Resurgence and Transseries in Quantum, Gauge and String Theories', 'Conceptual advances in lattice gauge theory', 'Results in SUSY Gauge Theories in Various Dimensions' and 'Numerical Holography'.

Members of PH-TH showed a high visibility at various 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. A particularly important on-going activity is the LHC Physics Centre at CERN (LPCC), which contributes with workshops, lectures and various working groups. In November, PH-TH held its annual 'TH retreat', offering members of the group a comprehensive overview of all of the on-going 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 2014 (see https://indico.cern.ch/event/302647/other-view?view=standard).