WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September 2018 issue of *CERN Courier*.

When is the LHC's birthday?

Ten years ago, on 10 September 2008, two yellow dots on a screen signalled the first time that protons had circulated CERN's Large Hadron Collider (LHC), marking the end of 25 years of design and construction. This issue of the *Courier* reflects on the media extravaganza that surrounded "first-beam day", and looks ahead as the machine and its experiments prepare for a luminosity upgrade (HL-LHC). The experience gained in organising, building and operating the LHC has been crucial for this upgrade and plans for future colliders, while a recent analysis reveals significant broader societal impact from the HL-LHC. But the LHC has more than one anniversary. Its first ever proton collisions were recorded on 20 November 2009, following the successful repair and consolidation of the machine after an electrical fault forced a pause in commissioning, and on 30 November 2009 the LHC eclipsed the Tevatron to become the world's most powerful collider, reaching an energy of 1.18 TeV per beam. The LHC physics programme began in earnest on 30 March 2010 with collisions at 3.5 TeV per beam and, for many physicists working on the ALICE, ATLAS, CMS and LHCb experiments, this was when the LHC fully came to life. That makes spring 2020 another golden opportunity to take stock of the LHC's immense contributions.

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CERNCOURIER
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CERN COURIER

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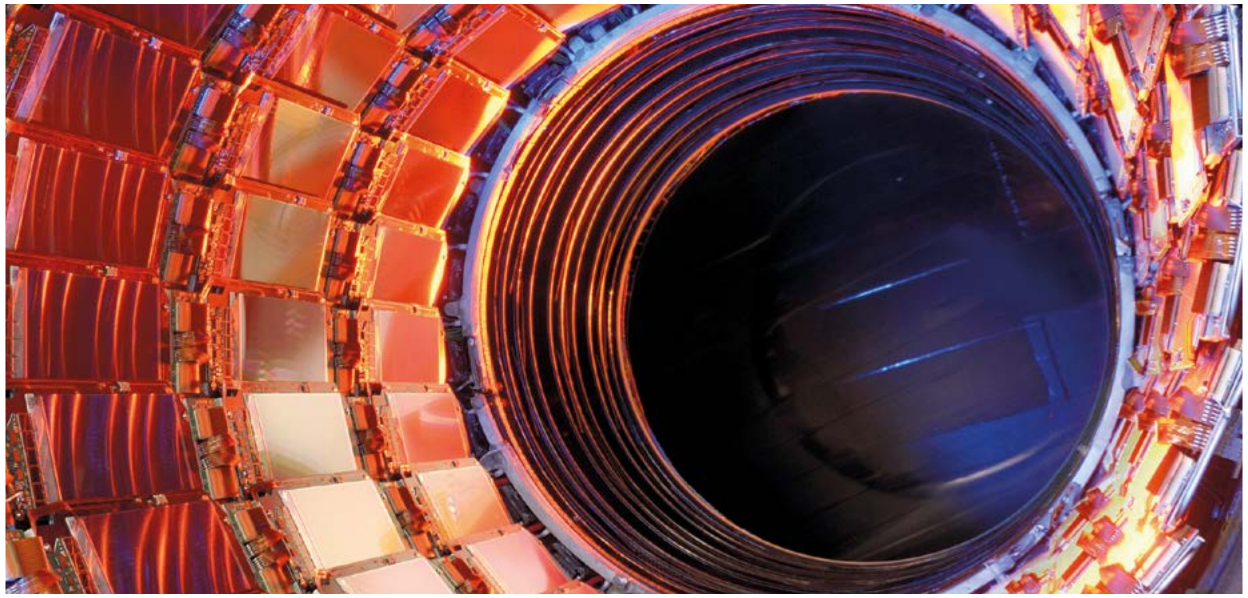
On the cover: Image of a LHC beam screen recorded on 10 September 2008, showing two spots corresponding to the successful circulation of protons once around the machine. p44 (Image credit: CERN.)



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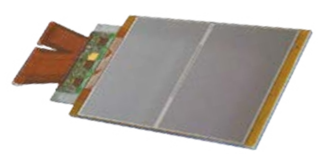

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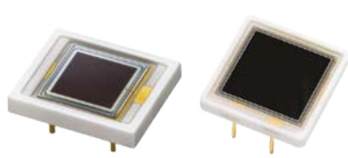

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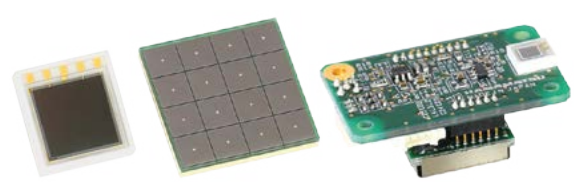

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Viewpoint

Lessons from the accelerator frontier

The switch-on and operation of the LHC bring vital experience to its upgrade and future colliders.

CERN-AC-0812002-05

The transport of a 15 m-long, 35-tonne superconducting dipole magnet from LHC sector 3-4 to the surface in December 2008 in order to be repaired.

By Lucio Rossi

When the Large Hadron Collider (LHC) started up a decade ago, on 10 September 2008, those of us who had been involved in designing and building the machine were extremely happy. I was in the CERN control centre that day, as was my predecessor, Romeo Perin, who first led the study for the LHC magnet design. Also present was Carlo Rubbia, without whose vision and battling spirit we would not have the LHC today, along with other former CERN Directors-General: Herwig Schopper, under whom initial discussions and workshops took place; Christopher Llewellyn-Smith, who got the LHC approved and secured international collaboration; Luciano Maiani, who took the decision to close LEP to make way for the LHC; and Robert Aymar, who saw the LHC to first beam.

That more than 300 journalists were present made it even more remarkable. CERN opened up to the world as it never did before and news of the event reached more than a billion people (see p44). But for many of us, our heads were already in the future, thinking about what was then simply called the LHC upgrade.

The first paper proposing a luminosity upgrade of the LHC was written in 1994 – the year the LHC was approved – and was inspired by Giorgio Brianti, who led the LHC design effort until the baton passed to Lyn Evans in 1993. He envisaged the benefits from a future superconductor, made of niobium tin rather than the niobium-titanium used in the LHC dipoles, to increase the luminosity of the LHC. Later, I proposed that INFN carry out research on this conductor and I have worked on the high-luminosity LHC (HL-LHC) ever since.

From a technical point of view, the LHC was a turning point in collider design, demanding a vast quantity of superconducting magnets with unprecedented field strengths. The past 10 years has also taught us that the machine is very well designed indeed (thanks Lyn!). The LHC works so well, in fact, that it's easy for operators to forget that it is a superconducting machine. I realised immediately when those first protons made their way around the ring that the LHC is, as we say in Italian, "bionic": it can do things beyond our expectations.

But we also learned, nine days later, when the breakdown of an electrical interconnect led to significant damage to one section of the machine, that the LHC is very fragile. This we will never forget: we have to be careful and we have to be humble, as a machine of this scale and complexity can stop working at any moment. The incident on 19 September happened in an interconnect between two magnets; it was not a technical difficulty but one of the LHC's innumerable complex interfaces that tricked us. Bad as it was, we could repair it in a reasonable time period. Had we made a technical mistake concerning the superconductor itself, or the basic magnet design, it would have been a potential show-stopper.

The LHC is so complicated that it's impossible not to make mistakes. What's important is that we learn from them. Not only did we learn how to repair and to react very fast, we also learned how to work cooperatively. It was a healthy sociological exercise for CERN, where, like in any large organisation, it is easy for people, divisions and departments to insulate themselves from others. After the incident, the spirit of collaboration has clearly been stronger.

This is definitely the case for the HL-LHC, where we are working not only on how to produce higher luminosity, but also on how to make it the most effective for the LHC experiments. In addition, and in contrast to the LHC, which was first approved and then sought partnership, HL-LHC has been a partnership with other institutions since the very beginning. It is another good lesson, and one that paves the way for a future supercollider beyond the LHC.

We are now exactly halfway through the HL-LHC programme, which was set up as a design study in 2010, approved with full budget in 2016, and will start operating in 2026. Now we have to complete the second half of the journey to generate a luminous future for our young colleagues. I will be long retired when the HL-LHC switches on, but I expect that, when it does, the CERN control centre will once again be a scene of celebration.

Lucio Rossi is head of the HL-LHC project. From 2001 he led the construction and procurement of the dipole magnets and superconductors for the LHC.

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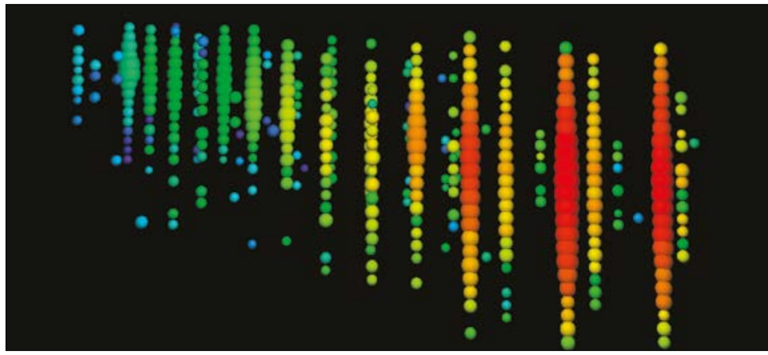
News

ASTROPARTICLE PHYSICS

IceCube neutrino points to origin of cosmic rays



IceCube collaboration

An event display of the high-energy neutrino event detected by IceCube. The coloured circles represent light collected by one of IceCube's 5000 or so photomultiplier tubes, while the colour gradient from red to green/blue shows the time sequence.

Since the discovery of high-energy extragalactic neutrinos by the IceCube collaboration in 2013, the hunt for the sources of such extreme cosmic events has been a major focus of neutrino astronomy. Now, in a multi-messenger measurement campaign involving more than 1000 scientists, IceCube and 18 independent partner observatories have identified such a cosmic particle accelerator – providing a first answer to the 100-year-old question concerning the origin of cosmic rays.

On 22 September 2017, IceCube – a cubic-kilometre neutrino detector installed in the 2.8 km-thick ice at the South Pole – registered a neutrino of likely astrophysical origin with a reconstructed energy of about 300 TeV. Within less than a minute from detection, IceCube's automatic alert system sent a notice to the astronomical community, triggering worldwide follow-up observations. The notice was the 10th alert of this type sent by IceCube to the international astronomy community so far.

The neutrino event pointed to a 0.15 square-degree area in the sky, consistent with the position of a blazar called TXS 0506+056, an active galaxy whose jet points precisely towards Earth. The Fermi gamma-ray satellite found the blazar to be in a flaring state with a rare seven-fold increase in activity around the time of the neutrino event, making it one of the brightest objects in the gamma-ray sky at that moment. The MAGIC gamma-ray telescope in La Palma, Spain, then also recorded gamma rays with energies exceeding hundreds of GeV from the same region.

The convergence of observations convincingly implicates the blazar as the most likely source. A worldwide team from the various observatories involved conducted a statistical analysis to determine whether the correlation between the neutrino and the gamma-ray observations was perhaps just a coincidence, and found the chance for this to be around one in 1000.

Following the 22 September detection, the IceCube team searched the detector's archival data and discovered a flare of more than a dozen lower-energy neutrinos detected in late 2014 and early 2015, which were also coincident with the blazar position. This independent observation greatly strengthened the initial detection of a single high-energy neutrino and was the start of a growing body of evidence for TXS 0506+056 being the first identified source of high-energy cosmic neutrinos. Furthermore, the distance to the blazar was determined to be about 4 billion light years (redshift $z = 0.34$) in the course of the follow-up observations, allowing the first luminosity determination for both gamma rays and neutrinos.

"It came as no surprise that on 12 July, the date of the release of the new observations, and on the following days, several studies were published devoted to modelling the source," says IceCube member Marek Kowalski from DESY. "It will be exciting to watch the high-energy astronomy community develop a coherent picture of the source over the next few months, as well as new strategies to identify similar events more frequently in the future."

The concerted observational campaign uses instruments located all over the globe and in space, spanning an energy range from radio waves, through visible light to X-rays and gamma rays, as well as neutrinos. It is thus a significant achievement for the nascent field of multi-messenger astronomy. Since neutrinos are produced through the collisions of charged cosmic rays, the new observation implies that active galaxies are also accelerators of charged cosmic-ray particles. "More than a century after the discovery of cosmic rays by Victor Hess in 1912, the IceCube findings have therefore for the first time pinpointed a compelling candidate for an extragalactic source of these high-energy particles," says IceCube principal investigator Francis Halzen.

Further reading

IceCube Collaboration 2018 *Science* **361** 147.
IceCube Collaboration *et al.* 2018 *Science* **361** eaat1378.

Sommaire en français

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PRECISION MEASUREMENT

Closing in on the muon's magnetic moment

A new experiment at Fermilab in the US, designed to make the most precise measurement of the muon's magnetic moment, has completed its first physics data-taking campaign, showing promising results. Experiment E989 is a reincarnation of the muon g-2 experiment at Brookhaven National Laboratory (BNL), which ran in the late 1990s and early 2000s and found the muon's anomalous magnetic moment, a_μ, to be approximately 3.5 sigma above the Standard Model prediction. The Fermilab experiment aims to resolve this long-standing discrepancy, revealing whether it is due to a statistical fluctuation or to the existence of new particles that are influencing the muon's behaviour.

The international E989 collaboration hopes to measure a_μ to a final precision of 140 parts per billion, improving on the BNL result by a factor of four. Following months of commissioning efforts beginning last autumn, the experiment started taking data in February. Its net accumulated dataset is already almost twice that obtained by BNL, although much of the initial run involved varying the operating conditions to optimise data collection and explore systematics.

The principle behind the Fermilab and BNL experiments is the same: muons start with their spins aligned with their direction of motion, but as they journey around the storage ring they precess at a frequency proportional to the magnetic field and to the value of a_μ. At experiment E989, muons are vertically focused in the ring via a system of electric quadrupoles, and the precession frequency is determined using a set of 24 electromagnetic calorimeters located along the inner circumference of the ring. The new experiment reuses the 1.45 T superconducting storage ring from BNL, which was shipped from Long Island to Chicago in 2015 and has since been rebuilt, its magnetic field now shimmed to a uniformity that exceeds BNL's by a factor of three. Nearly all of the other aspects of the experiment are new.

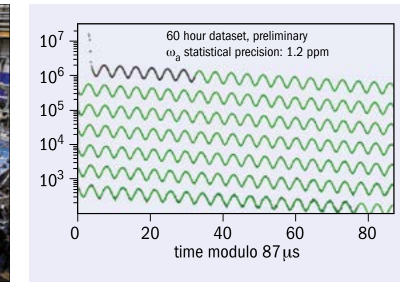
The Fermilab Muon Campus – which will also serve the Muon-to-Electron Conversion experiment in the future – provides an intense polarised muon beam that is devoid of the pion contamination that challenged the BNL measurement. Bunches of muons are injected into the storage ring and then "kicked" during their first rotation around the ring. "This is one of the most challenging aspects and one that the collaboration continues to develop because the kick quality affects the net storage efficiency and the momentum distribution," explains E989 member and former co-spokesperson David Hertzog.

A representative sample from a 60-hour-long dataset (see figure) demonstrates precession-frequency modulation on top of an exponentially decaying muon population. The collaboration is now evaluating data samples and developing different and independent approaches to extract the precession frequency and minimise systematic uncertainties. E989 researchers are also working to evaluate the average magnetic field and important beam-dynamics parameters.

In parallel, theorists are working hard on Standard Model calculations to reduce the uncertainties in the predicted value of a_μ – in particular concerning hadronic corrections, which are the most challenging to evaluate due to the complexities of quantum chromodynamics (QCD). In June, Alexander Keshavarzi from the University of Liverpool, UK, and colleagues used electron–positron collision data to reevaluate the hadronic contribution to a_μ, leading to the highest precision prediction so far. The following month, Thomas Blum of the University of Connecticut, US, and co-workers in the RBC and UKQCD collaborations reported a complete first-principles calculation of the leading-order hadronic contribution to a_μ from lattice QCD and quantum electrodynamics, showing improved precision.

Physicists will have to wait a bit longer for E989 to release a first measurement of a_μ, however. "Until we can closely examine the data quality – both precession data from detectors and field data from NMR probes – we are unable to predict the timetable," says Hertzog. "Our aim is sometime in 2019, but we will unblind only after we are certain that the analysis is complete – so stay tuned."

R Hahn



Left: the centrepiece of the Fermilab g-2 experiment (E989) is a 14 m-diameter electromagnet that generates an ultra-uniform magnetic field. Right: a typical anomalous-precession-frequency plot made from higher-energy positrons vs time-in-fill of muons in the storage ring. The 60-hour sample, when fitted (green) to a functional form that includes beam dynamics, pileup correction and basic gain stabilisation, gives a good χ^2 and a statistical precision of about 1.2 ppm.

Further reading

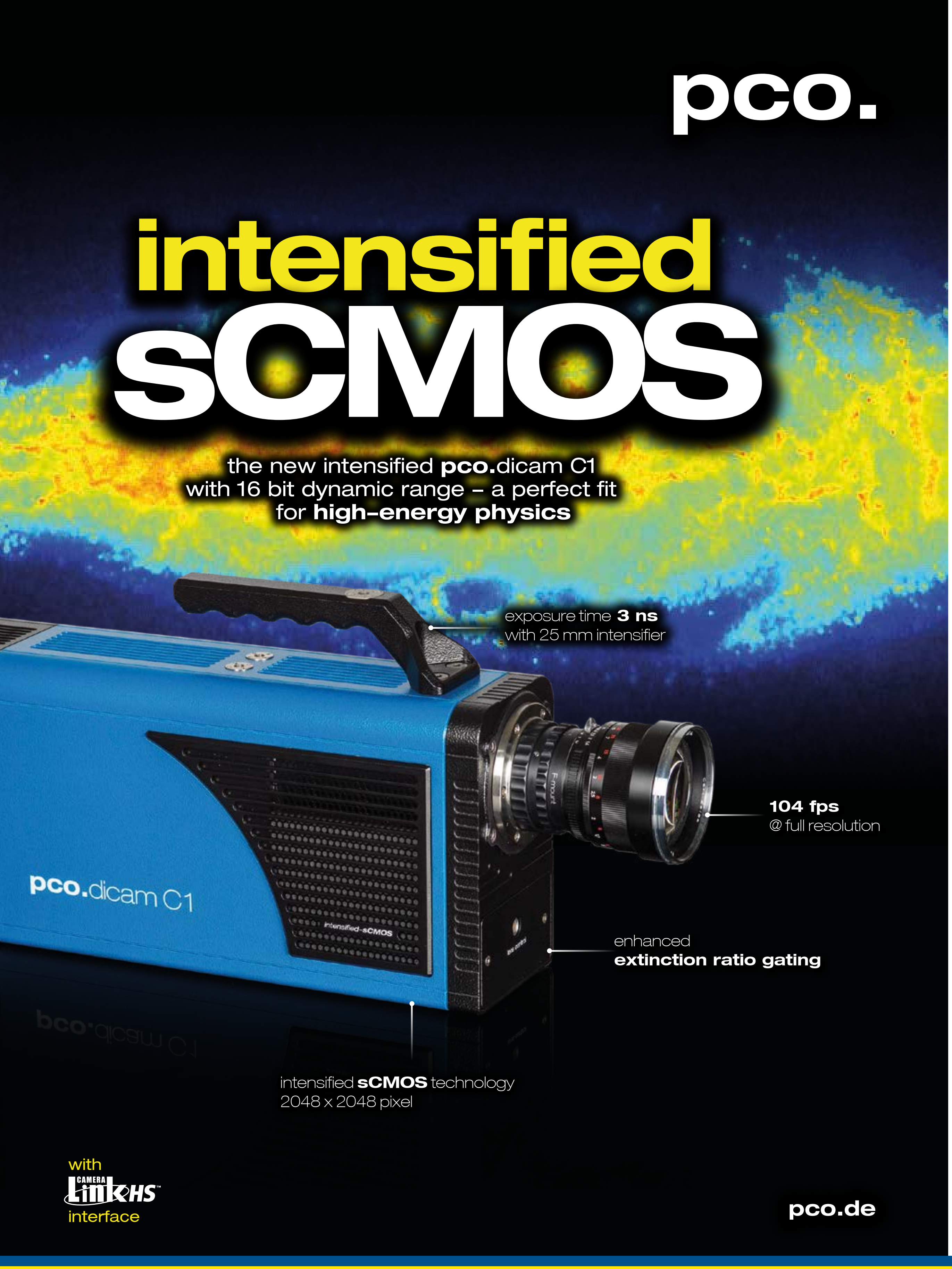
T Blum *et al.* 2018 *Phys. Rev. Lett.* **121** 022003.
A Keshavarzi *et al.* 2018 *Phys. Rev. D* **97** 114025.

EUROPEAN STRATEGY

Dates fixed for strategy update

During its closed session on 14 June, the CERN Council decided, by consensus, the venues and dates for two key meetings concerning the upcoming update of the European strategy for particle physics. An open symposium, during which the high-energy physics community will be invited to debate scientific input into the strategy update, will take place in Granada, Spain, on 13–16 May 2019. The European strategy group's drafting session will take place early the following year, on 20–24 January 2020, in Bad Honnef, Germany.

In addition, a special session organised by the European Committee for Future Accelerators on 14 July 2019, during the European Physical Society conference on high-energy physics in Ghent, Belgium, will provide a further opportunity for the community to feed into the drafting session (*CERN Courier* April 2018 p7).



IMAGING

First human 3D X-ray in colour

New-Zealand company MARS Bioimaging Ltd has used technology developed at CERN to perform the first colour 3D X-ray of a human body, offering more accurate medical diagnoses. Father and son researchers Phil and Anthony Butler from Canterbury and Otago universities in New Zealand spent a decade building their product using Medipix read-out chips, which were initially developed to address the needs of particle tracking in experiments at the Large Hadron Collider.

The CMOS-based Medipix read-out chip works like a camera, detecting and counting each individual particle hitting the pixels when its shutter is open. The resulting high-resolution, high-contrast images make it unique for medical-imaging applications. Successive generations of chips have been developed during the past 20 years with many applications outside high-energy physics. The latest, Medipix3, is the third generation of the technology, developed by a collaboration of more than 20 research institutes – including the University of Canterbury.

MARS Bioimaging Ltd was established in 2007 to commercialise Medipix3 technology. The firm's product combines spectroscopic information generated by a Medipix3-enabled X-ray detector with powerful algorithms to generate 3D images. The colours represent different energy levels of the X-ray photons as recorded by the detector, hence identifying different components of body parts such as fat, water, calcium and disease markers.

MARS Bioimaging Ltd

A 3D colour image of a wrist with a watch on, showing part of the finger bones in white and soft tissue in red.

So far, researchers have been using a small version of the MARS scanner to study cancer, bone and joint health, and vascular diseases that cause heart attacks and strokes. In the coming months, however, orthopaedic and rheumatology patients in New Zealand will be scanned by the new apparatus in a world-first clinical trial. "In all of these studies, promising early results suggest that when spectral imaging is routinely used in clinics it will enable more accurate diagnosis and personalisation of treatment," said Anthony Butler.

NEUTRINOS

Italy and US join forces on sterile neutrinos

On 28 June, the US Department of Energy and the Italian Embassy, on behalf of the Italian Ministry of Education, Universities and Research, signed a collaboration agreement concerning the international Short Baseline Neutrino (SBN) programme hosted at Fermilab. The SBN programme, started in 2015, comprises the development, installation and operation of three neutrino detectors on the Fermilab site: the Short Baseline Near Detector, located 110 m from the neutrino beam source; MicroBooNE, located 470 m from the source; and ICARUS, located 600 m from the source. ICARUS was refurbished at CERN last year after a long and productive scientific life at Gran Sasso National Laboratory.

Fermilab

MicroBooNE, a large 170-tonne liquid-argon time-projection chamber, first started collecting neutrino data in October 2015.

The SBN programme aims to search for exotic and highly non-reactive sterile neutrinos and resolve anomalies observed in previous experiments (*CERN Courier* June 2017 p25). Due to their different distances from the source, but employing the same liquid-argon technology, the three SBN detectors will be able to distinguish whether their measurements are due to transformations between neutrino types involving a sterile neutrino or are due to other previously-unknown neutrino interactions.

The signing of the SBN programme agreement is an addendum to a broader collaboration agreement on neutrino research that the US and Italy signed in 2015.

COMPUTING

Boosting high-performance computing in Nepal

On 28 June, 200 servers from the CERN computing centre were donated to Kathmandu University (KU) in Nepal. The equipment, which is no longer needed by CERN, will contribute towards a new high-performance computing facility for research and educational purposes.

With more than 15,000 students across seven schools, KU is the second largest university in Nepal. But infrastructure and resources for carrying out research are still minimal compared to universities of similar size in Europe and the US. For example, the KU school of medicine is forced to periodically delete medical imaging data because disk storage is at a premium, undermining the value of the data for preventative screening of diseases, or for population health studies. Similarly, R&D projects in the schools of science and engineering fulfill their needs by borrowing computing time abroad, either through online data transfer, marred by bandwidth, or by physically taking data tapes to institutes abroad for analysis.

CERN-201806-162-1

CERN director for research and computing, Eckhard Elsen (left), and Ram Prasad Subedi of the Permanent Mission of Nepal, Geneva, with the computing equipment.

"We cannot emphasise enough the need for a high-performance computing facility at KU, and, speaking of the larger national context, in Nepal," says Rajendra Adhikari, an assistant professor of physics at KU. "The server donation from CERN to KU will have a historically significant impact in fundamental research and development at KU and in Nepal."

A total of 184 CPU servers and 16 disk servers, in addition to 12 network switches, were shipped from CERN to KU. The CPU servers' capacity represents more than 2500 processor cores and 8 TB of memory, while the disk servers will provide more than 700 TB of storage. The total computing capacity is equivalent to more than 2000 typical desktop computers.

Since 2012, CERN has regularly donated computing equipment that no longer meets its highly specific requirements but is still more than adequate for less exacting environments. To date, a total of 2079 servers and 123 network switches have been donated to countries and international organisations, namely Algeria, Bulgaria, Ecuador, Egypt, Ghana, Mexico, Morocco, Pakistan, the Philippines, Senegal, Serbia, the SESAME laboratory in Jordan, and now Nepal. In the process leading up to the KU donation, the government of Nepal and CERN signed an International Cooperation Agreement to formalise their relationship (*CERN Courier* October 2017 p28).

"It is our hope that the server handover is one of the first steps of scientific partnership. We are committed to accelerate the local research programme, and to collaborate with CERN and its experiments in the near future," says Adhikari.

LHC EXPERIMENTS

ATLAS observes Higgs-boson decay to b quarks

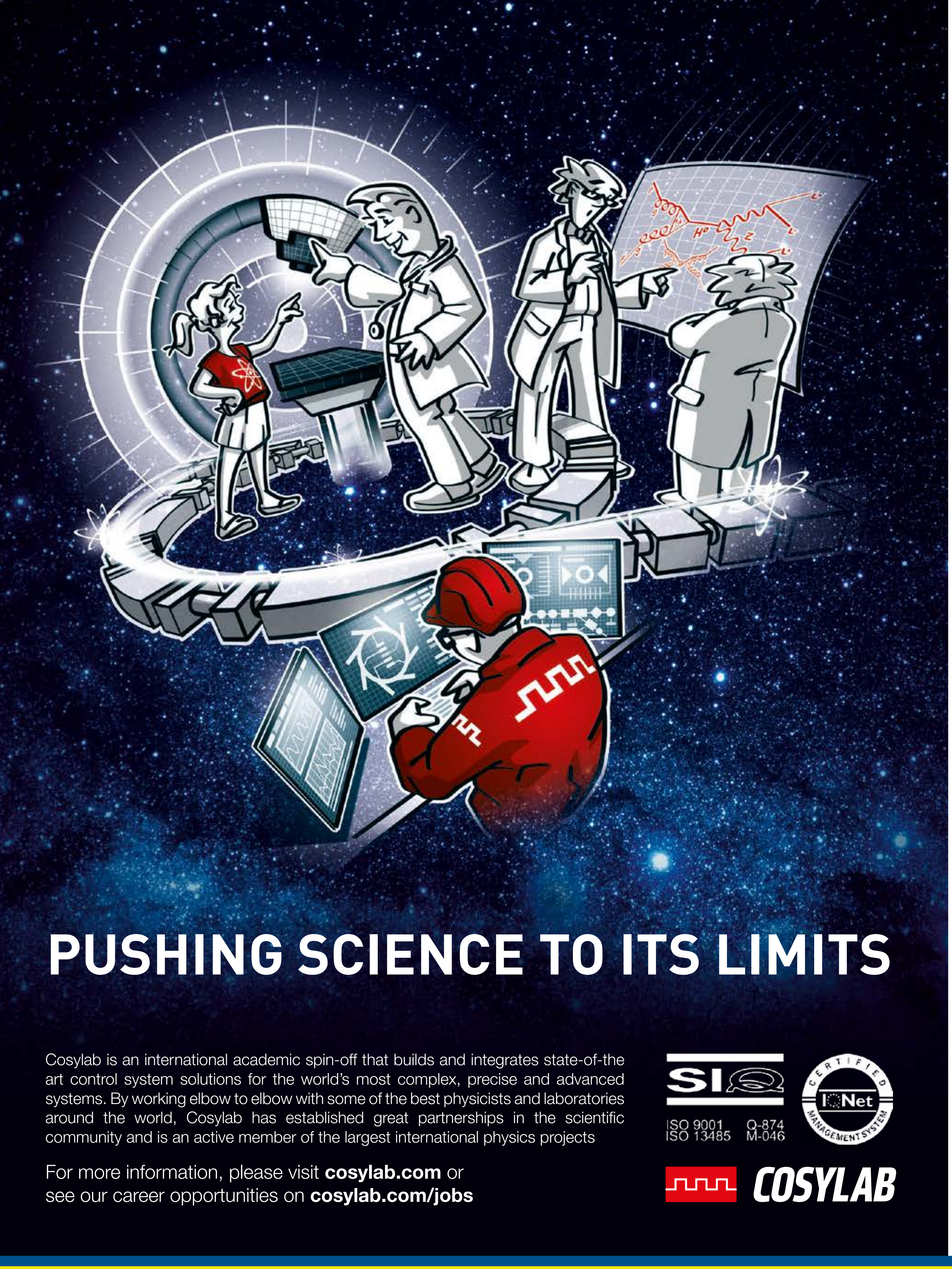
The Brout–Englert–Higgs mechanism solves the apparent theoretical impossibility of allowing weak vector bosons (the W and Z) to acquire mass. The discovery of the Higgs boson in 2012 via its decays into photons, Z and W pairs was therefore a triumph of the Standard Model (SM), which is built upon this mechanism. But the Higgs field is also predicted to provide mass to charged fermions (quarks and leptons) via "Yukawa couplings", with interaction strengths proportional to the particle mass. The observation by ATLAS and CMS of the Higgs boson decaying into pairs of τ leptons provided the first direct evidence of this type of interaction and, since then, both experiments have confirmed the Yukawa coupling between the Higgs boson and the top quark.

Six years after the Higgs-boson discovery, ATLAS had observed about 30% of its decays predicted by the SM. However, the favoured decay of the Higgs boson into a pair of b quarks, which is predicted to account for almost 60% of all possible decays, had remained elusive up to now. Observing this decay mode and measuring its rate is mandatory to confirm (or not) the mass generation for fermions via Yukawa interactions, as predicted in the SM.

At the 2018 International Conference on High Energy Physics (ICHEP) held in Seoul on July 4–11, ATLAS reported for the first time the observation of the Higgs boson decaying into pairs of b quarks at a rate consistent with the SM prediction. Evidence of the $H \to bb$ decay was earlier provided at the Tevatron in 2012, and one year ago by the ATLAS and CMS collaborations, independently. Given the abundance of $H \to bb$ decays, why did it take so long to achieve this observation?

The main reason is that the most copious production process for the Higgs boson in proton–proton collisions leads to a pair of particle jets originating from the fragmentation of b quarks (b-jets), and these are almost indistinguishable from the overwhelming background of b-quark pairs produced via the strong interaction. To overcome this challenge, it was necessary to consider production processes that are less copious, but exhibit features not present in strong interactions. The most effective of these is the associated production of the Higgs boson with a W or Z boson. The leptonic decays $W \to l\nu$, $Z \to ll$ and $Z \to \nu\nu$ (where l stands for an electron or a muon) allow for efficient triggering and a powerful reduction of strong-interaction backgrounds.

However, the Higgs-boson signal remains orders of magnitude smaller than the remaining backgrounds arising from top-quark or vector-boson production, which can lead to similar signatures. One way to discriminate the signal from such backgrounds is to select on the mass, m_{bb}, of pairs of b-jets identified by sophisticated b-tagging algorithms. When all WH and ZH channels are combined and the backgrounds (apart from WZ and ZZ production) subtracted from the data, the m_{bb} distribution (figure, left) exhibits a clear peak arising from Z-boson decays to b-quark pairs, ▷

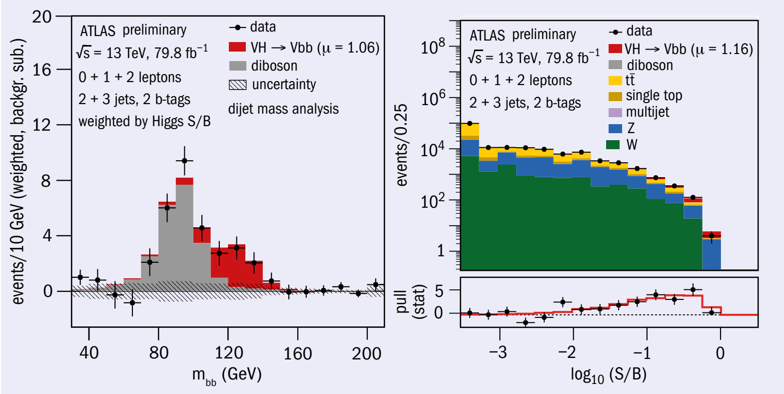


which validates the analysis procedure. The shoulder on the upper side is consistent in shape and rate with the expectation from Higgs-boson production.

Since this is not yet statistically sufficient to constitute an observation, the mass of the b-jet pair is combined with other kinematic variables that show distinct differences between the signal and the various backgrounds. This combination of multiple variables is performed using boosted decision trees for which a combination of all channels, reordered in terms of signal-to-background ratio, is shown in the right figure. The signal closely follows the distribution predicted by the SM with the presence of H→bb decays.

The analysis of 13 TeV data collected by ATLAS during Run 2 of the LHC between 2015 and 2017 leads to a significance of 4.9σ. This result was combined with those from a similar analysis of Run 1 data and from other searches by ATLAS for the H→bb decay mode, namely where the Higgs boson is produced in association with a top quark pair or via vector boson fusion. The significance achieved by this combination is 5.4σ, qualifying for observation.

Furthermore, combining the present analysis with others that target Higgs-boson decays to pairs of photons and Z bosons measured at 13 TeV yields the observation at 5.3σ of associated ZH or WH production, in agreement with the SM prediction. ATLAS has now observed all four primary Higgs-boson production modes at hadron colliders: fusion of gluons to a Higgs boson; fusion of weak bosons to a Higgs boson; associated production of a Higgs boson with two top quarks; and associated production of a Higgs boson with a weak boson. With these observations, a new era of detailed measurements in the Higgs sector opens up, through which the SM will be further challenged.



Left: the distribution of m_{bb} from all search channels combined after subtraction of all backgrounds except for WZ and ZZ production. Right: the combination of all boosted-decision-tree outputs reordered in terms of log(S/B), where S and B are the signal and background yields, respectively. The lower panel shows the "pull": that is the ratio of data minus background to the statistical uncertainty of the background. The deviation from zero indicates the presence of the H→bb signal.

● **Further reading**

ATLAS Collaboration 2018 ATLAS-CONF-2018-036.

CMS looks into the dark

Dark energy and dark matter together make up about 95% of the universe, yet we do not know the origin, constituents, or dynamics (apart from gravity) of these substances. Various extensions of the Standard Model (SM) of particle physics predict the existence of new particles as dark-matter candidates. One such model posits the existence of "dark quarks" that are charged under a new QCD-like force. Like normal SM quarks, dark quarks are only found in bound states (such as the dark proton, a stable dark-matter candidate resembling the ordinary proton) and they can only interact with SM quarks via a mediator particle. The similarity between the mechanisms of hadron production in dark and SM QCD would provide a natural explanation for the puzzling closeness of the observed energy densities of dark and baryonic matter.

In an attempt to explain the nature of dark matter, the existence of dark quarks was recently investigated by the CMS collaboration. If dark-QCD mediators were produced in pairs in the CMS detector, their signature would be striking: each mediator particle would decay into one dark quark and one SM quark, both of which hadronise and produce multiple dark and SM pions, respectively. Dark pions can travel sizable distances in the detector before decaying into detectable SM particles. Therefore, the signature would be two ordinary jets originating from the proton–proton collision, and two "emerging jets" composed of ▷

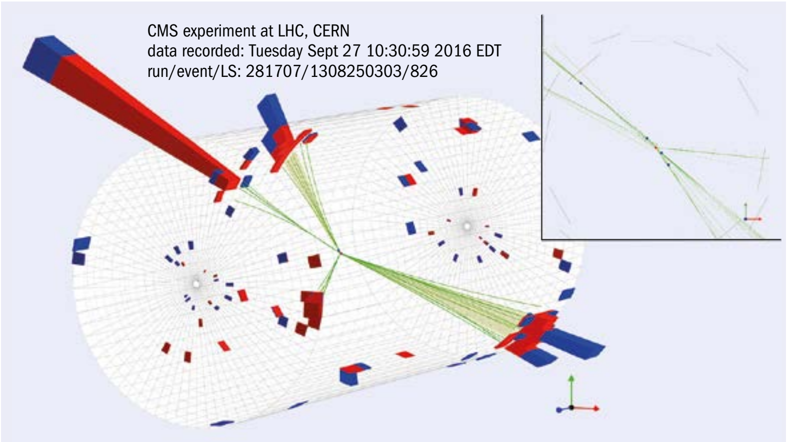


Fig. 1. A 3D tower view of an event with two jet candidates containing multiple displaced vertices. The inset shows the zoomed-in ρ–φ view with the innermost pixel layer. The red dot is the primary vertex while the blue ones are extra vertices reconstructed within the jet candidates.

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multiple neutral particles that decay at a significant distance away from their origin. Signal events could exhibit large missing transverse momentum from decays beyond the acceptance of the CMS detector.

To identify emerging jets, the CMS analysis relies on two discriminants that quantify the displacement of a jet's constituents from the collision point. One is based on the impact parameters of the tracks associated to the jet; the other is the fraction of a jet's energy carried by tracks compatible with the primary vertex. Figure 1 shows an event display for an emerging-jet candidate, with two jets containing multiple displaced vertices and consequently tagged by the discriminants. Substantial background is expected from the decays of B mesons and baryons, whose lifetime makes them more likely to pass the discriminating criteria. To model this background, the analysis derives flavour-dependent misidentification probabilities for jets.

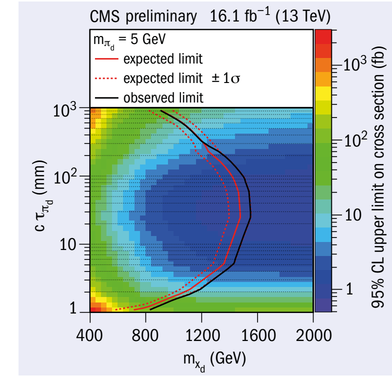


Fig. 2. Exclusion contours for predicted cross sections and observed upper limits at 95% CL on signal cross sections for models with a dark-pion mass of 5 GeV in the proper-decay-length ($c\tau_{\pi_d}$) versus dark-mediator mass (m_{X_d}) plane. The solid red (black) curve is the expected (observed) upper limit, with its one standard-deviation region enclosed in red dashed lines.

This first dedicated search for the emerging jet signature explores a broad dark-QCD parameter space with mediator masses between 0.4 and 2 TeV, dark-pion masses between 1 and 10 GeV, and dark-pion proper decay lengths between 1 mm and 100 cm. The observed number of events in the CMS data is consistent with the background-only expectation, excluding mediator particles with masses of 400–1250 GeV for dark-pion proper decay lengths between 5 and 225 mm (figure 2). While new data are being collected, the quest for dark matter at the LHC is broadening its scope towards new signatures.

Further reading

Y Bai and P Schwaller 2014 *Phys. Rev. D* **89** 063522.

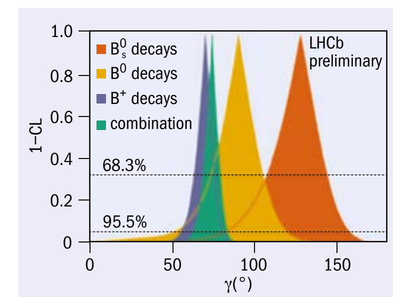
P Schwaller *et al.* 2015 *JHEP* **5** 59.

CMS Collaboration 2018 CMS-PAS-EXO-18-001.

LHCb tests consistency of unitarity triangle

Since the beginning of the LHC physics programme in 2010, the LHCb collaboration has been working to drive down the uncertainty on the least-precisely measured angle of the unitarity triangle, γ. The unitarity triangle exists in the complex plane and its area is a measure of the amount of CP violation in the Standard Model. Mathematically, the triangle represents a requirement that the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix is unitary, meaning that the number of quarks is conserved in weak interactions and that there are only three generations of quarks. If new physics exists and breaks these assumptions, it would show up as internal inconsistencies in the unitarity triangle – for example, the angles of the triangle might not add up to 180°. Checking the consistency of different measurements of the unitarity triangle is therefore an important test of the SM.

Experimentally, γ can be measured through the interference between $\bar{b} \to \bar{c}\, u\, \bar{s}$ and $\bar{b} \to \bar{u}\, c\, \bar{s}$ transitions. It is the only CKM angle that is easily accessible in tree-level processes and, as a result, it can be measured with negligible theoretical uncertainty. In the absence of new-physics effects at tree level, a precise measurement of γ can be compared with other observables related to the CKM matrix that are more likely to be affected by physics beyond the SM. Such comparisons are currently limited by the relatively large



Constraints on the unitarity-triangle angle γ from LHCb measurements grouped by the type of B meson considered, along with the overall combination. The y-axis shows (1–CL), where CL is the confidence level.

uncertainty on γ.

LHCb has recently made a model-independent study of the decay mode $B^\pm \to DK^\pm$ (where D could be D^0 or $\bar{D}^0$), with the D meson being reconstructed via the decays $D \to K^0_S \pi^+ \pi^-$ and $D \to K^0_S K^+ K^-$. This measurement is particularly important for determining γ, as it selects a single solution without ambiguities and with small uncertainty. Because the D meson undergoes a three-body decay, the distribution of events across the phase space (the Dalitz plot) carries information about the underlying amplitudes. And since the $B^\pm \to DK^\pm$ amplitudes depend on γ, it is possible to measure γ by comparing the distributions for B^+ and B^-. In practice, the distributions depend mainly on the amplitudes of the D decay, with only small CP-violating deviations introduced by γ. The measurement therefore demands a good understanding of the magnitudes of the D^0 and $\bar{D}^0$ decay amplitudes, as well as the strong phase differences between them, δ_D. The former comes from high-statistics calibration channels, and the latter from external measurements performed by the CLEO collaboration.

The new measurement uses 2 fb^{-1} of proton–proton collision data taken in 2015 and 2016, with signals of about 4100 $B^\pm \to D K^\pm$ decays for the more copious $D \to K^0_S \pi^+ \pi^-$ mode and about 560 for $D \to K^0_S K^+ K^-$. LHCb found $\gamma = 87^{+11}_{-12}{}^\circ$, which is consistent with the previous world average, as well as measuring other decay parameters $r_B = 0.087^{+0.013}_{-0.014}$ and $\delta_B = 101 \pm 11^\circ$. This is the most precise determination of γ from a single analysis, and LHCb has performed several other measurements of γ, each providing different constraints. Their combination ($\gamma = 74.0^{+5.0}_{-5.8}{}^\circ$, see figure) dominates the current world average and allows increasingly precise tests for new physics by probing the internal consistency of the unitarity triangle.

Further reading

LHCb Collaboration 2018 arXiv:1806.01202 (submitted to *JHEP*).

LHCb Collaboration 2014 *JHEP* **10** 097.

LHCb Collaboration 2018 LHCb-CONF-2018-002.

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Probing quark–gluon plasma with charmed mesons

The ALICE collaboration has released a new measurement of the production of D^0, D^+, D^{*+} and D_s^+ mesons, which contain a charm quark, in lead–lead (PbPb) collisions at a centre-of-mass energy per nucleon pair ($\sqrt{s_{NN}}$) of 5.02 TeV. These measurements probe the propagation of charm quarks in the quark–gluon plasma (QGP) produced in high-energy heavy-ion collisions. Charm quarks are produced early in the collision and subsequently experience the whole system evolution, losing part of their energy via inelastic (gluon radiation) or elastic ("collisional") scattering processes. The charm quarks emerge from the collision in D mesons, which are identified by their characteristic decays.

The result is reported in terms of the nuclear modification factor (R_{AA}), which is the ratio between the measured p_T distribution in heavy-ion and proton–proton (pp) collisions, scaled by the average number of binary nucleon–nucleon collisions in each nuclear collision. The figure shows the average R_{AA} of non-strange D mesons (D^0, D^+, D^{*+}) and strange (D_s^+) mesons in central (0–10%) PbPb collisions. For the non-strange mesons, a minimum of $R_{AA} \approx 0.2$ for $p_T = 6–10$ GeV/c indicates a significant energy loss for charm quarks. The R_{AA} is compatible with that of charged particles for $p_T > 8$ GeV/c, while it is larger at lower p_T. The comparison to light-flavour hadrons helps to study the colour-charge and quark-mass dependence of the in-medium parton energy loss.

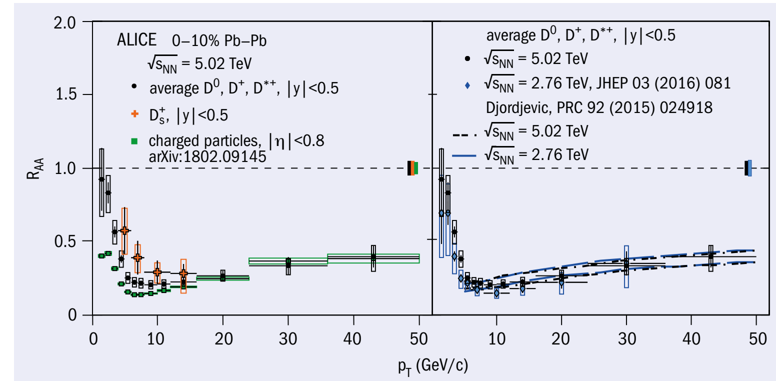
The R_{AA} of D_s^+ mesons is larger than that of non-strange D mesons. Though the experimental uncertainty is still large, such a difference would suggest that charm quarks also form hadrons by recombining with the surrounding light quarks in the QGP. This mechanism differs from the fragmentation process that is thought to be the main hadronisation mechanism in the absence of a medium. The recombination mechanism enhances the yield of particles with strangeness because strange quarks are copiously produced in the QGP.

The R_{AA} at LHC Run 2 is compatible with that measured at a lower centre-of-mass energy per nucleon pair of 2.76 TeV, but the larger collected data sample at Run 2 made it possible to reduce the uncertainties by a factor of about two. A similar suppression at the two energies is expected by the "Djordjevic model" (figure, right) due to the combination of a stronger suppression in the denser medium and a harder p_T distribution at 5.02 TeV with respect to 2.76 TeV.

The next PbPb run at the end of 2018, and the subsequent upgrade of the ALICE detector, will allow us to improve the measurement. This will shed further light on the energy loss and hadronisation of heavy quarks in the QGP and allow researchers to determine the transport coefficients describing the scattering power of the QGP and the diffusion of charm quarks in the medium.

Further reading

ALICE Collaboration 2018 arXiv:1804.09083.



Left: the average R_{AA} of prompt D^0, D^+ and D^{*+} mesons as a function of p_T compared to the R_{AA} of prompt D_s^+ and that of charged particles in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the 0–10% centrality class. Right: the average R_{AA} of prompt D^0, D^+ and D^{*+} mesons compared with the Djordjevic model in the 0–10% centrality class at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV.

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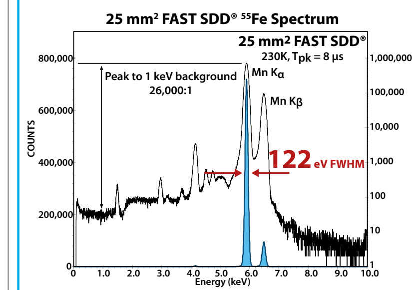

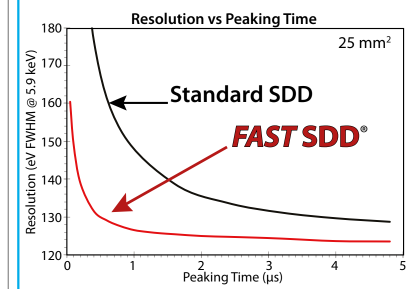

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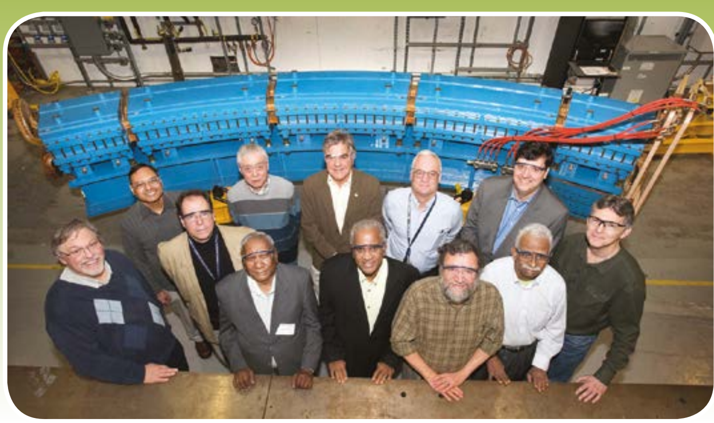
Best 30u (Upgradeable)	30	Best 15 + ^{123}I, ^{111}In, ^{68}Ge/^{68}Ga
Best 35	35–15	Greater production of Best 15, 20u/25 isotopes plus ^{201}Tl, ^{81}Rb/^{81}Kr
Best 70	70–35	^{82}Sr/^{82}Rb, ^{123}I, ^{67}Cu, ^{81}Kr + research



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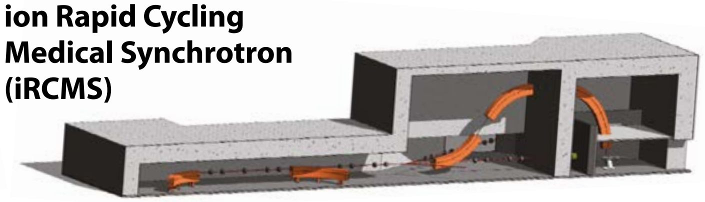

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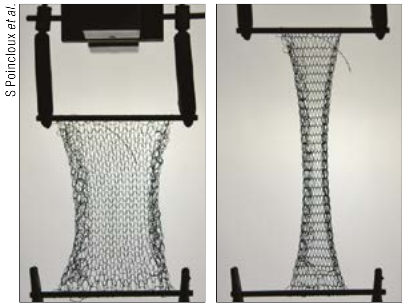
Sciencewatch

Compiled by John Swain, Northeastern University

Stretching the theory of knitting

A scarf knitted from a single thread can be pulled to twice its length, even though the thread itself hardly elongates. Curious about the elastic behaviour of his first child's baby clothes, physicist Frédéric Lechenault of the École Normale Supérieure in Paris set about understanding this phenomenon in more detail. Stretching a 20 cm-wide knitted fabric made from nylon fishing line along the vertical direction, Lechenault and colleagues watched how the positions and shapes of the stitches in the fabric changed. They found that the stitches at the sides moved mainly horizontally, whereas those in the middle moved mostly vertically. Assuming that the thread slides and bends but doesn't stretch, the team came up with a model that predicts the observed behaviour and could help in developing self-folding fabrics.



S Poincloux et al.

A new model predicts how stitches in a knitted fabric respond to stretching.

Further reading

S Poincloux *et al.* 2018 *Phys. Rev. X* **8** 021075.

A beating gallium heart

Certain liquid metals can be made to oscillate like a tiny heart via chemo-mechanical effects, but their "beat" is hard to control. Now Xiaolin Wang from the University of Wollongong, Australia, and colleagues have shown that liquid-gallium drops in an electrified graphite ring can be made to beat at a controllable frequency. The researchers place the ring on an incline submerged in a conducting fluid, letting gravity pull the drop down. When the drop hits the ring's inner wall, current flows through the drop and oxidises its outer surface. This oxidation induces a force between the drop and ring that pushes the drop back up the slope, after which the drop repeats its downward journey. This gallium "heart", which can go up and down the slope up to 610 times per minute, could be used as a fluid-based timing device.

Further reading

Z Yu *et al.* 2018 *Phys. Rev. Lett.* **121** 024302.

Removing atmospheric CO_2

In potentially good news for the fight against climate change, a study by researchers at Carbon Engineering in Calgary, Canada, shows that a technology for removing CO_2 from the atmosphere is closer than thought to commercial viability. The idea consists of dissolving CO_2 from air in potassium hydroxide to form potassium carbonate, which can be turned into calcium carbonate. The latter can then be heated to release CO_2, which can be stored underground or transformed into synthetic low-carbon fuels. Performing a detailed engineering and cost analysis of the technology, the researchers found that the cost of pulling one tonne of CO_2 from the atmosphere ranges between US\$94 and \$232 – much cheaper than the previous estimated cost of \$600 per tonne.

Further reading

D W Keith *et al.* 2018 *Joule* **2** 1.

Easter Island's huge hats

Easter Island in the Pacific Ocean is famous for its huge statues, many of which have hat-like structures, or "pukao", made from red scoria rock on their heads. How the multi-tonne pukao were moved and placed atop the statues, however, has long been a puzzle. Based on shared physical features of the structures, archaeological evidence and the physics necessary for pukao movement, Terry Hunt of the University of Arizona and colleagues now argue that the pukao were placed atop the statues by small groups of people using simple stone ramps.

Further reading

S W Hixon *et al.* 2018 *J. Archaeol. Sci. (in press).*

A row of statues at Easter Island, with four sporting a pukao. (Credit: iStock/Mlenny.)

18-bit entanglement record

Xi-Lin Wang and colleagues at the University of Science and Technology of China have entangled a record number of photon-based qubits while maintaining full control over each qubit. Exploiting three degrees of freedom of six photons – their paths, polarisations, and orbital angular momenta – the researchers attained genuine entanglement of 18 (6 × 3) qubits. Had 18 photons and only one degree of freedom been used instead, the entanglement generation, which is at the heart of quantum information processing, would be about 13 orders of magnitude less efficient.

Further reading

X-L Wang *et al.* 2018 *Phys. Rev. Lett.* **120** 260502.

Chocolate over cheese

People tend to like food rich in fat or carbohydrates, so it may not come as a surprise that we also prefer foods that are rich in both of these nutrients. Dana Small at Yale University and colleagues had volunteers bid money on various foods and found that among equally liked and equally caloric foods, the ones most likely to get a high bid were fatty and carbohydrate-rich items like cake and chocolate, rather than, say, cheese. Brain scans also showed an increase in activity in parts of the brain involved with addiction and reward.

Further reading

A G DiFeliceantonio *et al.* 2018 *Cell Metab.* **28** 33.

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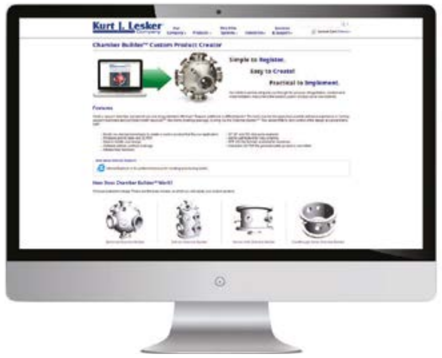

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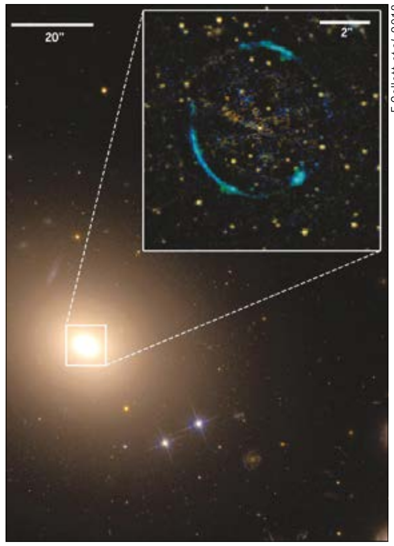
Relativity passes test on a galactic scale

Einstein's theory of gravity, general relativity, is known to work well on scales smaller than an individual galaxy. For example, the orbits of the planets in our solar system and the motion of stars around the centre of the Milky Way have been measured precisely and shown to follow the theory. But general relativity remains largely untested on larger length scales. This makes it hard to rule out alternative theories of gravity, which modify how gravity works over large distances to explain away mysterious cosmic substances such as dark matter. Now a precise test of general relativity on a galactic scale excludes some of these alternative theories.

Using data from the Hubble Space Telescope, a team led by Thomas Collett from the University of Portsmouth in the UK has found that a nearby galaxy dubbed ESO 325-G004 is surrounded by a ring-like structure known as an Einstein ring – a striking manifestation of gravitational lensing. As the light from a background object passes a foreground object, the gravity of the foreground object bends and magnifies the light of the background one into a ring. The ring system found by Collett's group is therefore a perfect laboratory with which to test general relativity on galactic scales.

But it isn't easy to make such a test, because the size and structure of the ring depend on several factors, including the distance of the background galaxy from Earth, and the distance, mass and shape of the foreground (lensing) galaxy. In previous tests the uncertainty on some of these factors resulted in large systematic errors in the modelling of the gravitational-lensing effect, allowing only weak constraints to be placed on alternative theories of gravity. Now Collett and colleagues' discovery of an Einstein ring around a relatively close galaxy, ESO 325-G004, along with high-resolution observations of that same galaxy taken with the Multi Unit Spectroscopic Explorer (MUSE) on the European Southern Observatory (ESO) Very Large Telescope, has allowed the most precise test of general relativity outside the Milky Way.



E Collett *et al.* 2018

Image of the nearby galaxy ESO 325-G004, produced using data from the Hubble Space Telescope. The inset shows the vicinity of the galaxy in more detail and uncovers an Einstein ring (blue) resulting from the gravitational lensing by ESO 325-G004 of light coming from a distant galaxy. Scale bars are in arc seconds.

The researchers derived the distances of the background galaxy and the lensing galaxy from measurements of their redshifts. Measuring the mass and the shape of the lensing galaxy is more complex, but was made possible here thanks to the MUSE observations that allowed the team to perform measurements of the motions of the stars that make up the galaxy relative to the galaxy's centre. Since these motions are governed by the gravitational fields inside the galaxy, they can be used to indirectly measure the mass and shape of ESO 325-G004.

The team put all of these measurements together and determined the gravitational effect that ESO 325-G004 should have on the background galaxy's light if general relativity holds true. The result, which, technically, tests the scale invariance of a parameter in general relativity called gamma, is almost in perfect agreement with general relativity, with an uncertainty of only 9%. Not only does it show that gravity behaves on a galactic scale in the same way as it does in our solar system, it also disfavours alternative gravity models, in particular those that attempt to remove the need for dark energy.

Further reading
E Collett *et al.* 2018 *Science* **360** 1342.

Picture of the month

This apparently quiet part of our galaxy shows an active state in which stars are formed. It can be found towards the constellation of Taurus between the Pleiades cluster of stars and the California emission nebula. Several bright blue stars are visible against brown dust clouds. Other stars are partly or fully obscured by dense dust columns. As the dust interacts mainly with the bluer part of the stars' light, the partly obscured stars appear red. If massive enough, the dense clouds of gas and dust that lie between the stars collapse gravitationally to form new stars. These new stars produce new dust in their atmospheres and destroy old clouds with their radiation and wind.

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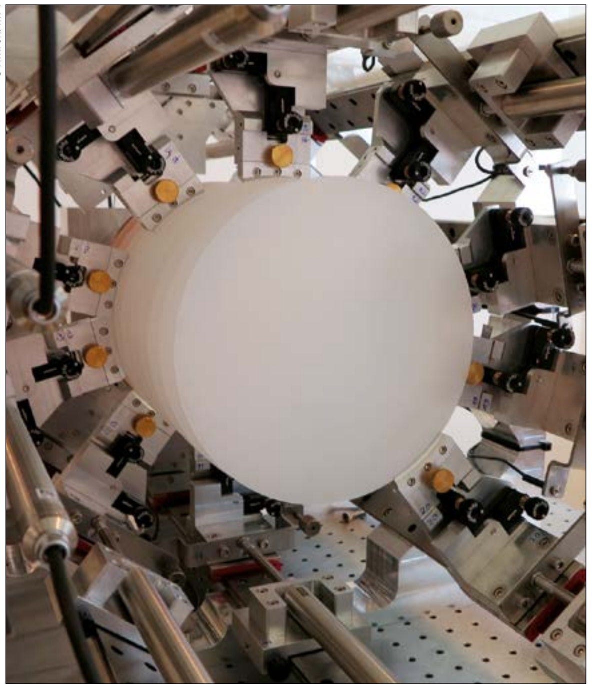


Search for WISPs gains momentum

Despite tremendous efforts, the search for the constituents of dark matter has so far been unsuccessful. Interest is therefore growing in new experiments that probe dark-matter candidates such as axions and other very weakly interacting sub-eV particles.

Understanding the nature of dark matter is one of the most pressing problems in physics. This strangely nonreactive material is estimated, from astronomical observations, to make up 85% of all matter in the universe. The known particles of the Standard Model (SM) of particle physics, on the other hand, account for a paltry 15%.

Physicists have proposed many dark-matter candidates. Two in particular stand out because they arise in extensions of the SM that solve other fundamental puzzles, and because there are a variety of experimental opportunities to search for them. The first is the neutralino, which is the lightest supersymmetric partner of the SM neutral bosons. The second is the axion, postulated 40 years ago to solve the strong CP problem in quantum chromodynamics (QCD). While the neutralino belongs to the category of weakly interacting massive particles (WIMPs), the axion is the prime example of a very weakly interacting sub-eV particle (WISP).

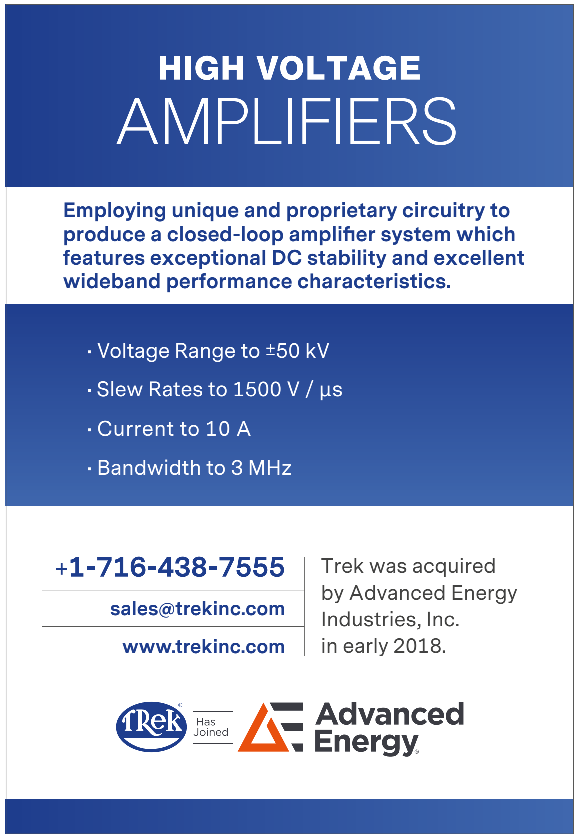
Neutralinos as WIMPs have dominated the search for cold dark matter since the mid-1980s, when it was realised that massive particles with a cross section of the order of the weak interaction would result in precisely the right density to explain dark matter. There have been tremendous efforts to hunt for WIMPs both at hadron colliders, especially now at CERN's Large Hadron Collider (LHC), and in large underground detectors, such as CDMS, CRESST, DARKSIDE, LUX, PandaX and XENON. However, up to now, no WIMP has been observed (*CERN Courier* July/August 2018 p9).

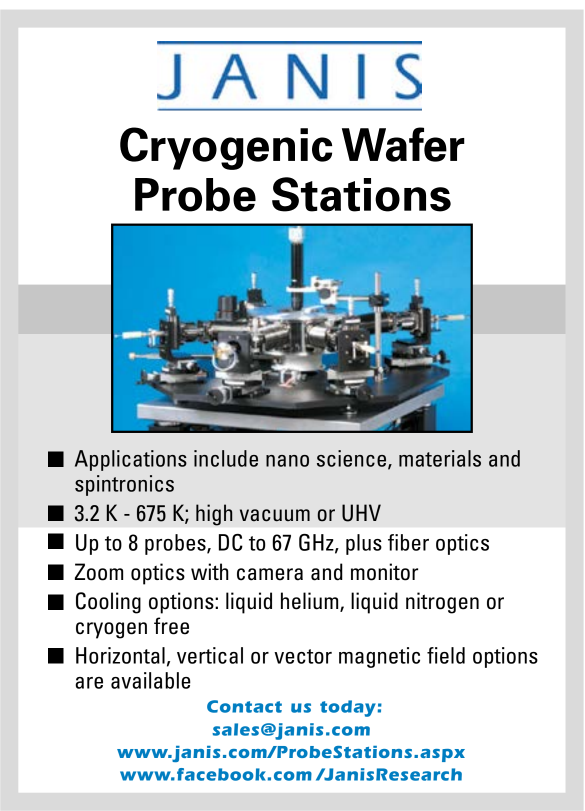
Very light bosons as WISPs are a firm prediction of models that solve problems of the SM by the postulation of a new symmetry which is broken spontaneously in the vacuum. Such extensions contain an additional scalar field with a potential shaped like a Mexican hat – similar to the Higgs potential in the SM (figure 1). This leads to spontaneous breaking of symmetry at a scale corresponding to the radius of the trough of the hat: excitations in the direction along the trough correspond to a light Nambu–Goldstone (NG) boson, while the excitation in the radial direction perpendicular to the trough corresponds to a heavy particle with a mass determined by the symmetry-breaking scale. The strengths of the interactions between such light bosons and regular SM particles are inversely proportional to the symmetry-breaking energy scale and are therefore very weak. Being light, very weakly interacting and cold due to their non-thermal production history, these particles qualify as natural WISP cold dark-matter candidates.

Image above: test setup of the MADMAX experiment with sapphire plates to allow the detection of axion–photon conversion.

Primordial production

In fact, WISP dark matter is inevitably produced in the early universe. When the temperature in the primordial plasma drops below the symmetry-breaking scale, the boson fields are frozen at a random initial value in each causally-connected region. Later, they relax towards the minimum of their potential at zero fields and oscillate around it. Since there is no significant damping of these field oscillations via decays or interactions, the bosons behave as a very cold dark-matter fluid. If symmetry breaking occurs after the likely inflationary-expansion epoch of the universe (corresponding to a post-inflationary symmetry-breaking scenario), WISP dark matter would also be produced by the decay of topological defects from the realignment of patches of the universe with random initial conditions. A huge region in parameter space spanned by WISP masses and their symmetry-breaking scales can give rise to the





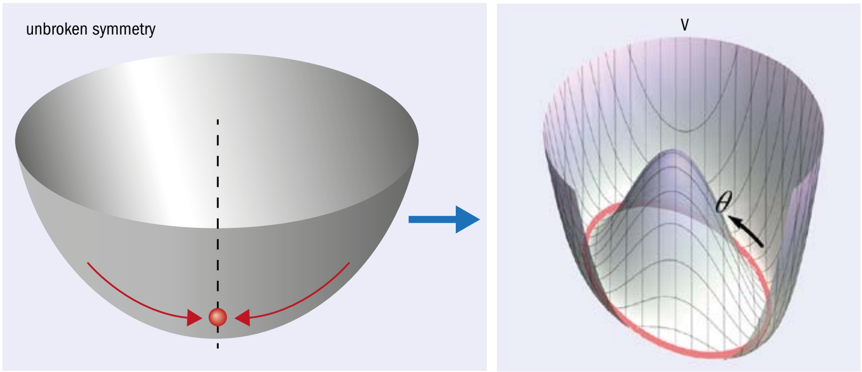


Fig. 1. The potential of a complex scalar field in primordial plasma in the very early universe (left) takes the form of a Sombrero (right) once the temperature drops below the symmetry-breaking scale. The energy-breaking scale corresponds to the radius of the valley from the centre, while the axion represents oscillations around one of the minima, which arise due to QCD gluon-field fluctuations.

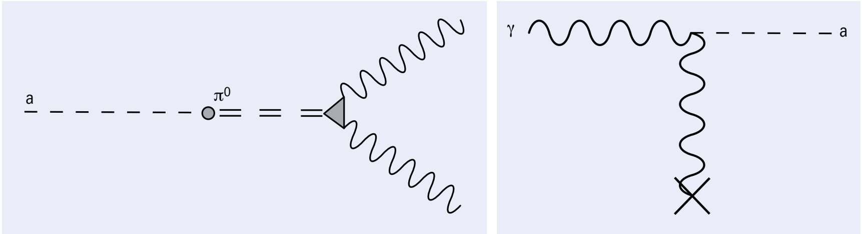


Fig. 2. Left: diagram showing axion–photon coupling via axion–pion oscillation. Right: via the Primakoff effect, a virtual photon can be borrowed from a static magnetic field (denoted by the cross) to induce photons to convert into axions or vice versa, as first suggested by P Sikivie.

observed dark-matter distribution.

The axion is a particularly well-motivated example of a WISP. It was proposed to explain the results of searches for a static electric dipole moment of the neutron, which would constitute a CP-violating effect of QCD. The size of this CP-violation, parameterised by the angle θ, is predicted to have an arbitrary value between $-\pi$ and π, yet experiments show its absolute value to be less than 10^{-10}. If θ is replaced by a dynamical field, $\theta(x)$, as proposed by Peccei and Quinn in 1977, QCD dynamics ensures that the low-energy effective potential of the axion field has an absolute minimum at $\theta=0$. Therefore, in vacuum, the CP violating effects due to the θ angle in QCD disappear – providing an elegant solution to the strong CP problem. The axion is the inevitable particle excitation of $\theta(x)$, and its mass is determined by the unknown breaking scale of the global symmetry.

Lattice-QCD calculations performed last year precisely determined the temperature and corresponding time after the Big Bang when axion cold dark-matter could have formed as a function of the axion mass. It was found that, in the post-inflationary symmetry breaking scenario, the axion mass has to exceed 28 µeV; otherwise, the predicted amount of dark matter overshoots the observed amount. Taking into account the additional production of axion dark-matter from the decay of topological defects, an axion with a mass between 30 µeV and 10 meV may account for all of the dark matter in the universe. In the pre-inflationary symmetry breaking scenario, smaller masses are also possible.

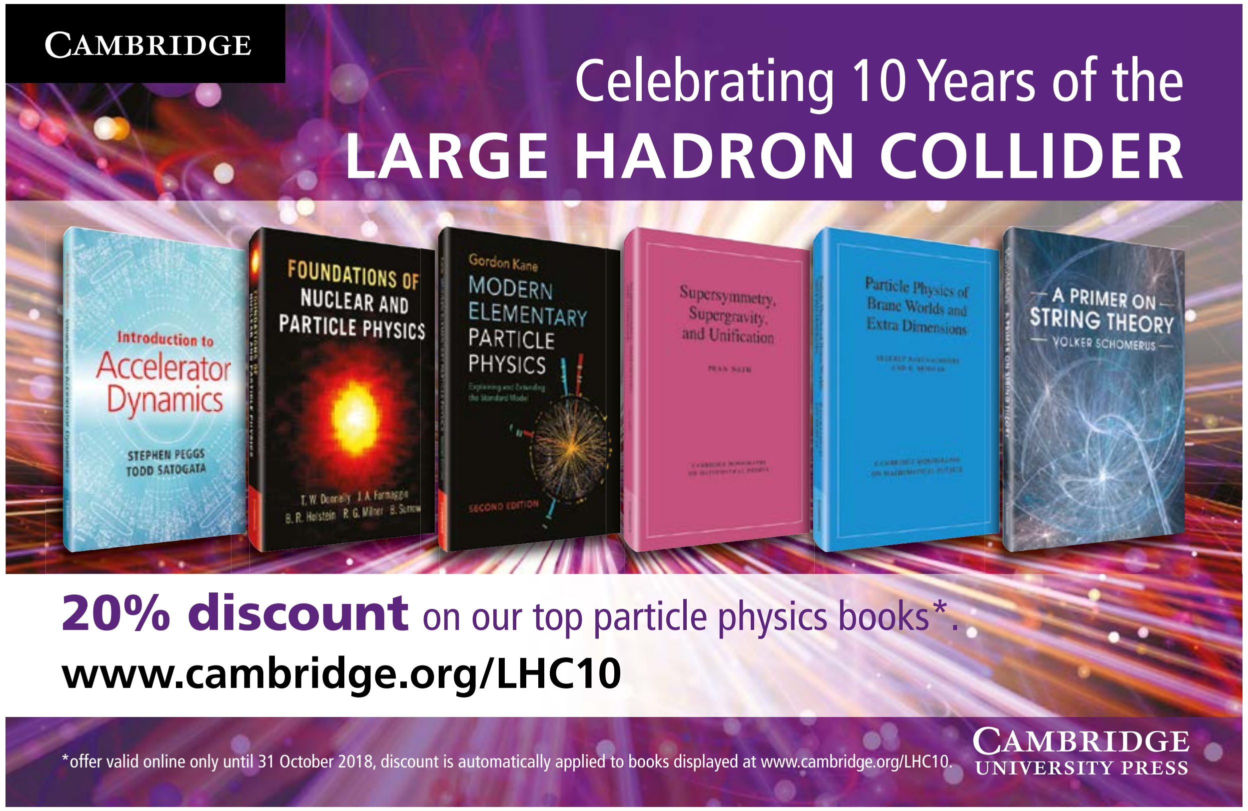
Thrilling data runs are expected to start in the early 2020s.

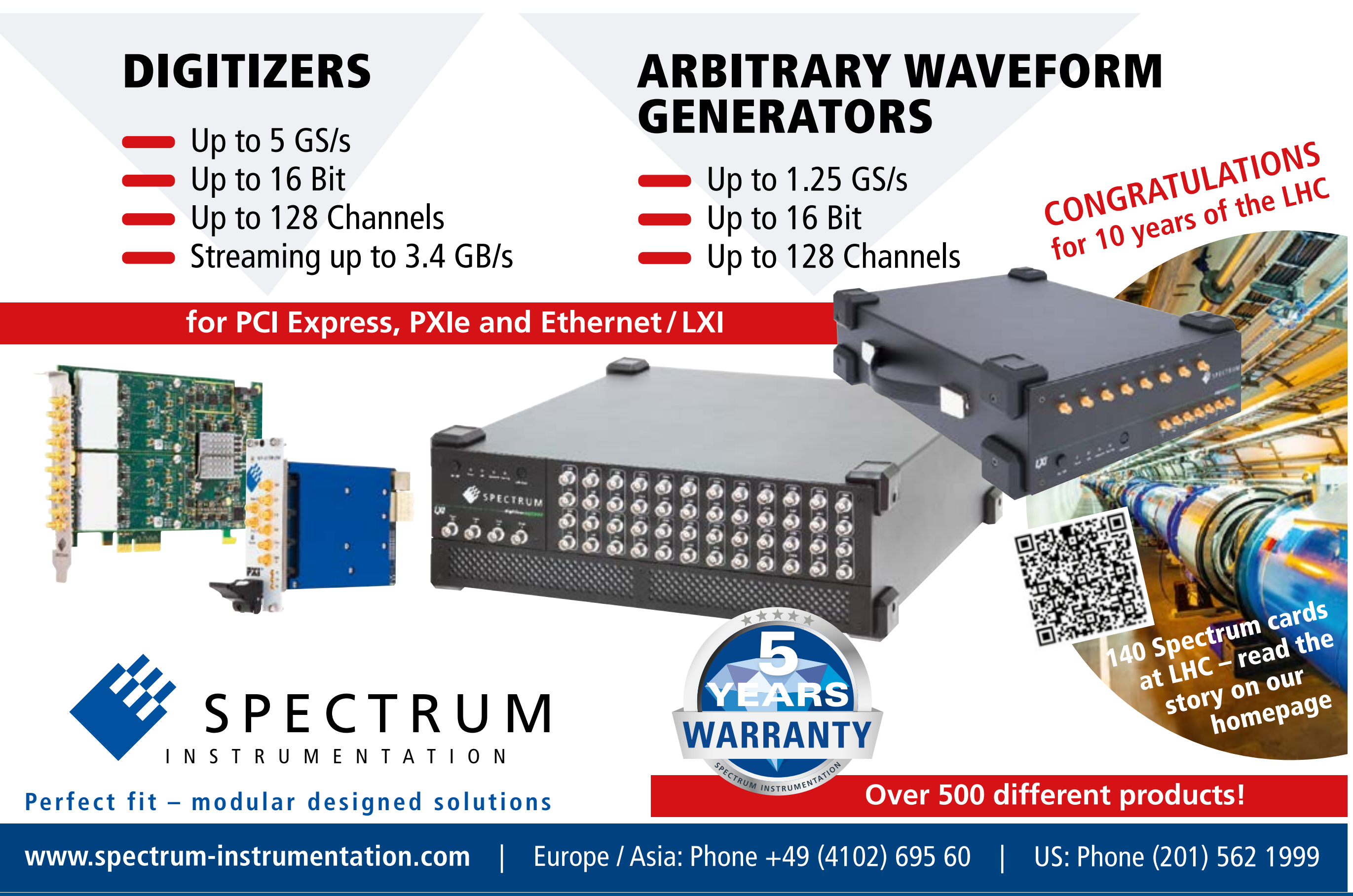
Axions are not the only WISP species that could account for dark matter. There could be axion-like particles (ALPs), which are very similar to axions but do not solve the CP problem of QCD, or lightweight, weakly interacting, so-called hidden photons, for example. String theory suggests a plenitude of ALPs, which could have couplings to photons, leptons or light quarks.

Due to their tiny masses, WISPs might also be produced inside stars or alter the propagation of photons in the universe. Observations of stellar evolutions hint at such signals: red giants, helium-burning stars and white dwarfs seem to be experiencing unseen energy losses exceeding those expected from neutrino emission. Intriguingly, these anomalies can be explained in a unified manner by the existence of a sub-keV-mass axion or ALP with a coupling both to electrons and photons. Additionally, observations suggest that the propagation of TeV photons in the universe suffers less than expected from interactions with the extragalactic background light. This, in turn, could be explained by the conversion of photons into ALPs and back in astrophysical magnetic fields, interestingly with about the same axion–photon coupling strength as indicated by the observed stellar anomalies. Both effects have been known for almost 10 years. They are scientifically disputed, but a WISP explanation has not yet been excluded.

Experimental landscape

Most experiments searching for WISPs exploit their possible mixing with photons. Given the small masses and feeble interactions of axions and ALPs, however, building experiments that are sensitive enough to detect them is a considerable challenge. In the 1980s, Pierre Sikivie of the University of Florida in the US suggested a way forward based on the conversion of axions to photons: in a static magnetic field, the axion can "borrow" a virtual photon from the field and turn into a real photon (figure 2). Most experiments search





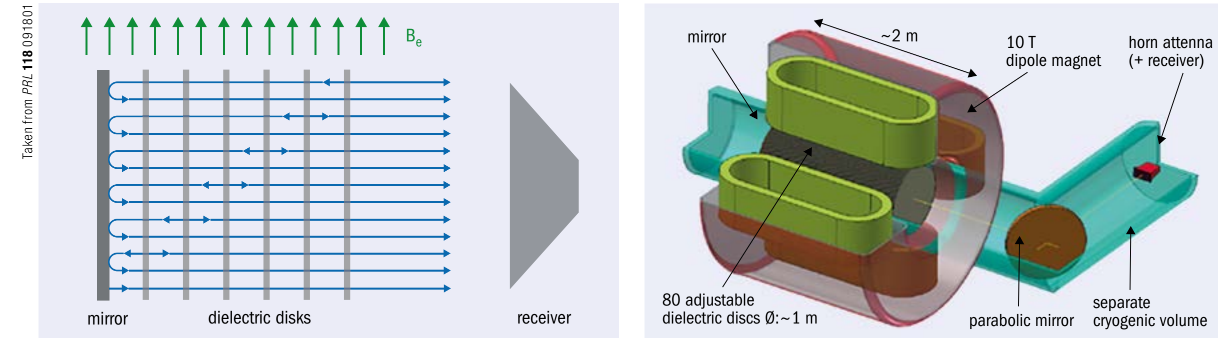


Fig. 3. The principle of a dielectric haloscope (left) and a schematic of the proposed MADMAX setup (right).

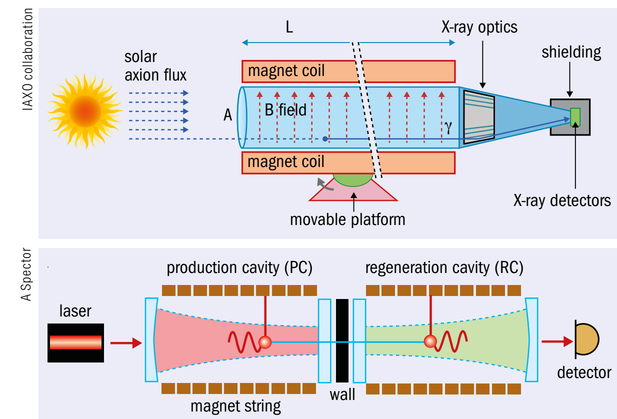


Fig. 4. Schematic principle of a helioscope (top) and light-shining-through-walls experiment (bottom).

for axions and ALPs in this way, with three main approaches being pursued: haloscopes, which look directly for dark-matter WISPs in the galactic halo of our Milky Way; helioscopes, which search for ALPs or axions emitted by the Sun; and laboratory experiments, which aim to generate and detect ALPs in a single setup.

Direct axion dark-matter searches differ in two aspects from WIMP dark-matter searches. First, axion dark matter would convert to photons, while WIMPs are scattered off matter. Second, the particle-number density for axion dark-matter, due to its low mass, is about 15 orders of magnitude larger than it is for WIMP dark matter. In fact, cold dark-matter axions and ALPs behave like a highly degenerate Bose–Einstein condensate with a de Broglie wavelength of the order of metres or kilometres for μeV and neV masses, respectively. Dark-matter axions and ALPs are thus much better pictured as a classical-field oscillation. In a magnetic field, they induce tiny electric-field oscillations with a frequency determined by the axion mass. If the de Broglie wavelength of the dark-matter axion is larger than the experimental setup, the tiny oscillations are spatially coherent in the experiment and can, in principle, be "easily" detected using a resonant microwave cavity tuned to the correct but unknown frequency. The sensitivity of such an experiment increases with the magnetic field strength squared, the volume of the cavity and its quality factor. Unfortunately, since the range of axion mass predicted by theories is huge, methods are required to tune the cavity to the frequency range corresponding to the respective axion masses.

This cavity approach has been the basis of most searches for axion dark-matter in the past decades, in particular the Axion Dark Matter Experiment (ADMX) at the University of Washington, US. Using a tuning rod inside the cavity to change the resonance frequency and, recently, by reducing noise in its detector system, the ADMX team has shown that it can reach axion dark-matter sensitivity. ADMX, which has been pioneering the field for two decades, is currently taking data and could find dark-matter axions at any time, provided the axion mass lies in the range 2–10 μeV. Meanwhile, the HAYSTAC collaboration at Yale University has very recently demonstrated that the same experimental approach can be expanded up to an axion mass of around 30 μeV. Since smaller-volume cavities (usually with lower quality factors) are needed to probe higher frequencies, however, the single-cavity approach is limited to axion masses below about 40 μeV. One novel method to probe higher masses is to use multiple matched cavities, as for example followed by the ADMX and the South Korean Center for Axion and Precision Physics.

Transitions

A different way to exploit the tiny electric-field oscillations from dark-matter axions in a strong magnetic field is to use transitions between materials with different dielectric constants: at surfaces, the axion-induced electromagnetic oscillations have a discontinuity, which is to be balanced by radiation from the surface. For a mirror with a surface area of 1 m^2 in a 10 T field, this would lead to an undetectable emission of around 10^{-27} W if axions make up all of the dark matter. Furthermore, the emission power does not depend on the axion mass. In principle, if a parabolic mirror with a surface area of 10,000 m^2 could be magnetised with a 10 T field, the predicted radiation power (10^{-23} W) could be focused and detected using state-of-the-art amplification techniques, but such an experiment seems impractical at present.

The axion is a particularly well-motivated WISP.

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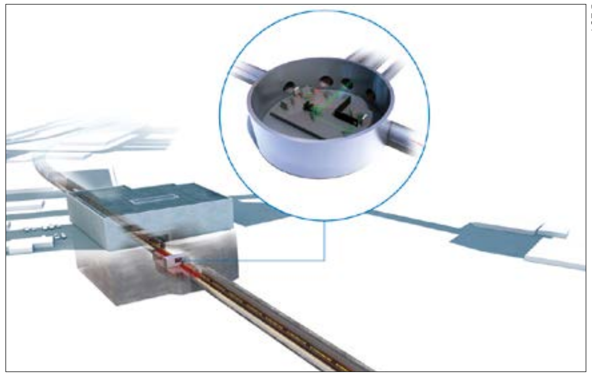
Fig. 5. The CAST experiment at CERN, which reuses a prototype dipole magnet from the LHC, photographed in December 2016.



DESY

Fig. 6. Schematic of the ALPS II experiment's final stage, which will re-use 20 HERA straightened dipoles in a section of the tunnel at DESY.

Alternatively, many magnetised dielectric discs in parallel can be placed in front of a mirror (figure 3): since the emission from all surfaces is coherent, constructive interference can boost the signal sensitivity for a given frequency range determined by the spacing between the discs. First studies performed in the past years at the Max Planck Institute for Physics in Munich have revealed that, for axion masses around 100 µeV, the sensitivity could be good enough to cover the predicted dark-matter axion mass range. The MADMAX (Magnetized Disc and Mirror Axion Experiment) collaboration, formed in October 2017, aims to use this approach to close the sensitivity gap in the well-motivated range for dark-matter axions with masses around 100 µeV. First design studies indicate that it is feasible to build a dipole magnet with the required properties using established niobium-titanium superconductor technology. As a first step, a prototype experiment is planned consisting of a booster with a reduced number of discs installed inside a prototype magnet. The experiment will be located at DESY in Hamburg, and first measurements sensitive to new ALPs parameter ranges are planned within the next few years.

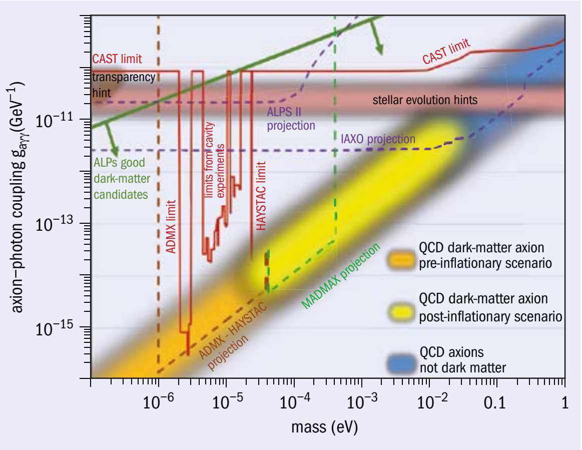


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Fig. 7. Axion mass versus axion–photon coupling parameter space showing sensitivities and regions that could explain dark matter, stellar anomalies and TeV-transparency hints.

Model independent searches

These direct searches for axion dark matter are very promising, but they are hampered at present by the unknown axion mass and rely on cosmological assumptions. Other, less-model dependent, experiments are required to further probe the existence of ALPs.

ALPs with energies of the order of a few keV could be produced in the solar centre, and could be detected on Earth by pointing a strong dipole magnet at the Sun: axions entering the magnet could be converted into photons in the same way they are in cavity experiments. The difference is that the Sun would emit relativistic axions with an energy spectrum very similar to the thermal spectrum in its core, so experiments need to detect X-ray photons and are sensitive to axion masses up to a maximum depending on the length of the apparatus (figure 4, top). This helioscope technique was brought to the fore by the CERN Axion Solar Telescope (CAST), shown in figure 5, which began operations in 2002 and has excluded axion masses above 0.02 eV. As a successor, the International Axion Observatory (IAXO) was formally founded in July 2017 and received an advanced grant from the European Research Council earlier this year. The near-term goal of the collaboration is to build a scaled-down prototype version of the experiment, called baby-IAXO, which is under discussion for possible location at DESY.

The third, laboratory-based, approach to search for WISPs also aims to generate and detect ALPs without any model assumption. In the first section of such an experiment, laser light is sent through a strong magnetic field so that ALPs might be generated via interactions of optical photons with the magnetic field. The second section is separated from the first one by a light-tight wall that can only be penetrated by ALPs. These would stream through a strong magnetic field behind the wall, allowing them to be re-converted into photons and giving the impression of light shining through a wall (figure 4, bottom).

Such experiments have been performed since the early 1990s, but no hint for any ALP has shown up. Today, the most advanced project in this laboratory-based category is ALPS II, currently being set up at DESY (figure 6). This experiment will use two optical resonators implemented into the apparatus to "recycle" the light before and increase the re-conversion probability of ALPs into photons behind the wall, allowing ALPS II to reach sensitivities beyond ALP–photon coupling limits from helioscopes. It also plans to use 20 dipoles from the former HERA collider, each of which has to be mechanically straightened, to generate the magnetic field.

Gaining momentum

Searches for very lightweight axions and ALPs, potentially explaining all of the dark matter around us, are strongly gaining momentum. CERN has been supporting such activities in the past (with solar-axion and dark-matter searches at CAST, and the OSQAR and CROWS experiments using the shining-light-through-walls approach) and is also involved in the R&D phase for next-generation experiments such as IAXO (*CERN Courier* September 2014 p17). With the new initiatives of MADMAX and IAXO, both of which could be located at DESY, and the ALPS II experiment under construction there, experimental axion physics in Europe is set to probe a large fraction of a well-motivated parameter space (figure 7). In addition to complementary experiments worldwide, the next 10 years or so should shine a bright light on WISPs as the solution to the dark-matter riddle, with thrilling data runs expected to start in the early 2020s.

Further reading

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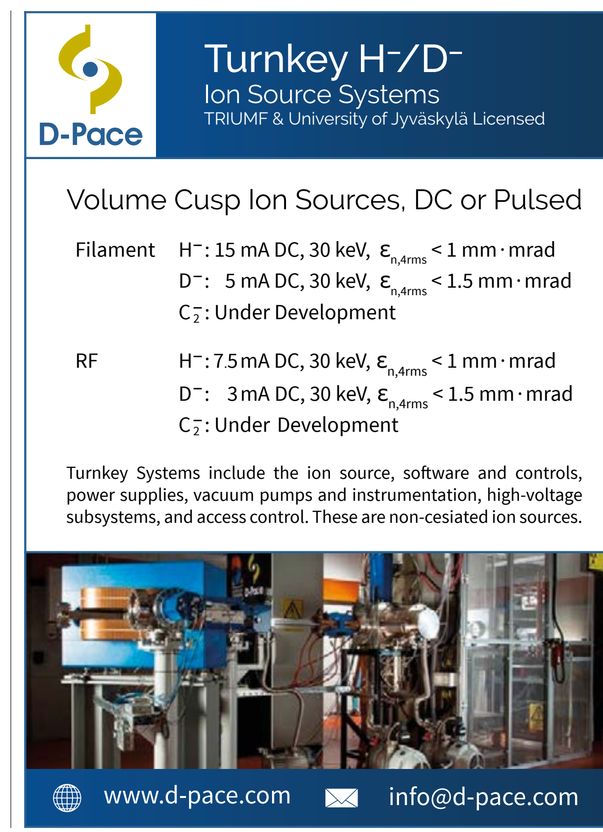
Résumé

La quête des WISP prend de la vitesse

La nature de la matière noire demeure à ce jour l'une des grandes énigmes de la physique. Les recherches portant sur des constituants de la matière noire semblables à des WIMP ayant jusqu'ici été infructueuses, l'intérêt se porte de plus en plus sur d'autres candidats à la matière noire, notamment les axions ou des particules semblables à ceux-ci. De nouvelles expériences, qui cherchent des particules de ce type – soit émises par le soleil soit produites en laboratoire – passent à présent à la vitesse supérieure. Parmi celles qui fleurissent en Europe, on peut citer IAXO, MADMAX et ALPS II. Ensemble, elles sonderont une grande partie d'un espace de paramètres bien déterminé.

Axel Lindner and **Andreas Ringwald**, DESY, Hamburg; and **Béla Majorovits**, Max Planck Institute for Physics, Munich.



Advertising feature

UHV Design advances bellows-free drive for critical beamline applications at CERN

Spring-loaded magnetically-coupled device provides a fail-safe solution that could reduce unscheduled downtime due to loss of ultra-high vacuum.

Compact, bellows-free actuator.

Innovative design

A customer enquiry for a linear power probe – a magnetically-coupled actuator that can operate remotely in vacuum – has led to a new fail-safe design that could improve the operability of beamlines around the world.

"CERN explained that they were looking for a product that would avoid using bellows", says Jonty Eyres, engineering director at UHV Design. The UK-based firm specializes in the design, manufacture and supply of motion and heating products specified for use in high- and ultra-high vacuum conditions.

"Bellows-sealed devices have been the go-to space for moving things in and out in a clean manner and with minimal outgassing", Eyres explains. Depending on the type of bellows used, and their application, their service life can reportedly range from 10 000 up to as many as 2 million actuations. But they won't last forever. And when they fail it can lead to an unexpected loss of vacuum and costly delays.

The challenge for Eyres and his colleagues was to come up with a solution that reproduced the clean operation of a bellows-sealed device, but in a fail-safe manner.

Over the past 20 years, the firm has developed considerable expertise in magnetically-coupled devices. Their bellows-free approach features an arrangement of magnets located inside and outside a rigid tubular vacuum envelope. Moving the magnetic housing on the outside advances and retracts an actuation shaft held centrally inside the device.

The team used specialized software to optimize both the magnetic coupling between the inside and the outside, and the screening of the device.

Online meetings allowed the client – in this case CERN – to voice the product criteria that were important to them. "We used the sessions to discover their feedback, the pros and cons and where we think the scope is in terms of performance", Eyres explains.

"Once we are confident in a prototype, the next stage is to put it on a vacuum rig and start running rigorous tests on performance and precision", says Eyres.

This includes carrying out residual gas analysis using a mass quadrupole device to examine how the mechanism affects the vacuum pressure. A major benefit of the firm's design is that there are no bellows to fail. But instead the team has to contend with moving parts in vacuum.

The engineers tackled this by keeping the contact areas to a minimum and using rolling parts, not sliding parts, to limit any pressure rise during operation. Preserving ultra-high vacuum conditions is critical.

Designed for cleanliness

But having rolling contacts isn't the end of the story. In addition, the materials combination must be inert to prevent the mechanism from bonding or sticking over time. And the requirement for absolute cleanliness means that all of the bearings have to be designed to operate without lubrication.

The company's solution was to use silicon nitride (a hard ceramic) ball races that pressed against two extremely tough shafts made out of tungsten carbide. This arrangement keeps the internal push-rod centrally supported, paving the way for precise movement into and out of the beamline. Furthermore, external constant force springs retract the in vacuum mechanism should any failure occur in the pneumatics driving the unit. In this fail-safe position, the linear actuator has no effect on the beam.

A system of flexures ensures that no undue stresses are placed on any of the critical parts during bake out as they expand at different rates according to their composition.

The firm's bellows-free solution brings together creative design, smart materials selection and precision operation. Now that the linear drive is in its final prototype phase the team is working towards fulfilling multiple orders from CERN for what will be a bolt-on solution pre-wired with all of the necessary cables and switches.

"Every beamline in the world needs beam diagnostics," Eyres comments. "And off the back of this project we're ready to work with more clients who are also looking to move away from bellows in critical areas."

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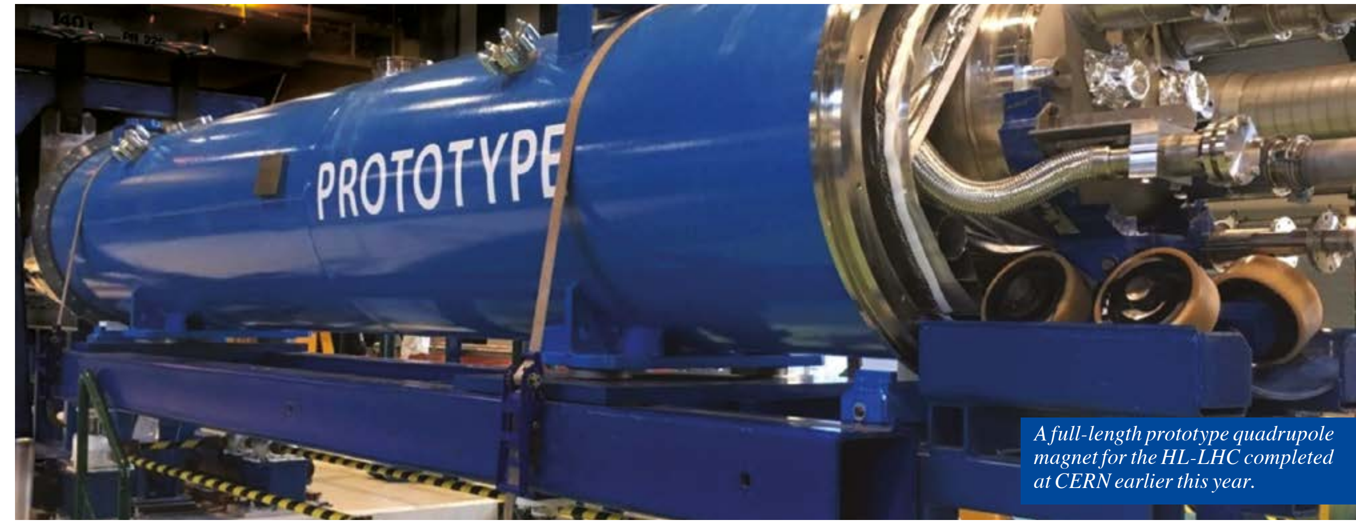

A full-length prototype quadrupole magnet for the HL-LHC completed at CERN earlier this year.

Procurement at the forefront of technology

The LHC, the largest and most complex scientific instrument ever conceived, could not have been built without good organisation, innovative procurement and careful oversight. The same is true of the high-luminosity LHC upgrade.

The completion of the Large Hadron Collider (LHC) in autumn 2008, involving a vast international collaboration and a ten-figure – yet extremely tight – budget, presented unprecedented obstacles. When the LHC project started in earnest in late 1994, many of the most important technologies, production methods and instruments necessary to build and operate a multi-TeV proton collider simply did not exist. CERN therefore had to navigate the risks of lowest-bidder economics, and balance the need for innovation and creativity versus quality control and strict procurement procedures. The impact of long lead times for essential components and tooling, in addition to contingency for business failures, cost overruns and disputes, also had to be minimised.

Procurement for the LHC demanded a new philosophy, especially regarding the management of risk, to keep the LHC close to budget. Excluding personnel costs, the total amount charged to the CERN budget for the LHC was 4.3 billion Swiss francs, which includes: a share of R&D expenses; machine construction, tests and pre-operation; LHC computing; and a contribution to the cost of the detectors. Associated procurement activities covered everything from orders for a few tens of Swiss francs to contracts exceeding 100 million Swiss francs each, from purchases of a single unit to the series manufacturing of hundreds of thousands of components delivered over periods of several years. To give some figures, the construction of the LHC required: 1170 price enquiries and tender invitations to be issued; the negotiation, drafting and placing of 115,700 purchase orders and 1040 contracts; and the commitment of 6364 different suppliers and contractors, not including subcontractors.

Unconventional contracting

CERN's organisational model also required LHC spending to take account of many national interests and to ensure a fair industrial return to Member States. In addition, CERN made special arrangements with a number of non-Member States for the handling of their respective additional contributions, part of which was provided in cash and part as in-kind deliverables. Procurement for the main components of the LHC fell into three distinct categories: civil engineering; superconducting magnets and their associated components; and cryogenics.

Although the main tunnel for the LHC already existed, the total value of necessary civil-engineering activities was around 500 million Swiss francs, requiring an unconventional division of tasks between CERN, consulting engineers and contractors

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ATL-PHO-INST-2002-022-1

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Fig. 1. A number of events occurred during construction that necessitated amendments to the LHC contracts. During construction of the ATLAS caverns and access shafts (left), the design of a vault using reinforced concrete beams was found to be technically unacceptable and had to be replaced. During excavation at the CMS site (right), meanwhile, the discovery of unforeseeable ground conditions required significant changes to the approach and led to the submission of disputes to an adjudication panel. In all cases, they were successfully resolved.

BUL-PHO-2004-036-1

CERN-HI-0704008-03

Fig. 2. The main components and tooling required to assemble the LHC dipole cold-masses were purchased by CERN and delivered to contractors (left, showing cold masses at German company Noell in 2003), who would then return the assembled cold masses to CERN for final insertion into the vacuum vessels (right, showing the final dipole being lowered into the LHC tunnel in April 2007). This approach was also applied to the superconducting strands and cables, the quantities of which were so huge that all major European manufacturers, as well as one US and one Japanese firm, were involved.

(figure 1). The next major procurement task was to supply CERN with the LHC's superconducting magnets, the contractual, technical and logistical challenges of which are difficult to exaggerate. The LHC contains some 1800 superconducting twin-aperture main dipole and quadrupole magnets, as well as their ancillary corrector magnets, all of which are very large and needed to be assembled with absolute precision. The total value of the magnets amounted to approximately 50% of the value of the whole LHC machine, with two thirds of this amount taken up by the dipoles alone (figure 2). CERN opted for an unusual policy to manufacture the LHC magnets, acting both as supplier and client to contractors, and the perils of this approach became apparent when one of the contractors unexpectedly became insolvent.

There is kudos to be gained by being associated with projects at the limits of technology.

Problems also impacted the third major LHC procurement stage: the unprecedented cryogenics system required to cool the superconducting magnets to their 1.9 K operating temperature. A 27 kilometre-long helium distribution line called the QRL was designed to distribute the cryogenic cooling power to the LHC (figure 3), and, since several firms in CERN Member States were competent in such technology, CERN outsourced the task. But, by the spring of 2003, serious technical production problems, in addition to the insolvency of one of the subcontractors, forced CERN to take on a number of QRL tasks itself to keep the LHC on track.

At the end of 2018, the LHC will enter a two-year shutdown to prepare for the high-luminosity LHC (HL-LHC) upgrade, which aims to increase the total amount of data collected by the LHC by a factor of 10 and enable the machine to operate into the 2030s. Following five years of design study and R&D, the HL-LHC project was formally approved by the CERN Council in June 2016 with a budget of 950 million Swiss francs (excluding the upgrade of injectors and experiments). Tendering for civil engineering and for con-


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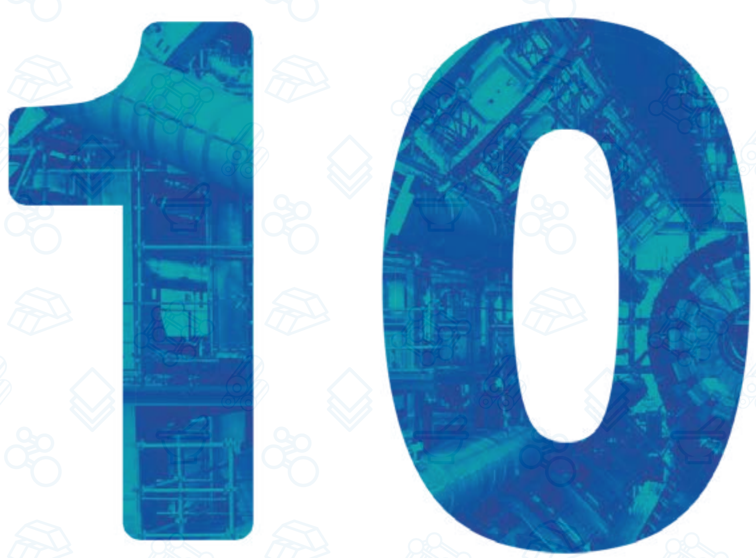
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Breakdown of works for the high-luminosity LHC

More than half of the HL-LHC project cost concerns technical infrastructure and, in particular, the civil-engineering work required at the ATLAS and CMS sites. The rest is consumed by the 11 T dipoles and other magnets, new cryogenic equipment, compact superconducting crab cavities, and numerous other components:

- **Caverns**
The underground structures required at the ATLAS site in Switzerland and the CMS site in France consist of a new shaft (70 to 80 m deep, 5 m in radius), a service cavern (50 m long, 8 m in radius) and a service gallery (300 m long) for cryogenic, cooling and ventilation, radio-frequency equipment, magnet power converters and other technical equipment.

- **Surface works**
Overground works involve the construction of buildings for general services and the machinery needed to operate the equipment installed underground. The work required at each point covers five new buildings representing a total additional floor area of 6200 m², as well as technical galleries, concrete slabs, roads, drainage and landscaping.

Members of CERN's procurement service photographed with the bids received for the HL-LHC civil engineering contracts.

- **Magnets**
11 T superconducting two-in-one dipole magnets based on niobium–tin cable and a family of various other magnet types (e.g. dipoles, quadrupoles, sextupoles, octupoles, decapoles and dodeacpoles) based on either niobium–tin or niobium–titanium superconducting cable are necessary to increase the probability of collisions.

- **Cryogenics**
At both ATLAS and CMS, new 1.9 K cryogenic plants will be needed, while at P4 a new 4.2 K cryogenic plant is required. These comprise a warm compressor station connected to a helium-buffer storage, cold boxes, compressors and a system of cryogenic distribution lines.

- **Advanced RF**
HL-LHC requires compact superconducting radio-frequency "crab" cavities with ultra-precise phase control for beam rotation to increase the probability of proton–proton collisions, which are currently undergoing tests in the SPS.

- **Other technologies**
New technologies are also required for beam collimation, high-power lossless superconducting links, machine protection, ultra-high vacuum, beam diagnostics, transfers, kickers and numerous other aspects of the HL-LHC.

struction and testing of the main hardware components has started, and some of the contracts are in place. A total of around 90 invitations to tender and price enquiries have been issued, and orders and contracts for some 131 million Swiss francs have already been placed. In June, a groundbreaking ceremony at CERN marked the beginning of HL-LHC civil engineering.

From a procurement point of view, the HL-LHC is a very different beast to the LHC. First, despite the relatively large total project cost, the production volumes of components required for HL-LHC are much smaller. Hence, although the HL-LHC will rely on a number of key innovative technologies to modify the most complex and critical parts of the LHC (see box above), these concern just 1.2 km of the total machine's 27 km circumference. Second, the HL-LHC project is being executed roughly two decades later, in a totally different technological and industrial landscape.

A key factor in much of CERN's procurement activities is that each new accelerator or upgrade brings more challenging requirements and performances, pushing industry to its limits. In the case of the LHC, the large production volumes were an incentive for potential suppliers to invest time and resources, but this is not always the case with the much smaller volumes of the HL-LHC.

From a procurement point of view, HL-LHC is a very different beast to the LHC.

CERN-EX-0605016-03

Fig. 3. Installation of the cryogenic distribution line (QRL) in LHC sector 1-2, the last to be equipped, in May 2006. Each sector involved placing 325 elements and carrying out almost 2000 internal welds.

Sometimes the market is simply not willing to invest the time and money required as the perceived market is too small, which can lead to CERN designing its own prototypes or working alongside industry for many years to ensure that firms build the necessary competence and skills. Whereas in the days of LHC procurement, companies were more willing to take a long-term view, today many companies' objectives are based on shorter-term results.

This makes it increasingly important for CERN to convey the many other benefits of collaborating on projects such as the HL-LHC. Not only is there kudos to be gained by being associated with projects at the limits of technology, but there are clear commercial pay-offs. A study related to LHC procurement and contracting, published in 2003, demonstrated clear benefits to CERN suppliers: some 38% had developed new products, 44% had improved technological learning, 60% acquired new customers thanks to the CERN contracts, and all firms questioned had derived great value from using CERN as a marketing reference. Another, more recent, study of the cost-benefits analysis of the LHC and its upgrade is currently being conducted by economists at the University of Milan, providing evidence of a positive and statistically significant correlation between LHC procurement and supplier R&D effort, innovation capacity, productivity and economic performance (see p51).

The success of any major big-science project depends on the quality and competence of the suppliers and contractors. There is no "one-size-fits-all" solution in procurement for different requirements and, if a strategy does not work as planned because of unforeseeable conditions, it must be changed. The 36-strong CERN procurement team maintains a supplier database and organises and attends industry events to connect with businesses. It also uses national industrial liaison officers to help find suitable companies in those countries and reaches out to other research labs, all while involving engineers and physicists in the search for new potential suppliers. In the end, the realisation of major international projects such as the LHC and HL-LHC is all about good teamwork between the people responsible for the various activities within the host facility and their suppliers and contractors.

● Parts of this article were drawn from the recently republished book *The Large Hadron Collider: A Marvel of Technology*, edited by L Evans.

Résumé

Les achats à la pointe de la technologie

Une cérémonie de premier coup de pioche s'est déroulée en juin au CERN pour marquer le début des travaux de génie civil pour le LHC à haute luminosité (HL-LHC). Les appels d'offres pour le HL-LHC ont à présent commencé ; des contrats pour plus de 131 millions de francs suisses ont déjà été conclus. Il faut se rappeler que le succès de tout projet scientifique d'envergure dépend entre autres de la qualité et de la compétence des fournisseurs et contractants, et que les achats pour le HL-LHC sont très différents de ceux qui avaient été faits pour le LHC. D'abord, les volumes de production sont beaucoup plus faibles, et ensuite, le projet HL-LHC ayant lieu environ vingt ans plus tard, le contexte technologique et industriel est extrêmement différent. L'équipe du CERN chargée des achats aura donc de nombreux défis à relever.

Anders Unnervik, head of the CERN procurement and industrial services group.

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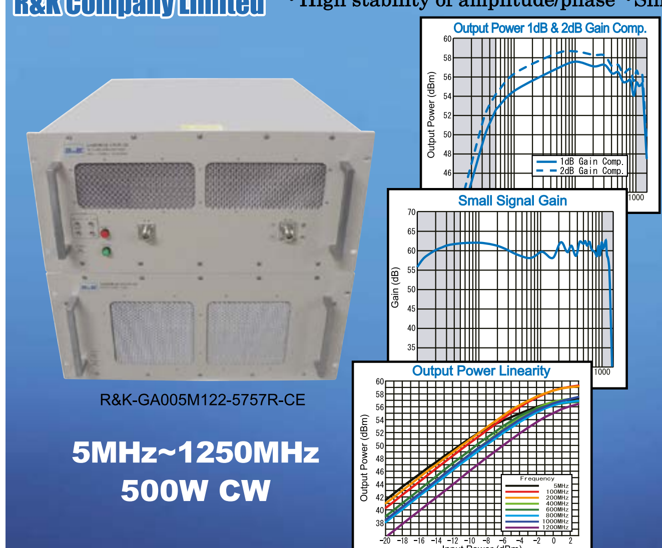

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CA114BW2-6171RP	114MHz ± 1MHz	12kW	30 ~ 100μs	0.50%	Water
CA186BW3-7878R-LB	185.7MHz ± 1.5MHz	60kW	CW	100%	Water
CA200BW0.4-7383RP	200MHz ± 0.2MHz	200kW	~ 1.1ms	3.30%	Water
CA324BW10-7181RP	324MHz ± 5MHz	120kW	210 ~ 600μs	3.00%	Air
CA358BW2-6878RP	358.54MHz ± 1MHz	64kW	10ms	10.00%	Water&Air
CA509MBW6-7373R	509MHz ± 3MHz	20kW	CW	100%	Water&Air
CA571BW2-6070RP	571MHz ± 1MHz	10kW	10 ~ 100μs	0.50%	Water
CA1300BW10-6372R	1300MHz ± 5MHz	16kW	CW	100%	Water
CA2856BW20-5861RP	2856MHz ± 10MHz	1.2kW	5μs	0.05%	Air
CA5712BW20-6157RB	5712MHz ± 10MHz	450W	1μs ~ 5μs	0.05%	Water
GA11424BW200-5757RP	11.424GHz ±100MHz	500W	1.5μs	1.00%	Air

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A009K401 Series	10kHz ～ 400MHz	25W ～ 500W CW	Air
A101K501 Series	100kHz ～ 505MHz	40W ～ 200W CW	Air
A001M102 Series	1MHz ～ 1000MHz	10W ～ 250W CW	Air
A080M102 Series	80MHz ～ 1000MHz	75W ～ 4kW CW	Air
GA005M122-5757R-CE	5MHz ～ 1250MHz	500W CW	Air
A501M272 Series	500MHz ～ 2700MHz	5W ～ 120W CW	Air
A801M202 Series	800MHz ～ 2000MHz	50W ～ 600W CW	Air
GA102M252 Series	1000MHz ～ 2500MHz	50W ～ 2kW CW	Air
A202M402 Series	2000MHz ～ 4000MHz	10W ～ 50W CW	Air
GA701M402 Series	690MHz ～ 4000MHz	5W ～ 800W CW	Air
GA701M602 Series	700MHz ～ 6000MHz	10W ～ 200W CW	Air
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Advertising feature

Positioning at a High Level: 20 Tons of Precision Technology for X-Ray Microscopy

Mechanical precision components, stable control, and engineering know-how are the essential basics of high-precision, complex motion and positioning solutions. An example of this, with very special challenges can be found in the KIT (Karlsruher Institut für Technologie, Germany). In a joint project the Institute for Photonic Science and Synchrotron Radiation (IPS) and the Institute for Microstructure Technology (IMT) for the ANKA synchrotron radiation source (Angströmquelle Karlsruhe) developed a new X-ray microscopy and quality assurance system for X-ray optical elements, abbreviated to MiQA Station (X-ray Microscope and Quality Assurance Station). The Beamline experts at PI (Physik Instrumente) supported them in this endeavor.

Image 2: The massive granite construction of the base guarantees the necessary overall stiffness of the system. Hoverpads allow easy moving of the 20-ton machine. (Source: PI)

To ensure progress with research, the MiQA system (image 1) had to have a very flexible design in order to make a wide range of experiments possible in X-ray microscopy and the study of X-ray optical elements. However, the flexibility does present very special technical challenges. For example, X-ray optical elements such as lenses, grids, detectors and the sample need to be positioned with the utmost precision, and must remain stable for a long time in order to allow high-resolution measuring in the X-ray beam. This means that around 60 very different motorised axes need to be controlled sensitively and synchronised to each other. This is the reason why the KIT got PI on board as industrial partner for implementing this task and providing support during building of machine and putting it into operation afterwards.

Image 1: The beamline specialists from PI designed and produced the MiQA system and also put it into operation at the ANKA electron synchrotron on the premises of the KIT (Karlsruher Institut für Technologie). (Source: PI)

Air bearing linear drives on a stable machine base

The 20 ton system has a modular construction. The base itself has volume of 4900 mm × 2200 mm × 600 mm and is made of granite (image 2). The machine's retractable feet allow rough alignment of the entire machine (tip/tilt/Z) with a resolution of better than 100 microrads. The feet of the machine are supplied with compressed air for lateral fine alignment (yaw) and therefore float on air cushions. Triangulation sensors help with setting the air cushions. Despite the high weight, it is possible to move the system to another location easily. For this purpose, the machine's feet are retracted, the hoverpads on the underneath activated, and MiQA floats, so to say, to the new location. To simplify the move, there is also a common electrical interface on the base of the machine that is available to the entire measuring system for the higher level beamline control.

The base of the machine is designed for positioning a maximum of six X-ray optical elements. For the highest flexibility, each element is placed on its own positioning module, which can move along the path of the beam on massive, parallel rails independently of the other modules. The modules are driven by linear motors and glide on air bearings. Absolute encoders are integrated to provide position feedback and the maximum travel range is 2800 mm. The central sample module then moves each sample along the path of the beam over a travel range of 3500 mm. To ensure the best possible stability during the experiment, each module can be disconnected from the air supply so that it is seated firmly on its rail and holds its position steadily.

Hexapods position the X-Ray optics

Four further modules serve to position the X-ray lenses and grids. Hexapods are the driving force here (image 3) for precision alignment in six degrees of freedom. Because hexapods are parallel-kinematic systems, the center of rotation can be set as desired by software commands in order to adapt the focus of the X-ray optical element. This accelerates the alignment process considerably. Two of these optical X-ray modules are also equipped with goniometers and piezo scanners to allow a large range of angular motion around the axis of the beam as well as nanometer-precision phase scanning of for example, X-ray grids. They can be attached to all of the hexapods if necessary. If anything needs to be changed, it is not necessary to reroute any cables because corresponding connectors are integrated into all of the modules. Furthermore, the machine's software automatically detects where the components are mounted.

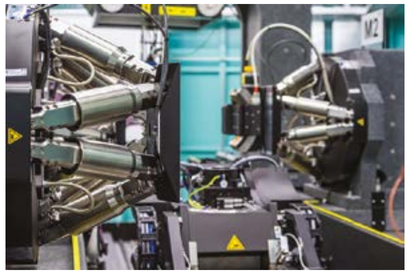

Image 3: Hexapods align the X-ray optics in up to six axes. Additional goniometers allow rotation around the beam path. (Source: PI)

Powerful parallel kinematics for exact positioning of detectors

The detector portal module positions the camera with the detector optics in three degrees of freedom. A parallel-kinematic system also guarantees high stiffness and stability. It provides two lateral degrees of freedom perpendicular to the beam and one degree of rotational freedom around the beam axis. The center of rotation can also be set as desired by software to adapt it to the detector geometry. Because the detector used by the KIT is large and heavy (approx. 60 kg), the parallel-kinematic system was constructed so that high precision is ensured and, at the same time, high stability.

The heart of the system is the sample module (image 4), which allows various experimental schemes. It is also designed for high stiffness, stability, and precision. Viewed from bottom to top, a hexapod, a goniometer, a rotational axis with air bearing, and a three-axis NEXLINE PiezoWalk positioner are stacked on top of each other. The heavy-duty hexapod allows alignment in six degrees of freedom with any center of rotation. In addition to the sample, it was also necessary to consider that positioning devices with a weight 250 kg have to be moved. Such a load inevitably leads to deformation of the joints and this makes submicrometer repeatability impossible. To overcome this challenge, six additional unloaded struts, equipped with absolute encoders, were used only for measuring the position of the uppermost platform (image 5). A separate outer servo loop then compensates any deformation of the hexapod's drive struts based on the data collected by the measuring legs. The hexapod's repeatability is then better than 100 nanometers.

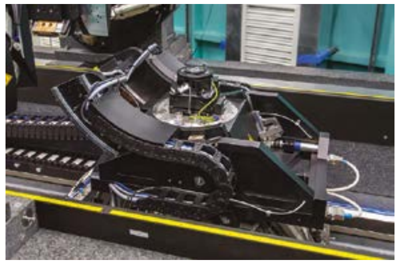

Image 4: The positioning mechanics of the sample module: the hexapod with its six active and six redundant struts for position feedback sits underneath. The goniometer guides are above and alignment in the X, Y, and Z direction as well as the rotation stage setting are visible. (Source: PI)

The large goniometer on the hexapod allows tilting of a flat and extended sample in the beam and characterization with laminographic methods. Its travel range is 0°–60° around the beam axis. To increase the stability and reproducibility, it is preloaded mechanically with additional motors that counteract the actual goniometer drive. The intensity of the force depends on the tilt angle while considering the distribution of the mass of the structure and the position of the component above it.

The actual degree of rotational freedom for the tomography is achieved with a high-precision air bearing. The deviation of the sample position measured 100 mm above the stage is less than 85 nm to 130 nm, depending on the tilt angle of the goniometer below it. This is achieved by careful construction and precision tuning of the compressed air supplied to the bearing. A three-axis positioning system is mounted on the rotational stage that is used for compensating errors in three degrees of freedom and aligning the sample. Here, NEXLINE PiezoWalk drives, which are distinguished by their high stiffness and feed force of several 100 N, provide the driving force. They are able to compensate errors dynamically in a range of a few micrometers, are designed for positioning and holding forces of up to 800 N, and work at low velocities. NEXLINE stages with crossed roller bearings are used in the application to ensure stiffness and resolution over comparatively large travel ranges. A sample scan for STXM (scanning transmission X-ray microscopy) or respectively ptychography is also possible with a resolution of less than 10 nm.

Physik Instrumente in brief

Well known for the high quality of its products, PI (Physik Instrumente) has been one of the leading players in the global market for precision positioning technology for many years. PI has been developing and manufacturing standard and OEM products with piezo or motor drives for 40 years. Continuous development of innovative drive concepts, products and system solutions, and more than 200 technology patents distinguish the company history today. PI develops, manufactures and qualifies all core technology itself: from piezo components, actuators, motors, magnetic direct drives through air bearings and magnetic and flexure guides, to nanometrological sensors, control technology and software. PI is therefore not dependent on components available on the market to offer its customers the most advanced solutions. The high vertical range of manufacturing allows complete control over processes and this allows flexible reaction to market developments and new requirements. By acquiring the majority shares in ACS Motion Control, a worldwide leading developer and manufacturer of modular motion controllers for multi-axis drive systems, PI can also supply customised complete systems for industrial applications that make the highest demand on precision and dynamics. In addition to four locations in Germany, the PI Group is represented internationally by fifteen sales and service subsidiaries.

Image 5: The heavy-duty hexapod has six additional and unloaded struts equipped with absolute encoders that are used for measuring the position of the uppermost platform. (Source: PI)

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The day the world switched on to particle physics

When the Large Hadron Collider circulated its first protons 10 years ago, it made headlines around the globe. What was it that drove one of the biggest media events science has ever seen, and is the LHC still able to capture the public imagination?

When Lyn Evans, project leader of the Large Hadron Collider (LHC), turned up for work at the CERN Control Centre (CCC) at 05:30 on 10 September 2008, he was surprised to find the car park full of satellite trucks. Normally a scene of calm, the facility had become the focus of global media attention, with journalists poised to capture the moment when the LHC switched on. Evans knew the media were coming, but not quite to this extent. A few hours later, as he counted down to the moment when the first beam had made its way through the last of the LHC's eight sectors, the CCC erupted in cheers – and Evans wasn't even aware that his impromptu commentary was being beamed live to millions of people. "I thought I was commenting to others on the CERN site," he recalls. The following weekend, he was walking in the nearby ski town of Megève when a stranger recognised him in the street.

Of all human endeavours that have captured the world's attention, the events of 10 September 2008 are surely among the most bizarre. After all, this wasn't something as tangible as sending a person to the Moon. At 10:28 local time on that clear autumn Wednesday, a bunch of subatomic particles made its way around a 27 km-long subterranean tube, and the spectacle was estimated to have reached an audience of more than a billion people. There were record numbers of hits to the CERN homepage, overtaking visits to NASA's site, in addition to some 2500 television broadcasts and 6000 press articles on the day. The event was dubbed "first-beam day" by CERN and "Big Bang day" by the BBC, which had taken over a room in the CCC and devoted a full day's coverage on Radio 4. Google turned its logo into a cartoon of a collider – such "doodles" are now commonplace, but it was a coup for CERN back then. It is hard to think of a bigger media event in science in recent times, and it launched particle physics, the LHC and CERN into mainstream culture.

Image above: physicists in the CERN Control Centre on 10 September 2008, as protons were about to make their first turns around the LHC. Credit: CERN-HI-0809002-42.

It is all the more incredible that no collision data, and therefore no physics results, were scheduled that day; it was "simply" part of the commissioning period that all new colliders go through. When CERN's previous hadron collider, the Super Proton Synchrotron, fired up in the summer of 1981, says Evans, there was just him and Carlo Rubbia in the control room. Even the birth of the Large Electron Positron collider in 1989 was a muted affair. The LHC was a different machine in a different era, and its birth offers a crash course in the communication of big-science projects.

News values

Fears that the LHC would create a planet-eating black hole were a key factor behind the enormous media interest, says Roger Highfield, who was science editor of the UK's *The Telegraph* newspaper at the time. "I have no doubt that the public loved all the stuff about the hunt for the secrets of the universe, the romance of the Peter Higgs story and the deluge of superlatives about energy, vacuum and all that," says Highfield. "But the LHC narrative was taken to a whole new level by the potty claim by doomsayers that it could create a black hole to swallow the Earth. When 'the biggest and most complex experiment ever devised' was about to be turned on, it made front-page news, with headlines like, 'Will the world end on Wednesday?'".

The conspiracies were rooted in attempts by a handful of individuals to prevent the LHC from starting up in case its collisions would produce a microscopic black hole – one of the outlandish models that the LHC was built to test. That the protons injected into the LHC that day had an energy far lower than that of the then-operational Tevatron collider in the US, and that collisions were not scheduled for weeks afterwards, didn't seem to get in the way of a good story. Nor, for that matter, did CERN's efforts to issue scientific reassurances. Indeed, when science editor of *The Guardian*, Ian Sample, turned up at CERN on first-beam day, he expected to find protestors chained to the fence outside, or at least waving placards asking physicists not to destroy the planet. "I did not see a single protestor – and I looked for them," he says. "And yet, inside the building, I remember one TV host doing a piece to camera on how the world might end when the machine switched on. It was a circus that the media played a massive part in creating. It was shameful and it made the media who seriously ran with those stories look like fools."

The truth is the black-hole hype came long after the LHC had started to capture the public imagination. As the machine and its massive experiments progressed through construction in the early 2000s, the project's scale and abstract scientific goals offered an appeal to wonder. Though designed to explore a range of phenomena at a new energy frontier, the LHC's principal quarry, the Higgs boson, had a bite-sized

> **There was a clear prediction that people could grab on to – the discovery of a new particle.**
> *Geoff Brumfiel, National Public Radio*

CERN-HI-0809004-02

Journalists on the CERN site on first-beam day.

description: the generator of mass. It also had a human angle – a real-life, white-haired Professor Higgs and a handful of other theorists waiting to see if their half-century-old prediction was right, and international teams of thousands working night and day to build the necessary equipment. Nobel laureate Leon Lederman's 1993 book *The God Particle*, detailing the quest for the Higgs boson, added a supernatural dimension to the enterprise.

"I am confident that no editor-in-chief of any newspaper in the world truly understood the Higgs field, the meaning or significance of electroweak symmetry breaking, or how the Higgs boson fits into the picture," continues Sample. "But what they did get was the appeal of hunting for a particle that in their minds explained the origin of mass. It is such an intriguing concept to imagine that we even need to explain the origin of mass. Isn't it the case that matter just has mass, plain and simple? All of this, in addition to the sheer awe at the engineering and physics achievement, made for an enormously exotic and appealing story."

There were also more practical reasons for LHC's media extravaganza, notes Geoff Brumfiel, a reporter at *Nature* at the time and now a senior editor at *National Public Radio* in the US. The fact that pretty much every country and region on Earth had somebody working on the LHC meant that there was a local story for thousands of news outlets, he says, plus CERN's status as a publicly funded institution made it possible for the lab to open up to the world. "There was also great visual appeal: the enormous, colourful detectors, deep underground, teeming with little scientists in hard hats – it just *looked* cool. That was hugely important for cable news, television documentary producers, etc." In addition, says Brumfiel, something actually happened on first-beam day – there was something for journalists to see. "That's always big in the news business. A big new machine was turning on and might or might not work. And when it worked there were lots of happy people to look at and hear."

There are so many things that make it work for the media: it's a bloody enormous machine. Pull it out the ground, and stand it up like a hula hoop and it reaches five miles into the sky. That is one insane machine.

Ian Sample, The Guardian

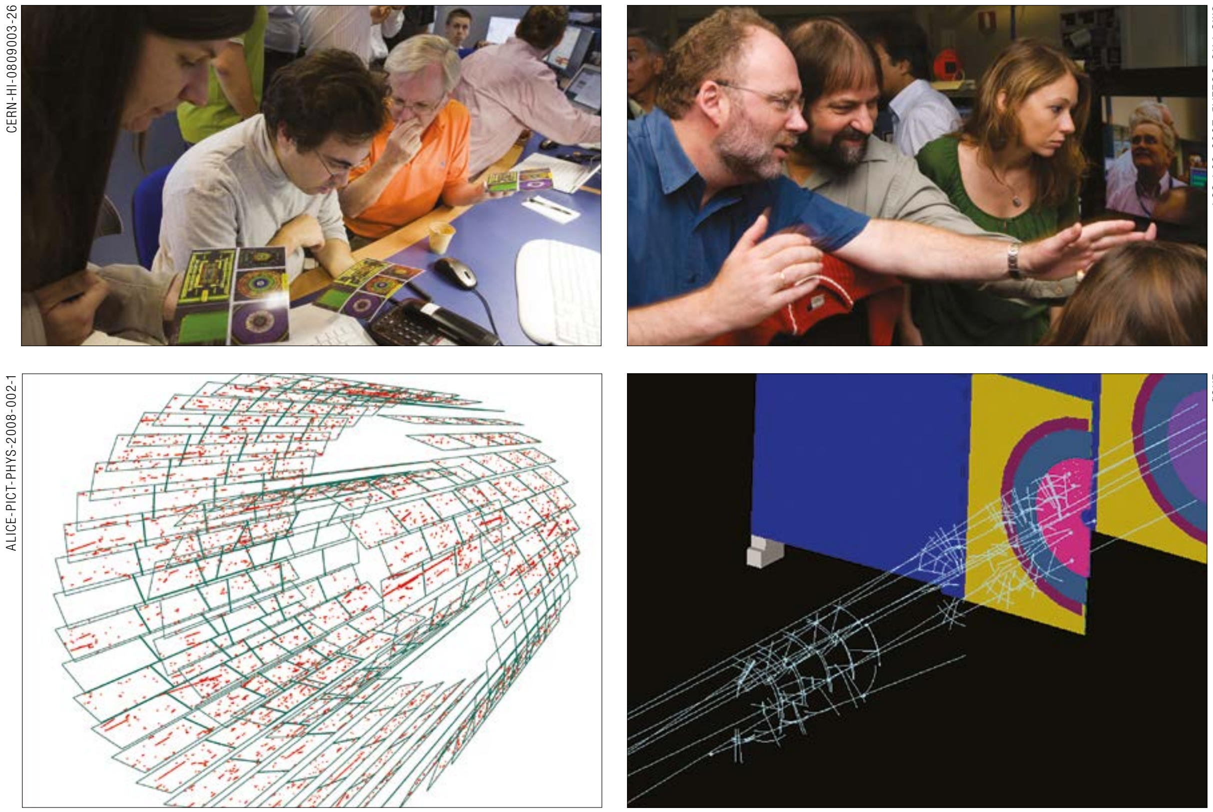
Strategy first

Despite the many external factors influencing LHC communications, the switch-on would never have had the huge reach that it did were it not for a dedicated communication strategy, says James Gillies, CERN's head of communications at the time. It started as far back as 2000, when Dan Brown's science-fiction novel *Angels & Demons*, about a plot to blow up the Vatican using antimatter stolen from CERN, was published. "Luckily for us, it didn't sell, but it alerted us to the fact that the notion that CERN could be dangerous was bubbling up into popular culture," says Gillies. A few years later, the BBC made a drama documentary called *End Day*, which examined a range of ways that humanity might not last the century – including a black hole being created at a particle accelerator. Then, when Dan Brown's next book, *The Da Vinci Code*, became a bestseller, CERN realised that *Angels & Demons* would be next on people's reading list – so it had better act. "That led to one of the most peculiar conversations that I've ever had with a CERN director general, and resulted in us featuring fact and fiction in *Angels & Demons* on the CERN website," says Gillies. "Our traffic jumped by an order of magnitude overnight and we never looked back." CERN later played a significant role in the screen adaption of the book, and Sony Pictures included a short film about CERN in its Blu-ray release.

The first dedicated LHC communications strategy was put in place in 2006. The perception of CERN as portrayed in *End Day* and *Angels & Demons* was so wide off the mark that is was laughable, says Gillies, so he took it as opportunity to lead the conversation about CERN and be transparent and timely. In addition to actions such as working with science communicators in CERN Member States and beyond, to organise national media visits for key journalists, he says, "the big idea is that we took a conscious decision to do our science in the public eye, to involve people in the adventure of research at the forefront of human knowledge". Publicly fixing the date for first beam was a high-risk strategy, but it paid off. The scheduled LHC start-up exceeded the expectations of everyone involved. Both proton beams made a full turn around the machine and one beam was captured by the radio-frequency system, showing that it could be accelerated. For the thousands of people working on the LHC and its experiments, it marked the transition from 25 years of preparation to a new era of scientific discovery. But the terrain was about to get tougher.

Once the journalists had departed and the champagne bottles were stacked away, the LHC teams continued with the task of commissioning away from the spotlight, with a view to obtaining collisions as soon as possible. Then, a couple of days after first-beam day, a transformer powering part of the LHC's cryogenic system failed, forcing a pause in commissioning during which the teams decided to test the last octant of the machine for high-current operations. While ramping the magnets towards 9.3 kA on 19 September, one of the LHC's 10,000 superconducting-dipole interconnects failed, ultimately damaging roughly 400 m of the machine. Evans described the event, which set operations back by 14 months, as "a kick in the teeth". But CERN recovered quickly (see p5) and, today, Evans says that he is glad that the fault was discovered when it was. "It would have been a disaster had it happened five years in. As it was, we didn't come under criticism. We were pushing the limits of technology."

CERN-HI-0809003-26 CMS-PHO-COLLAB-2008-004-354 ALICE-PICT-PHYS-2008-002-1 LHCb



Top: scenes from first-beam day in the ATLAS (left) and CMS control rooms. Although there were no collisions that day, the experiments were able to record "splash" events – whereby protons strike a collimator and spray secondary particles into the detectors. Bottom: splash events in the ALICE (left) and LHCb detectors recorded during injection tests in the weeks before first-beam day.

The timing of the incident was doubly fortuitous: the same week it took place, US investment bank Lehman Brothers filed for the largest bankruptcy in history, with other banks looking set to follow suit. The world might not have been consumed by a black hole, but the prospect of a distinctly more real financial Armageddon dominated the headlines that week.

To collisions and beyond

The coming to life of the LHC is a thrilling story, a scientific fairytale. From its long-awaited completion, to the tense sector-by-sector threading of its first beam in front of millions of people and the incident nine days later that temporarily ruined the party, the LHC finally arrived at a new energy frontier in November 2009 (achieving 1.18 TeV per beam). Its physics programme began in earnest a few months later, on 30 March 2010, at a collision energy of 7 and then 8 TeV. Barely two years later, the LHC produced its first major discovery – the Higgs boson, announced to a packed CERN auditorium on 4 July 2012 by the ATLAS and CMS collaborations and webcast around the world. The discovery was followed by the award of the 2013 Nobel Prize in Physics to Peter Higgs and François Englert. The CERN seminar was the first time that the pair had met, with cameras capturing Higgs wiping a tear from his eye as the significance of the event sunk in. Since 2015, the LHC has been operating at 13 TeV while notching up record levels of performance, and the machine is now being prepared for its high-luminosity upgrade (HL-LHC).

Has the success of LHC communications set the bar too high? The CERN press office tracked a steady increase in the number of LHC-related articles in the period leading up to the switch-on, in addition to an increasing number of visits by the media and the public. Coverage peaked around September 2008, died down a little, then picked up again four years later as the drama of the Higgs-boson discovery started to unfold. When ATLAS and CMS announced the discovery, press coverage exceeded even that of first-beam day. Of the top 10-read items on *The Guardian* website, says Sample, stories about the Higgs made up eight or nine of them, when there were plenty of other big news stories around that day. Why? "The absolute competence and dedication and hard work of those scientists and engineers was so refreshing compared to the crooks, bullies, liars and murderers that we write about every day," he says. "Perhaps people enjoyed reading about something positive, about people doing astounding work, about something far bigger than the world they normally encounter in the news."

Today, press coverage of the LHC remains higher than it was

CERN-HI-0810033-11

VIPs from CERN Member States and other countries at the LHC's official inauguration on 21 October 2008.

CERN

Tom Hanks, Ayelet Zurer and Ron Howard at CERN in February 2009 promoting the film *Angels & Demons*.

before the switch-on, with an average of 200 clippings per day worldwide. The number of media visits to CERN, having peaked in around 2008 and 2012, is now at the level that it was before the switch-on, corresponding to around 300 media outlets per year. The LHC's life so far has also coincided with the explosion of social-media tools. CERN's first ever tweet, on 7 August 2008, announced the date for first-beam day, and today the lab has more than two million Twitter followers – rising at a rate of around 1000 per day. During the announcement of the Higgs-boson discovery in 2012, CERN's live tweets reached journalists faster than the press release and helped contribute to worldwide coverage of the news.

Framing the search for the Higgs boson as the LHC's only physics goal was never the message that CERN intended to put out, but it's the one that the media latched on to. Echoing others working in the media who were interviewed for this article, Brumfiel thinks that the LHC has largely left the public eye. In terms of the media, he says, "It's a victim of its own success: it was designed to do one thing, and it's done it."

The challenge facing communications at CERN today is how to capitalise on the existing interest while constructing a new or updated narrative of exploration and discovery. After all, in terms of physics measurements, the LHC is only getting into its stride – having collected just 5% of its expected total dataset and with up to two decades of operations still to go. Although the LHC has not yet found any conclusive signs of physics beyond the Standard Model, it is clear from astronomical and other observations that such phenomena are out there, somewhere. In the absence of direct discoveries, identifying the new physics will be a hard slog involving ever more precise measurements of known particles – a much tougher sell to the public, even if it is all part of the same effort to uncover the basic laws of the universe.

Yes, the public still cares about the quest to reveal the deepest secrets of the cosmos.
Roger Highfield, Science Museum

"CERN has managed to build upon previous communication successes as the public is already interested, so they can simply strap a camera onto a drone, fly it around and a lot of people will happily watch!" says David Eggleton of the Science Policy Research Unit at the University of Sussex in the UK, who studies leadership and governance in major scientific projects such as the LHC. "But, just like with the scientists, the public is going to need something new and exciting to focus on – even if the pay-off is 10 years in the future, so it depends on how the laboratory wants to strategise – do they want to pitch HL-LHC as the next big machine or is it just going to be articulated as an upgrade with the FCC (Future Circular Collider) becoming the thing to capture the public's imagination?"

Theoretical physicist and science populariser Sabine Hossenfelder of the Frankfurt Institute for Advanced Studies in Germany thinks the excitement surrounding the switch-on of the LHC has come back to haunt the field, going so far as to label the current situation in particle physics a "PR disaster". Before the LHC's launch in 2008, she says, some theorists expressed themselves confident that the collider would produce new particles besides the Higgs boson. "That hasn't happened. The big proclamations came almost exclusively from theoretical physicists; CERN didn't promise anything that they didn't deliver. That is an important distinction, but I am afraid in the public perception the subtler differences won't matter."

Cultural icon

At least for now, and in some countries, the LHC has become embedded in popular culture. The term "hadron collider" is the new "rocket science" – a term dropped into commentary and public discourse to denote the pinnacle of human ingenuity. The LHC has inspired books, films, plays, art and, crucially, adverts – in which firms have used high-production visuals to associate their brands with the standards of the LHC. The number of applications for physics degrees, in the UK at least, soared around the time that the LHC switched on, and the event also launched the television career of ATLAS physicist Brian Cox, who went on to further engage a primed public. Annually, around 300,000 people apply to visit CERN, less than half of whom can be accommodated.

If the communications surrounding the LHC have proved one thing, it is that there is an inherent interest among huge swathes of the global population in the substance of particle physics. Highfield, who is now director of external affairs at the Science Museum in the London, sees this on a daily basis. "Although I think physicists would have liked to have seen more surprises, I know from my work at the Science Museum that the public has a huge appetite for smashing physics," he says. In November 2013, the Science Museum launched *Collider*, an immersive exhibition that blended theatre, video and sound art with real artefacts from CERN to recreate a visit to the laboratory. The exhibition went on international tour, finishing in Australia in April 2017, having pulled in an audience of more than 600,000 people. "Yes, the public still cares about the quest to reveal the deepest secrets of the cosmos," says Highfield.

From a communications perspective, the switch-on of the LHC proves the importance of a clear strategy, the rewards from taking risks, and the difficulty in keeping control of a narrative. For Evans, the LHC changed everything. "Of all the machines that I've worked on, never before has there been such interest," he says. "Before the LHC, no one knew what you were talking about. Now, I can get into a cab in New York or speak to an immigration officer in Japan, and they say: oh, cool, you work at CERN?".

CERN-HI-1207138-38

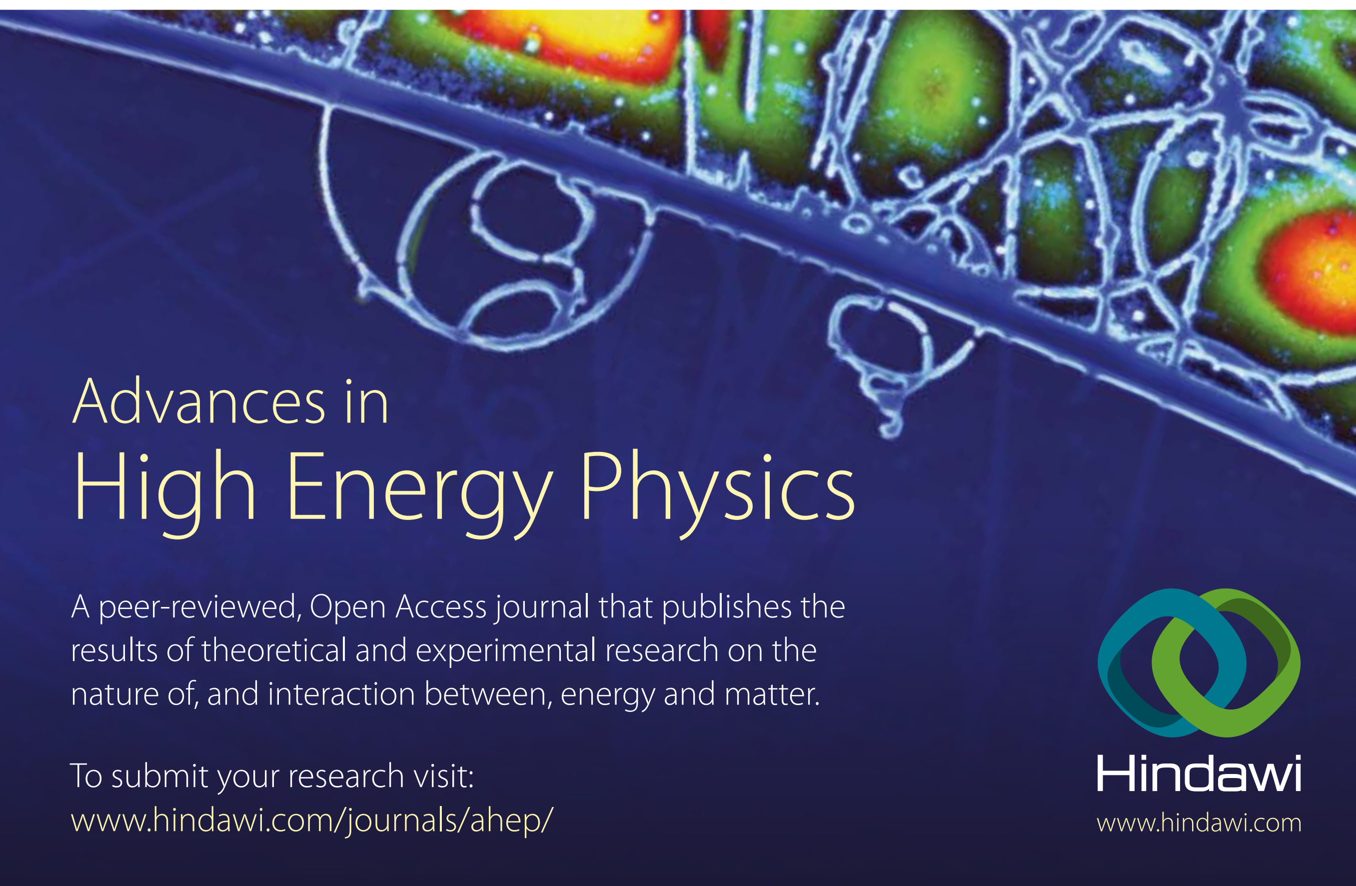
Journalists at a press conference at CERN on 4 July 2012, following results presented by ATLAS and CMS in the main auditorium.

Résumé

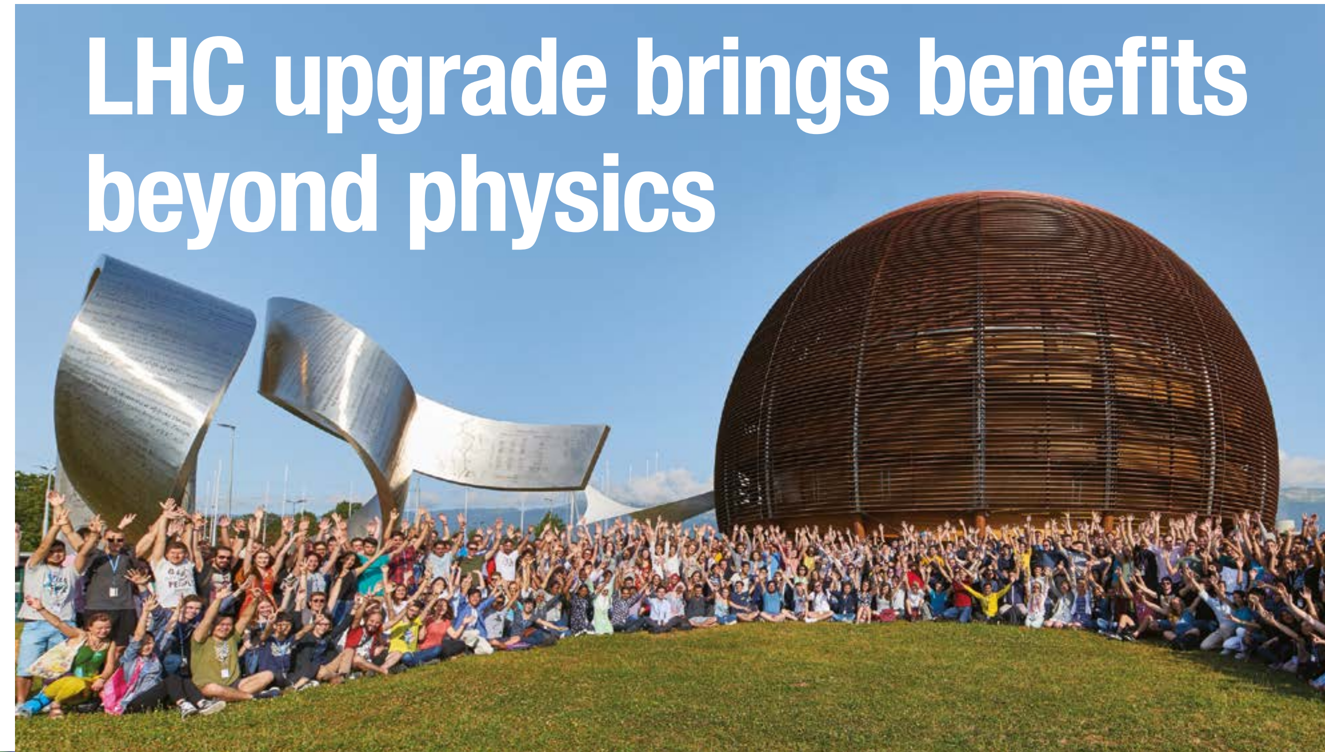
Le jour où le monde s'est mis à l'heure de la physique des particules

De toutes les aventures humaines qui ont attiré l'attention du monde, les événements du 10 septembre 2008 figurent sans doute parmi les plus bizarres. À 10 h 28, heure locale, par un beau mercredi de fin d'été, un paquet de protons a parcouru un tube souterrain de 27 km de circonférence – et on estime que plus d'un milliard de personnes ont suivi cet événement. Le jour des « premiers faisceaux » a été marqué par un nombre record de visites de la page web du CERN, quelque 2500 passages à la télévision, et environ 6 000 articles de presse. Il s'agissait à n'en pas douter du plus grand déploiement médiatique jamais vu dans le domaine de la science, et cet événement a propulsé la physique des particules, le LHC et le CERN sous les yeux du monde entier.

Matthew Chalmers, editor *CERN Courier*.



LHC upgrade brings benefits beyond physics



A recent analysis of the cost and benefits of the high-luminosity LHC reveals a quantifiable return to society in terms of scientific, economic and cultural value.

CERN is a unique international research infrastructure whose societal impacts go well beyond advancing knowledge in high-energy physics. These do not just include technological spillovers and benefits to industry, or unique inventions such as the World Wide Web, but also the training of skilled individuals and wider cultural effects. The scale of modern particle-physics research is such that single projects, such as the Large Hadron Collider (LHC) at CERN, offer an opportunity to weigh up the returns on public investment in fundamental science.

Recently, the European Commission (EC) introduced requirements for large research infrastructures to estimate their socioeconomic impact. A quantitative estimate can be obtained via a social cost–benefit analysis (CBA), a well-established methodology in economics. Successfully passing a social CBA test is required for co-financing major projects with the European Regional Development Fund and the Cohesion Fund. The EC's Horizon 2020 programme also specifically mentions that the preparatory phase of new projects that are members of the European Strategy Forum on Research Infrastructures (ESFRI) should include a social CBA.

Against this background, our team at the University of Milan in Italy was invited by CERN's Future Circular Collider (FCC) study to carry out a social CBA of the high-luminosity LHC (HL-LHC) upgrade project, also preparing the ground for further analysis of larger, post-LHC projects. Involving three years of work and extending an initial study concerning the LHC carried out between 2014 and 2016, the report assesses the HL-LHC's economic costs and benefits until 2038, once the machine has ceased operations. Here, we summarise the main findings of our analysis, which also includes the most comprehensive survey to date concerning the public's willingness to pay for CERN investment projects.

Estimating value

Since the aim of the HL-LHC project is to extend the discovery potential of the LHC after 2025, it is also expected to prolong its impact on society. To evaluate such an effect, we require a CBA model that estimates the expected net present value (NPV) of a project at the end of a defined observation period. The NPV is calculated from the net flow of discounted benefits generated by the investment. Uncertainty surrounding the estimation of costs and benefits is tackled with Monte Carlo simulations based on probabilities attached to the variables underlying the analysis. For the HL-LHC, the relevant benefits were taken to be: the value of

Image: CERN's 2018 intake of summer students; training for young researchers is estimated to be one of the biggest benefits of the HL-LHC upgrade to wider society. Credit: CERN-201807-172-36.

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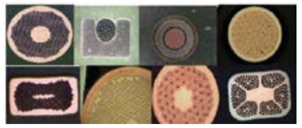

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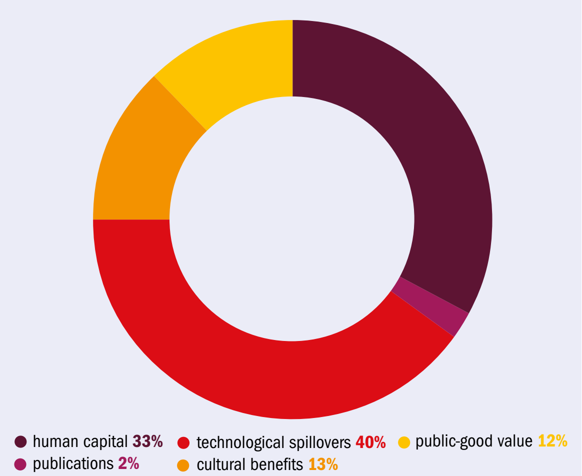

Fig. 1. The total identified benefits of the HL-LHC broken down by contribution: 1993–2038.

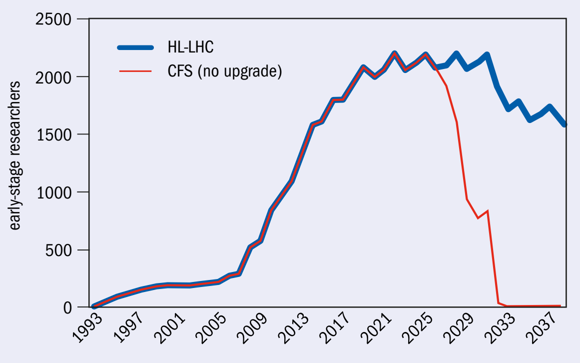

Fig. 2. The number of early-stage researchers over the period 1993–2038 for the HL-LHC (thick line) and for the counterfactual scenario with no upgrade (CFS, thin line). Early-stage researchers are technical students, doctoral students and post-doctoral researchers younger than 30 years of age who are enrolled in a CERN education programme, as well as CERN-registered users who are between 30 and 35 years of age.

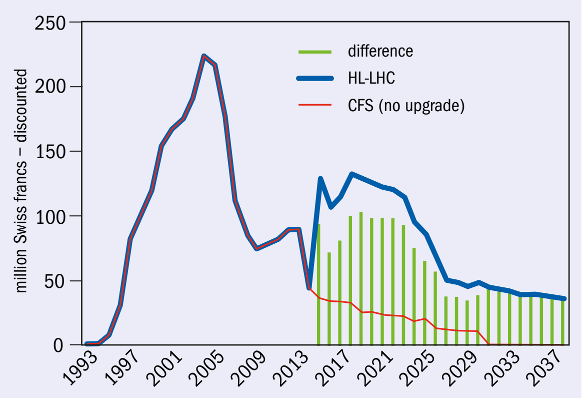

Fig. 3. Benefits for high-tech suppliers to CERN: 1993–2038. The figure shows the discounted benefits over the 1993–2038 period for the HL-LHC (thick line), counterfactual scenario (CFS, thin line) and their difference (bars).

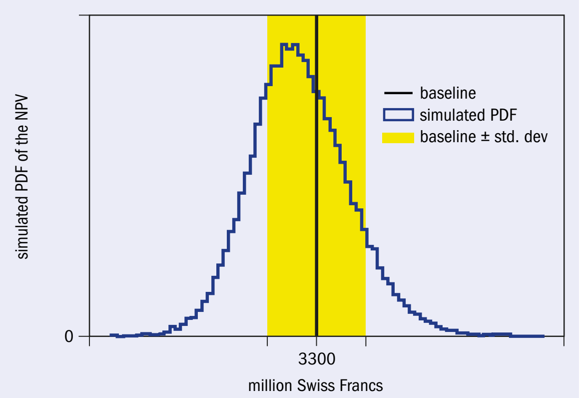

Fig. 4. Simulated probability density function (PDF) of the net present value (NPV) of the HL-LHC based on 50,000 Monte Carlo runs. The baseline value (vertical black line) is an initial "best guess" based on the extent and shape of the distribution.

training for early-stage researchers; technological or industrial spillovers to industry; cultural effects for the public; academic publications for scientists; and the public-good value for citizens (figure 1). A research infrastructure passes the CBA test when, over time, the cumulated benefits exceed its costs for society, i.e. when the expected NPV is greater than zero. It is the methodology of a CBA not to account for scientific discoveries and results, since the aim of such studies is to quantify extra benefits that come from this type of investment.

Each Swiss franc invested in HL-LHC pays back approximately 1.8 Swiss francs in societal benefits.

Two scenarios were considered: a baseline scenario with the HL-LHC upgrade and a counterfactual scenario that includes the operation of the LHC until the end of its life without the upgrade. In both scenarios, the total costs include past and future expenditures attributed to the LHC accelerator complex and by the four main LHC experiment collaborations: ATLAS, CMS, LHCb and ALICE. The difference between the total cost (which includes capital and operational expenditures) in the two scenarios is about 2.9 billion Swiss francs.

HL-LHC benefits

For the HL-LHC, one of the most significant benefits, representing at least a third of the total, was the value of training for early-stage researchers (figure 2). It was shown that the 2038 cohort of early-

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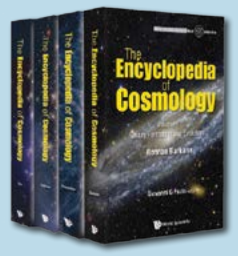

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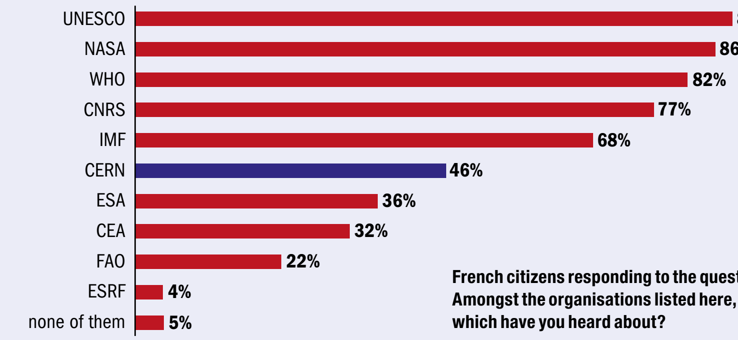
The perception of CERN and its value as a public good

CERN advances knowledge about the nature and the origins of the universe. In that sense, the activity/product of its research can be considered a public good. The "public good value" represents the benefit due to the citizens' preference for new knowledge that might be generated even if practical applications are still unknown. The adjective "public" relates to the idea that the use by one individual does not reduce its value and availability to others. This is very much like the social preference for the conservation of biodiversity or of cultural heritage. But to what extent is the public actually willing to pay for supporting particle-physics research at CERN and, specifically, the laboratory's plans to expand its current accelerator complex? Such a general question can be translated into two specific objectives: the first assesses the public's awareness about CERN (see figure), and the second measures people's willingness-to-pay based on two investment scenarios.

To meet these objectives, the FCC Study asked the University of Milan to design a survey addressed to French citizens. Then, CERN selected the polling firm Eumetra MR for the sampling and interviews of 1005 adults. The survey, after careful preparation that lasted two years, including consultation with CERN staff and international experts, and pre-testing, was launched in February 2018, in compliance with best practice in the field. It targeted a representative sample of the adult French population in terms of income, education, gender and age, and rigorous statistical standards were applied. The main difference between this survey and previous studies about the image of CERN or how CERN is perceived is that questions about the willingness to financially contribute to new particle accelerators through taxation were introduced, following the most updated international academic standards and techniques used to elicit people's preferences.



French citizens responding to the question: Amongst the organisations listed here, which have you heard about?

The survey conveyed several main results. The first is that the awareness of what CERN and its research activities are is much less than that for other international organisations such as UNESCO, NASA, WHO, IMF and the CNRS (the French National Centre for Scientific Research). Second, the study revealed a large attitude divide between respondents who are willing to pay (51%) and respondents who say that they cannot or do not want to contribute (49%); the willingness to pay is higher for those people who are aware about what CERN is and what it does.

Last but not least, two measures of the public's willingness-to-pay for CERN were estimated: a maximum "unconditional sample average", which amounts to €13.5 per person per annum; and a lower "bounded conditional sample average", which amounts to €4 per person per annum. The latter is calculated by taking into account the respondents' socioeconomic characteristics (income, gender, education, age) and their interests and opinions (being interested in physics, agreeing that CERN contributes to increased knowledge of the universe, and being aware about CERN).

It is interesting to compare these results to the actual contribution of French citizens to CERN through taxation, which in 2017 amounted to €2.7 per person per annum. Therefore, even considering the most conservative estimate, French citizens' willingness to pay €4 to support CERN's investments in particle-physics research is higher than their actual tax contribution by a factor of 1.5.

The survey shows that there is potential for raising public awareness about CERN's research activities. In fact, respondents who are more aware are also the ones willing to contribute more to CERN's research programmes.

stage researchers will enjoy a "salary premium" due to their experience at the HL-LHC or LHC until 2080, as confirmed by surveys of students, formers students and more than 330 team leaders.

The economic benefit from industrial spillovers, software and communication technologies is another major factor, together representing 40% of the project's total benefits. Software and communication technology represents 24% of the total benefits in this category, while the rest comes from the additional profits for high-tech companies involved in the HL-LHC (figure 3). We looked at the value of hi-tech procurement contracts for the HL-LHC, drawing from three different empirical analyses: an econometric study of the company accounts in the long-term, before and after the first contract with CERN; a survey of more than 650 CERN suppliers; and 28 case studies. In the case of HL-LHC, incremental profits for firms represent 16% of the total benefits from sales to customers other than CERN, and this percentage increases to 29% if we consider the difference between HL-LHC and the counterfactual scenario of no HL-LHC upgrade.

CERN and society

Cultural effects, while uncertain because they depend on future announcements of discoveries and communication strategies, were estimated to contribute 13% to the total HL-LHC benefits. More than half of this comes from onsite visitors to CERN and its travelling exhibitions.

Contributing just 2% of the total benefits in the HL-LHC scenario, scientific publications (relating to their quantity and citations, not their contents) represent the smallest overall socio-

CERN-GE-1005103-50

The exhibition Universe of Particles *in CERN's Globe of Science and Innovation — one of the contributors to CERNs cultural impact.*

economic benefit category. This is expected given the relatively small size of the high-energy physics community compared to other social groups.

The public-good value of HL-LHC, estimated to be 12% of the total, was inferred from a survey of taxpayers' willingness to pay for a research infrastructure such as CERN. A first estimate was carried out in our assessment of the LHC benefits published in 2016, but recently we have refined this estimate based on an extensive survey in one of CERN's two host states, France (see box on previous page). A similar survey is planned in CERN's other host state, Switzerland.

Taking all this into account, including the uncertainties in critical variables and relying on Monte Carlo simulations to estimate the probabilities of costs, benefits and the NPV of the project, our analysis showed that the HL-LHC has a clear, quantifiable economic benefit for society (figure 4). Overall, the ratio between the incremental benefits and incremental costs of the HL-LHC with respect to the continued operation of the LHC under normal consolidation (i.e. without high-luminosity upgrade) is 1.8. This means that each Swiss franc invested in the HL-LHC upgrade project pays back approximately 1.8 Swiss francs in societal benefits, mainly stemming from the value of the skills acquired by students and postdocs, and from industrial spillovers. The study is also based on very conservative assumptions about the potential benefits.

What conclusions should CERN draw from this analysis? First, given that the benefits to early-stage researchers are the single most important societal benefit, CERN could invest more in activities facilitating the transition to the international job market. Similarly, cooperative relations with suppliers of technology and the development of innovative software, data storage, networking and computing solutions are strategic levers that CERN could use to boost its social benefits. Finally, cultural effects, especially those related to onsite visitors and social media, have great potential for generating societal benefits, hence outreach and communication strategies are important.

There are also lessons regarding CERN's investments in future particle accelerators. The HL-LHC project yields significant socio-economic value, well in excess of its costs and in addition to its scientific output. Extrapolating these results, it can be expected that future colliders at CERN, like those considered by the FCC study, would bring the same kind of social benefits, but on a bigger scale. Further research is needed on the socio-economic impact of new long-term investment scenarios.

Further reading

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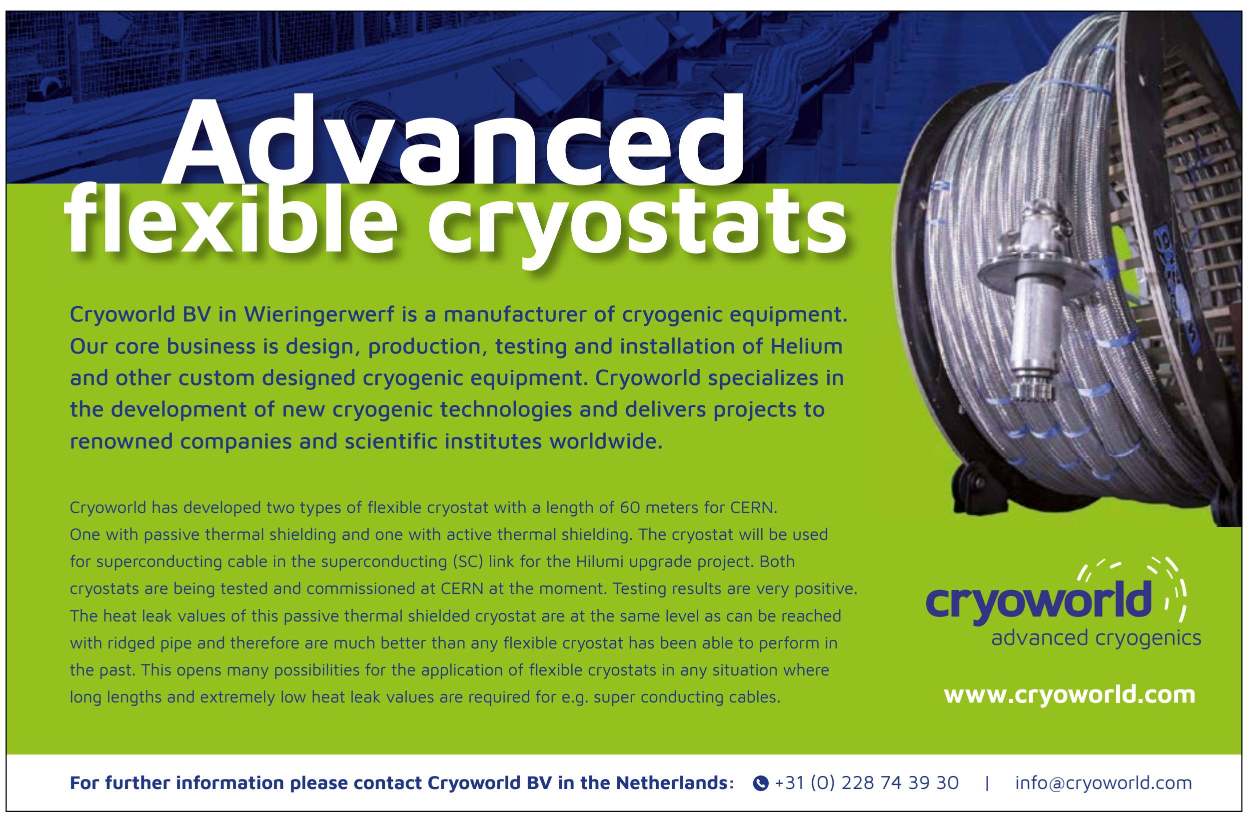
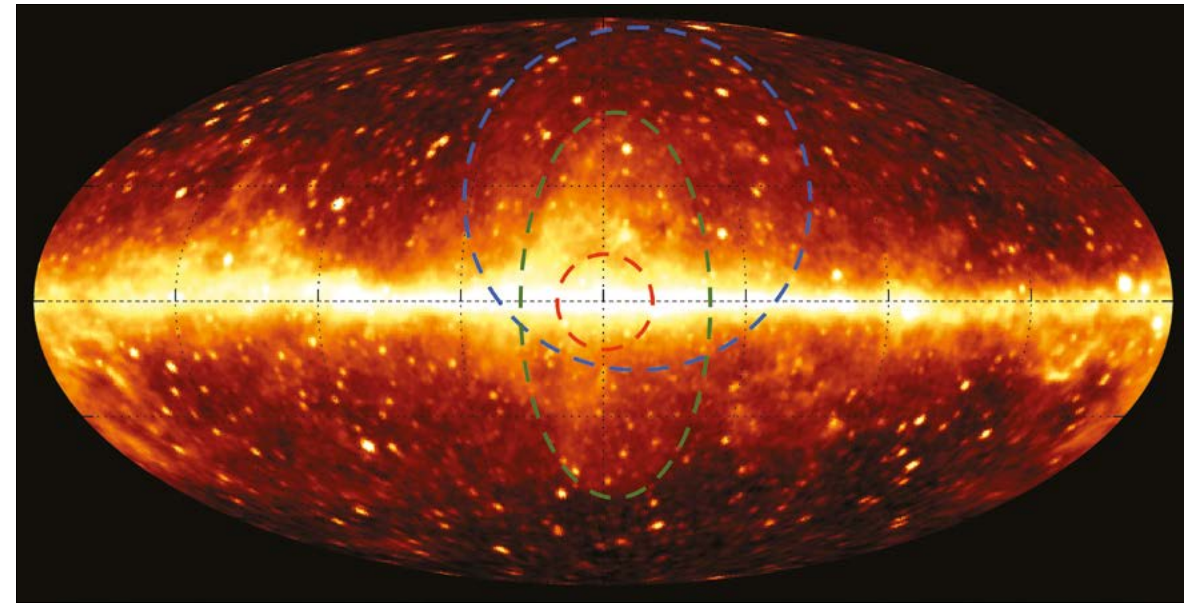
Résumé

Des retombées au-delà de la physique pour l'amélioration du LHC

Le CERN est un institut de recherche international unique en son genre, dont les retombées sur la société dépassent largement la sphère des progrès de la connaissance en physique des hautes énergies. Ces retombées comprennent non seulement les avancées technologiques et les bénéfices pour l'industrie, ou des inventions exceptionnelles telles que le world wide web, mais aussi la formation de spécialistes et des effets culturels plus généraux. Une analyse récente des coûts et des bénéfices du HL-LHC a montré des retombées quantifiables pour la société en termes de valeur scientifique, économique et culturelle. Cette analyse prépare également le terrain pour des études ultérieures du même type, qui porteront sur des projets plus grands, après le LHC.

Andrea Bastianin and **Massimo Florio**, University of Milan; **Francesco Giffoni**, CSIL Centre for Industrial Studies Milan.





Fermi-LAT

Elephants in the gamma-ray sky

The discovery of large-scale features in the gamma-ray sky in approximately the same direction continues to puzzle researchers, calling for multi-wavelength observations with the next generation of telescopes.

High-energy gamma rays provide a window into the physics of cosmic objects at extreme energies, such as black holes, supernova remnants and pulsars. In addition to revealing the nature of such objects, high-energy gamma-ray signals test general relativity and the Standard Model of particle physics. Take for example gamma-ray bursts, which can last from 10 milliseconds to several hours and are emitted by sources located up to several billion light-years away from Earth. A comparison between the arrival times of the bursts' X-rays and gamma rays has been used to exclude modifications of Einstein's general relativity that predict different arrival times. Also, in some theories in which dark matter is in the form of weakly interacting massive particles (WIMPs), dark-matter particles can annihilate into gamma-ray photons and other Standard Model particles. Significant effort is therefore being spent in searches for dark-matter annihilation signals in the gamma-ray band, including searches towards the Milky Way centre, which is estimated to contain a large amount of dark matter.

Studies of individual gamma-ray emitting sources and diffuse gamma-ray emission, which could include a galactic dark-matter annihilation signal, have benefited greatly from the launch of the large-area telescope on board NASA's Fermi Gamma-ray Space Telescope (Fermi-LAT) in June 2008. Fermi-LAT, which observes gamma rays with energies from about 20 MeV to 1 TeV, has discovered more than 3000 point sources that have enabled researchers to significantly improve models of known galactic and extragalactic gamma-ray-emitting objects. But Fermi-LAT has also thrown up some surprising discoveries (figure 1). One of these is the so-called Fermi bubbles – two large gamma-ray lobes above and below the galactic centre that, intriguingly, have no clear counterpart in the X-ray and radio bands.

A second unexpected discovery by Fermi-LAT was an excess of gamma-ray radiation near the galactic centre with an energy of a few GeV. Interestingly, the excess has properties that are consistent with an annihilation signal from dark-matter particles with a mass of a few tens of GeV. The excess is visible up to 10 or 15 degrees away from the galactic centre – an elephant at a distance of four metres from an observer would have a similar apparent size.

Fig. 1. (Above) View of the gamma-ray sky constructed from 6.5 years of 1–6.5 GeV data from the Fermi-LAT telescope, with outlines of Loop I (blue), the Fermi bubbles (green) and an approximate extension of the galactic-centre GeV excess (red). The colours denote the strength of the gamma-ray emission, from low (black) to high (yellow).

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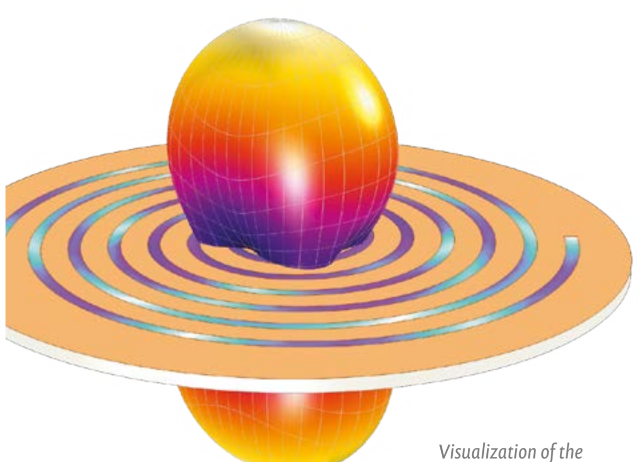
AT THE HIGHEST LEVEL

Heinzinger has played a role in research for a very long time thanks to its expertise and passion. In addition to the European CERN facility in Geneva, companies, universities, colleges and state institutions are investing in research. Whether it be testing and measuring equipment, accelerator technology or HV power supplies for particle detectors: High-specification technical equipment from Heinzinger helps to produce reliable and resilient results in laboratories and testing centers all over the world.



Visualization of the log-scaled norm of the electrical field on the slotted surface and far-field radiation pattern of a spiral slot antenna.

This spiral antenna was optimized with EM simulation.

Wireless communication, sensing, positioning, and tracking. All of these technologies can take advantage of the spiral slot antenna's consistent radiation pattern and impedance over a large bandwidth. To optimize spiral slot antenna designs for particular applications, engineers can turn to EM analysis software that calculates S-parameters and far-field patterns.

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The Fermi bubbles, spanning 110 degrees from the northern to the southern edge, have an apparent size comparable to that of an elephant located one metre away.

Finally, there is a third, even larger, feature in the gamma-ray, radio and X-ray bands called Loop I. The challenge of explaining these three "elephants" in the gamma-ray sky has puzzled physicists and astronomers for years – tens of years in the case of Loop I. Are the features related to each other? Are they located near the galactic centre or close to us? And is the GeV gamma-ray excess caused by dark-matter annihilation or by astrophysical phenomena such as pulsars?

Loop I

The largest of the gamma-ray elephants, Loop I, has been known since the 1950s from its radio emission (figure 2a). Its large angular size – it stretches up to 80 degrees above the galactic plane – could easily be explained if it were a nearby feature. For instance, it could be the combined emission from a "superbubble", the collective remnant of several supernova explosions taking place in a localised region. Such a bubble easily reaches a size of a few hundred light-years, and if the distance to the bubble was also a few hundred light-years, then it would appear very large, up to 90 degrees in angular size. In this scenario, the galactic magnetic field would drape around the expanding bubble and high-energy cosmic-ray electrons from sources in the galactic disk, compressed by the expansion of the bubble, would produce synchrotron emission that would appear as a huge, ring-like structure in the sky. A possible location of the underlying supernova explosions would be the Scorpius–Centaurus stellar cluster located a few hundred light-years away from Earth.

Loop I, or at least its brightest part, known as the North Polar Spur, is also seen at other wavelengths, in particular at gamma-ray (figure 1) and soft X-ray (figure 2b) wavelengths. While the gamma rays can be produced through inverse Compton emission by the same cosmic-ray electrons that produce the synchrotron radio emission, the soft X-ray emission is probably produced by hot interstellar gas. The approximate angular alignment between the radio and X-ray emissions of the North Polar Spur suggests that they both belong to Loop I. Yet there are several differences between the X-ray and radio emissions. For example, a bright, ring-like feature in X-rays that is crossing the North Polar Spur could be explained by the collision of the hypothetical Loop I superbubble with another bubble containing the solar system, the local hot bubble. One can even trace back the motion of stars within a few hundred light-years from us to find a population of stars with members that could have exploded as supernovae up to about 10 million years ago and inflated the local hot bubble.

However, apparent X-ray absorption at the southern part of the North Polar Spur by neutral gas located along the line of sight points to a different interpretation. Detailed spectral modelling of this absorption has recently shown that the amount of gas required to explain the absorption puts the X-ray emitting structure at distances far beyond a few hundred light-years. This lower bound on the distance to the X-ray structure favours models of Loop I as a galactic-scale phenomenon, for example the product of a large-scale outflow from the galactic-centre region, as opposed to the nearby superbubble. More X-ray data is needed to pin down the nature of Loop I, but if this feature is indeed a large-scale galactic structure, then it might be related to the second elephant in the sky – the Fermi bubbles.

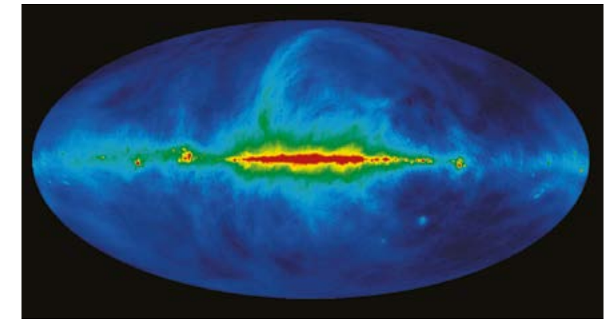


Fig. 2(a). The radio sky at 408 MHz as observed by a suite of radio telescopes, including the Parkes and Jodrell Bank telescopes, and cleaned by Remazeilles and colleagues (see further reading). Red represents higher intensity. Loop I is the ring-like structure seen in the Northern hemisphere. Image credit: NASA Legacy Archive for Microwave Background Data Analysis.

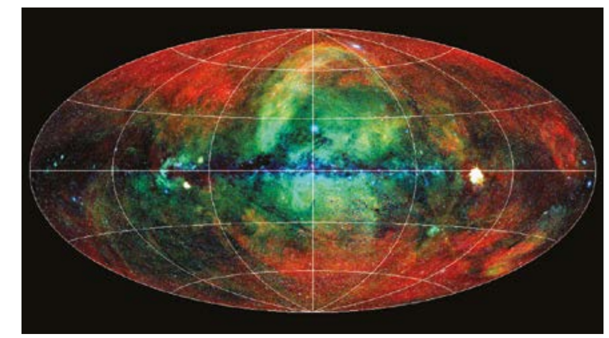
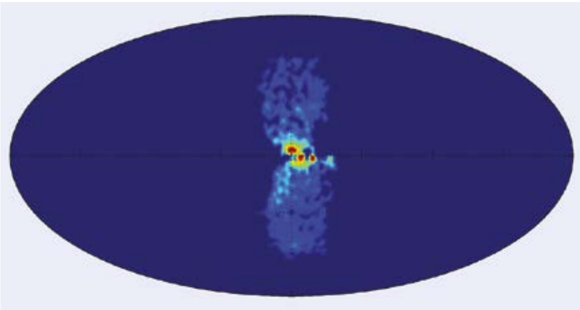


Fig. 2(b). Composite image of the X-ray sky as seen by the ROSAT satellite. Blue denotes higher energies (0.9–2 keV), green middle energies (0.5–0.9 keV) and red lower energies (0.1–0.4 keV). Loop I is the ring-like structure seen in the Northern hemisphere. Image credit: Max Planck Institute for Extraterrestrial Physics.

Fermi bubbles

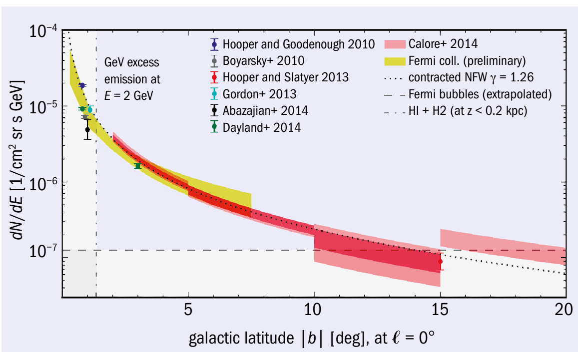
The Fermi bubbles consist of two large gamma-ray lobes above and below the galactic centre, each of which is slightly larger than the distance from Earth to the galactic centre (about 25,000 light-years). They appear smaller than Loop I and were discovered in 2010 with about a year and a half of Fermi-LAT data. From observations of galaxies other than the Milky Way, we know of two possible mechanisms for creating such bubbles: emission from a supermassive black hole at the galactic centre, or a period of intensive star formation (a starburst) and supernova explosions. Which of these processes is responsible for the formation of the Fermi bubbles in our galaxy is not yet known.

Even the mechanism for producing the gamma rays in the first place is not yet resolved: it could be due to interactions between cosmic-ray protons and galactic gas, or inverse Compton scattering of high-energy electrons off interstellar radiation fields. Both



Fermi-LAT

Fig. 3. An all-sky model of the Fermi bubbles derived from the Fermi-LAT data for gamma rays with energies between 1 GeV and 9 GeV. The emission is stronger (red) near the galactic plane than away from it. A slight displacement of the Fermi bubbles from the galactic centre to the right is visible.



Calore *et al.* 2015

Fig. 4. Profile of the GeV-excess intensity as a function of galactic latitude, as measured by various groups. The emission extends from the galactic centre to at least 10–15°, and is compatible with that from a slightly contracted dark-matter-halo profile (dotted line).

of these options have caveats. For the first, it's unclear, for instance, how one can collect and keep the high density of cosmic rays required to compensate for the low density of gas at large distances from the galactic plane. It's also unclear whether the pressure of cosmic rays will expel the gas and create a cavity that will make the gas density even lower. For the inverse-Compton-scattering hypothesis, one would need electrons with energies up to 1 TeV. If these electrons were accelerated to such energies at the beginning of the expansion of the Fermi bubbles, then the bubbles' expansion velocity would be about 10,000 km s^{-1} – at least 10 times larger than the typical observed outflow velocities.

Moreover, even though the Fermi bubbles are similar in shape to gamma-ray lobes in other galaxies, which are typically visible in X-ray and radio wavelengths, they have no clear counterpart in X-rays and radio waves at high latitudes. Perhaps the Fermi bubbles are unique to the Milky way. Then again, perhaps astronomers have simply struggled to detect in other galaxies gamma-ray lobes that are "quiet" in the radio and X-ray bands.

A study of the gamma-ray emission from the Fermi bubbles at low latitudes could shed light on their origin, as it may point to the supermassive black hole at the galactic centre or to a region away from the centre, which would support the starburst scenario. Although the diffuse foreground and background gamma-ray emission from the Milky Way near the galactic centre is very bright, making it hard to interpret the observations, several analyses of Fermi-LAT gamma-ray data have revealed an increased intensity of gamma-ray emission from the Fermi bubbles near the galactic plane and a displacement of the emission relative to the galactic centre (figure 3). The higher intensity of the emission at the base of the Fermi bubbles opens up the possibility for a detection with ground-based very-high-energy gamma-ray Cherenkov telescopes, such as the upcoming Cherenkov Telescope Array, which is expected to start taking data with a partial array in 2022 and with the full array in 2025. At low energies, below 100 GeV, the flux from the base of the Fermi bubbles may also be confused with the third elephant in the sky – the galactic-centre GeV excess.

Galactic-centre GeV excess

The first hints of an extended excess of gamma rays from the centre and bulge of the galaxy at energies around a few GeV and with an almost spherical morphology were presented in 2009, before the discovery of the Fermi bubbles. However, given that the diffuse foreground gamma-ray emission along the galactic plane is very bright, and also rather uncertain towards the galactic centre, it took a long time to prove that the excess is not caused by mis-modelling of foreground components (such as inverse Compton scattering of high-energy electrons and hadronic interactions of the stationary distribution of cosmic rays along the line of sight). The spectrum of the excess has a peak at a few GeV, hence the name "GeV excess", whereas the components of the diffuse foreground have a power-law structure around a few GeV.

Intriguingly, the combined GeV centre and bulge emission has properties that are largely compatible with expectations from a dark-matter annihilation signal: the emission is extended, up to at least 10–15 degrees away from the galactic centre, with a profile that is consistent with that from a slightly contracted dark-matter-halo profile (figure 4). At energies below about 1 GeV, the gamma-ray emission grows steeply, and has a maximum at a few GeV with a cut-off or a significant softening at higher energies, which is expected for a signal from dark-matter annihilation.

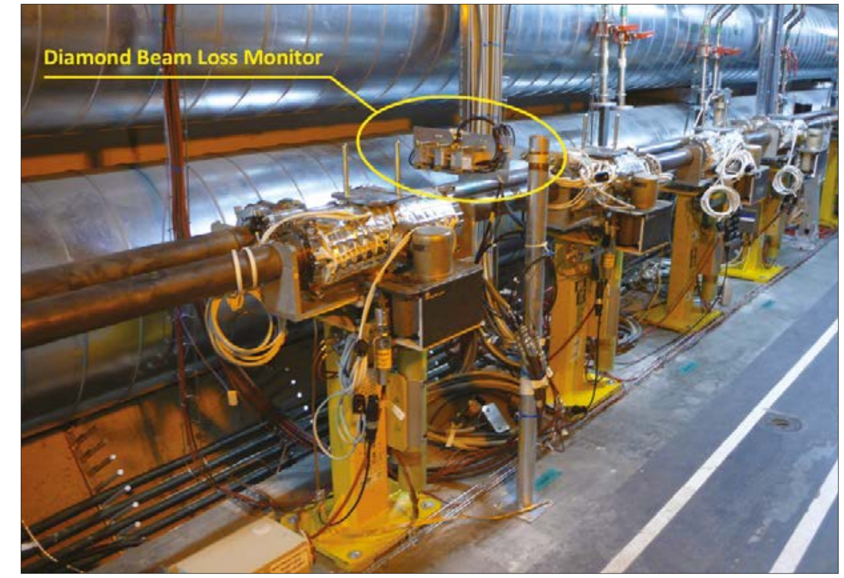
Given the high stakes of claiming a discovery of a dark-matter annihilation signal, corroborating evidence for this hypothesis must be found, or alternative astrophysical explanations must be confidently excluded. Unfortunately, neither has happened up to now. Quite the contrary: there are several sources of gamma-ray emission near the galactic centre that could, within uncertainties, together account for all of the bulge and centre emission. For example, massive molecular-gas clouds near the galactic centre show clear indications of star-formation activity, which results in cosmic-ray production and associated gamma-ray emission in the inner galaxy. While the hadronic cosmic rays from such activity are not likely to explain the GeV excess, because their gamma-ray emission is not as extended as the GeV excess, inverse Compton emission from cosmic-ray electrons linked with such an activity can be extended over many degrees and is expected to contribute

Advertising feature

10 Years of LHC Diamonds

by C. Weiss

Ten years ago, the machine of the superlatives went into operation at CERN. The Large Hadron Collider (LHC) is the world's largest, emptiest and coldest machine. It was built to find the heaviest particle predicted in the standard model of physics.



The CIVIDEC Diamond Beam Loss Monitor at the LHC collimation area IP7.

To achieve its goal technology was pushed to its cutting edge and, in order to protect this masterpiece of engineering from damage, an ultra-fast and radiation-resistant diagnostic system was developed for CERN, the Diamond Beam Loss Monitors (DBLMs).

In 2008 it was a group of visionaries who understood – in line with the old adage – that a machine is only as good as its diagnostics. The LHC was equipped with a diagnostic system capable of correlating beam losses with the individual bunches in the accelerator on a turn-by-turn basis. This proved to be a powerful tool for machine protection and development.

The DBLMs were developed in collaboration with the R&D company **CIVIDEC Instrumentation**, which focusses its research efforts on radiation diagnostic systems for the harshest environments. Following the vision to fully exploit the electronic properties of Chemical Vapour Deposition (CVD) Diamond for such applications, **CIVIDEC** now provides off-the-shelf solutions for a very wide and varied field of applications.

State of the art

Today, the DBLMs are used in the LHC and all its pre-accelerators, the full five-gear system of CERN, as part of the beam diagnostic system. They are installed as complementary instrumentation to the standard beam loss ionization chambers, which quantify beam losses on a turn-by-turn basis. The additional bunch-to-bunch information, provided by the DBLMs, makes it possible to qualify single-bunch instabilities or cross-talk in the machine and to measure the tune of single LHC bunches.

DBLMs have been in operation in the collimation area (IP7) since the last start-up of the LHC in 2010. Their continuous operation since then proves their excellent radiation resistivity and reliability. Bunch-to-bunch beam loss analysis in real time is provided via the time loss histogram of the data Read Out System **ROSY®**, which was customized for the LHC-DBLMs.

This technological innovation for the LHC also led to further applications of CIVIDEC Diamond Beam Diagnostics for high-precision measurements. Nowadays, solutions for medical machines, cyclotrons, synchrotrons and linear accelerators are also provided by **CIVIDEC Instrumentation** for beam characterization, such as phase measurements for the stable operation of the machine during cancer treatments. In addition, various solutions for neutron and X-ray diagnostics are available, where the robustness of diamond sensors is again exploited.

A look into the future

The application of **CIVIDEC Diamond Detectors** at Linac4 for emittance monitoring, to optimize the beam parameters from an early stage in the CERN accelerator chain, provides a glimpse into the future of diamonds for LHC.

An exciting upgrade of the LHC-DBLMs is also about to be realized: the installation of cryo-DBLMs in the cold mass of LHC magnets for *in situ* beam loss diagnostics. And, no doubt, further diagnostic challenges to be solved with CVD diamond technology are yet to come.

Erich Griesmayer is CEO of CIVIDEC Instrumentation and has been working at CERN for more than 20 years. He is associated professor at the Vienna University of Technology and Member of ATLAS and n_TOF at CERN.

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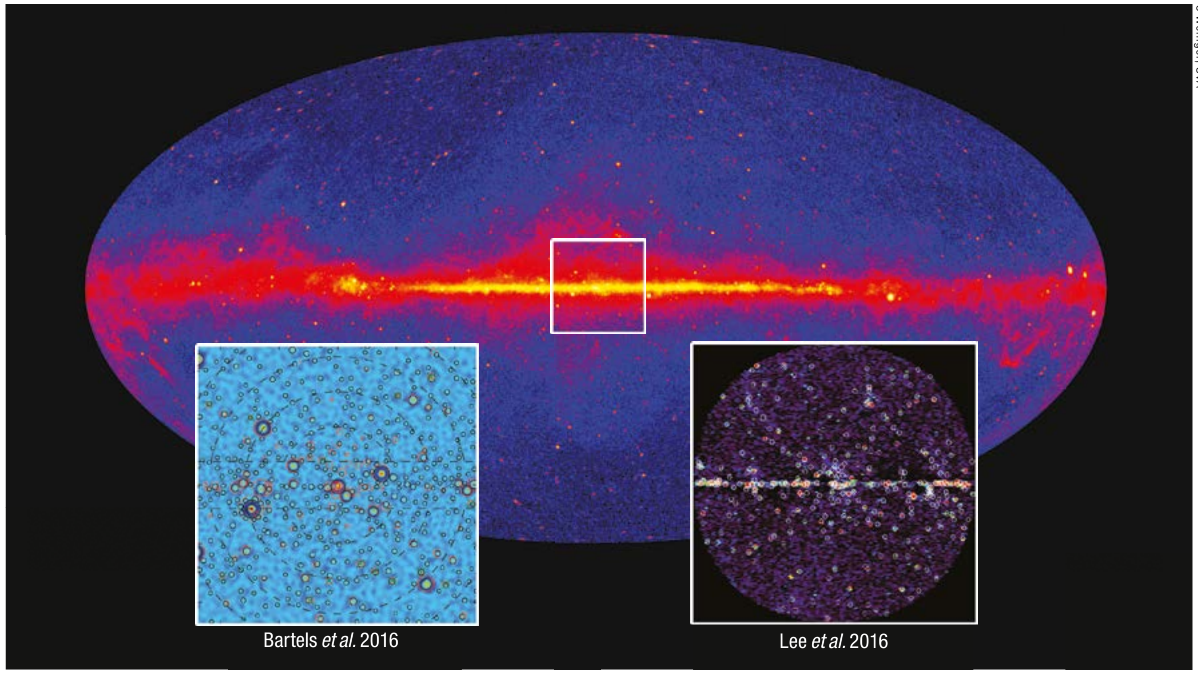

Fig. 5. Main picture: a gamma-ray image of the sky, as seen by Fermi LAT. The colour scale is similar to that of figure 1 but emphasises the bright disk emission. Insets: two independent statistical analyses suggest that the GeV-excess emission at the centre (small white box) is from a population of numerous but faint point sources.

to the GeV emission. However, given that the energy spectrum expected for this inverse Compton emission is significantly flatter than the observed GeV excess, it is unlikely that this component accounts completely for the GeV-excess emission.

Arguably, the most plausible explanation for the GeV-excess emission from the galactic bulge and centre is a population of thousands of millisecond pulsars – highly magnetised neutron stars with a rotational period of 1–10 ms. They can emit gamma rays for billions of years before they lose energy, and their gamma-ray spectrum, as observed by Fermi-LAT, is similar to the spectrum of the GeV excess. It is plausible that millisecond pulsars in the bulge follow a similar spatial distribution as the majority of bulge stars. Indeed, recent analyses showed that the profile of the GeV-excess emission in the inner galaxy is better described by the boxy stellar bulge, rather than by a spherically symmetric dark-matter profile. Moreover, several detailed statistical analyses found evidence that the emission is more likely to be from a population of numerous but faint point sources, such as millisecond pulsars in the bulge, rather than from truly diffuse emission, such as that resulting from the annihilation of dark-matter particles (figure 5).

Future observations with radio telescopes such as MeerKAT in South Africa, expected to start taking data this year, and its successor, the Square Kilometre Array (SKA), the first construction phase of which is expected to end in 2020, should be able to test whether millisecond pulsars exist in the inner galaxy and can explain the GeV excess.

Additional multi-wavelength observations will provide new information about the three elephants in the sky. In particular, the eROSITA experiment, the successor of the X-ray ROSAT satellite, will survey the whole sky in X-rays and will be one order of magnitude more sensitive than ROSAT. With the eROSITA data, astronomers will search for a possible cavity carved out by cosmic rays in the Fermi bubbles and will estimate the distance to the North Polar Spur using the absorption of soft X-rays from the spur by the distribution of gas along the line of sight.

Possible connections

On the high-energy gamma-ray front, the upcoming Cherenkov Telescope Array is expected to detect the Fermi bubbles near the galactic plane above a few hundred GeV. This detection should help to answer the question of whether the Fermi bubbles are linked to the galaxy's central supermassive black hole or to a different source away from the galactic centre. On the other side of the electromagnetic spectrum, the new generation of radio-telescope arrays, MeerKAT and SKA, should, as mentioned, be able to confirm or rule out the millisecond-pulsar hypothesis for the GeV excess. If the millisecond-pulsar hypothesis is excluded, then the dark-matter interpretation will remain as one of the plausible explanations. By contrast, a confirmation of the millisecond-pulsar hypothesis will significantly constrain the dark-matter hypothesis.

The presence of the three elephants in the gamma-ray sky in approximately the same direction raises the question of whether they are connected. One of the possible connections between the Fermi bubbles and Loop I is that Loop I is created by galactic gas pushed away by the expansion of the bubbles. In this case, the two elephants would become one, where Loop I is an outer part and the Fermi bubbles are an inner part. This scenario looks especially plausible for the northern bubble because Loop I extends beyond it.

The overlap between the GeV excess and the Fermi bubbles in the galactic-centre region provides the exciting possibility of a connection between the two. Models that try to explain the GeV excess with an additional population of cosmic-ray electrons, star formation and cosmic-ray acceleration processes, can connect the gamma-ray emission in the bulge with that at higher latitudes in the Fermi bubbles. Also, the mechanism underpinning the formation of the bubbles – whether it is linked to activity of the galaxy's central supermassive black hole or to a burst of star formation – might affect the properties of the GeV excess. Future observations and analyses will help to settle the nature – common or not – of the three elephants in the sky, and might point to new physics such as dark-matter annihilation in the Milky Way. Studying the gamma-ray sky will no doubt be an exciting journey for many years to come.

Further reading

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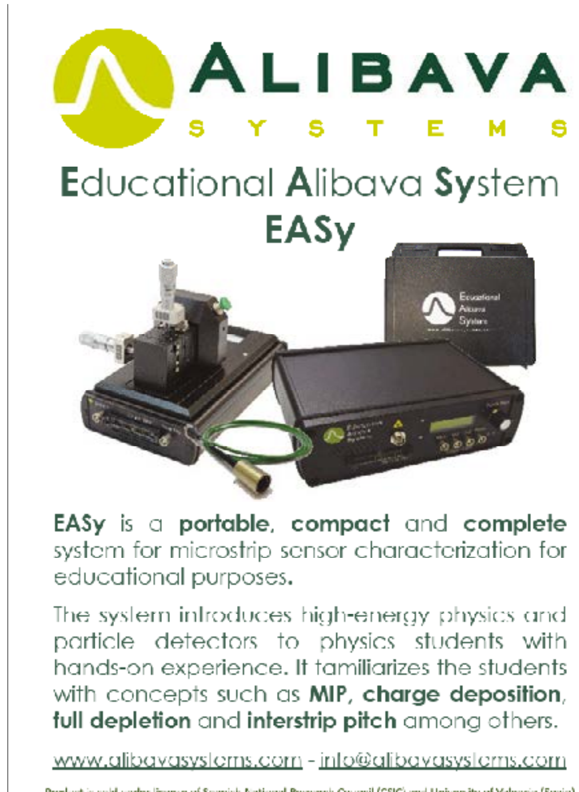
Résumé

Des mastodontes dans le ciel du rayonnement gamma

Le télescope spatial Fermi de la NASA a dévoilé plusieurs éléments inhabituels dans le ciel des rayons gamma. Le premier de ces phénomènes étranges est l'existence de deux grands lobes de rayons gamma, au-dessus et au-dessous du centre de la galaxie, qui n'ont pas d'équivalent clair dans les bandes des rayons X et des ondes radio. Un autre phénomène notable est l'observation d'un excédent de rayonnement gamma, d'une énergie de quelques GeV, à proximité du centre de la galaxie. Enfin, un troisième phénomène, d'une ampleur encore plus grande, apparaît dans les bandes des rayonnements gamma, des ondes radio et des rayons X ; celui-ci est appelé « Loop I ». La difficulté d'expliquer la présence de ces trois « mastodontes » dans le ciel des rayons gamma intrigue les physiciens et les astronomes depuis des années.

Stefan Funk and **Dmitry Malyshev**, Erlangen-Nürnberg University, **Philipp Mertsch**, RWTH Aachen University and **Christoph Weniger**, University of Amsterdam.



Faces & Places

Awards

IOP award winners for 2018 announced

Each year, the UK Institute of Physics (IOP) recognises outstanding and exceptional contributions to physics. 2018 sees five awards go to those working in high-energy physics and related fields.

Jenny Thomas from University College London received the Michael Faraday Medal and Prize "for her outstanding investigations into the physics of neutrino oscillations, in particular her leadership of the MINOS/MINOS+ long-baseline neutrino-oscillation experiment". MINOS was one of the seminal oscillation experiments, confirming that accelerator neutrinos change type as they travel. Thomas was one of a handful of people who orchestrated the formation of the collaboration, becoming co-spokesperson in 2010 and leading the proposal of a new phase of the MINOS experiment, MINOS+.


J Thomas, KCL, S Bates, M Alexander, R Hahn/Fermilab, J Ramage

Prize winners (clockwise from top left): Jenny Thomas, Bobby Acharya, Michael Begg, Hiranya Peiris, Stefan Söldner-Rembold and James Ramage.

Bobby Acharya from the International Centre for Theoretical Physics in Italy and King's College London won the Lawrence Bragg Medal and Prize "for his contributions as the driver of several projects to teach and promote physics in the developing world, with the ultimate aim of developing sustainable physics research in those countries". Acharya is involved with the ATLAS experiment at the LHC, and specialises in the phenomenological consequences of string/M-theory.

The winners of the Katharine Burr Blodgett Medal and Prize, awarded for outstanding and sustained contributions to the organisation or application of physics in an industrial or commercial context, were Michael Begg and James Ramage from Tesla Engineering Ltd "for the transformation of Tesla Engineering Ltd from a manufacturer of conventional magnets for particle accelerators into a world leader of magnets for high-energy physics, MRI and oncology equipment".

Stefan Söldner-Rembold from the University of Manchester received the James Chadwick Medal and Prize, reserved for distinguished contributions to particle physics, in recognition of "his contributions to pioneering experimental work in high-energy particle physics and his international leadership in Higgs and neutrino physics". Söldner-Rembold is co-spokesperson of the Deep Underground Neutrino Experiment (DUNE) and has held many leadership roles, including being spokesperson of the D0 experiment at Fermilab from 2009 to 2011.

Finally, the Fred Hoyle Medal and Prize, made for distinguished contributions to astrophysics, gravitational physics or cosmology, went to Hiranya Peiris from University College London and the Oskar Klein Centre for Cosmoparticle Physics, Stockholm. She was cited "for her leading contributions to understanding the origin and evolution of cosmic structure, by pioneering an interdisciplinary approach that combines theoretical, statistical and observational cosmology, astrophysics, numerical relativity and theoretical physics".

The award ceremony will take place on 20 November at the Royal Lancaster London Hotel.

Markov prize for Boos and Gorbunov


INR RAS

From left to right: Valery Rubakov, co-chairman of the Markov Readings; 2018 laureates Eduard Boos and Dmitry Gorbunov; and Leonid Kravchuk, director of INR RAS.

The Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS) has awarded its 2018 Markov prize to Eduard Boos from Lomonosov Moscow State University and Dmitry Gorbunov from INR RAS for their "outstanding contributions to the theoretical studies of hypothetical elementary particles and developments of methods for their experimental search". Boos was recognised for, among other achievements, participating in the creation of a new method of event simulation that takes into account loop corrections and a new method of optimising kinematical variables. Gorbunov was recognised for, among other things, the development of an experimental programme to search for new physics in the goldstino sector and suggesting direct experimental tests of the minimal extension of the Standard Model, in addition to putting forward the idea that blazars are sources of ultra-high-energy cosmic rays (see p7). The award was presented at the 15th Markov Readings, a series of international seminars held in commemoration of the prominent Russian scientist Moisey Markov, in Moscow on 13 May.

Young scientists Trnka and Gray win awards

Particle physicists Jaroslav Trnka and Heather Gray have each received a Young Scientist Prize in Particles and Fields from the International Union of Pure and Applied Physics (IUPAP). The prizes, each consisting of a medal and a €1000 cash award, were presented at the 39th International Conference on High Energy Physics in Seoul, Korea, on 4–11 July.

K Higgins

H Gray

Jaroslav Trnka (left) and Heather Gray received IUPAP Young Scientist Prizes in Particles and Fields.

Trnka, an assistant professor at the University of California, Davis, was awarded the prize "for the discovery and exploration of new physical and mathematical principles underlying the dynamics of particle scattering amplitudes in a wide range of theories".

Gray, a divisional fellow at Lawrence Berkeley Laboratory in the US, received the prize "for her broad and creative contributions as well as leadership in performance and physics analysis in the ATLAS experiment and beyond, culminating in her strong role in the searches and initial measurements of Higgs boson interactions with quarks".

Two researchers awarded CMS thesis honour

On 25 June, the CMS collaboration presented its annual PhD thesis awards to two recipients, Luca Cadamuro and Felice Pantaleo, from a total of 18 theses nominated. Theses written on any CMS-related topic, including physics analysis, simulation, computing, detector development and engineering, are eligible for nomination. The theses are critiqued on originality, clarity of writing and content, and impact on CMS and in high-energy physics. Cadamuro received his PhD from École polytechnique, University of Paris-Saclay, for his thesis work on a search for the production of two Higgs bosons. Pantaleo received his PhD from the University of Hamburg for his work on new track-reconstruction techniques for CMS.

CMS-PHO-COLLAB-2018-012-5

Luca Cadamuro (left) and Felice Pantaleo with their engraved plaques.

Filipino and Indian students win BL4S competition

High-school students from the International School of Manila, Philippines, and R.N. Podar School in Mumbai, India, were the winners of the 2018 Beamline for Schools (BL4S) competition – a CERN initiative open to high-school students from all over the world who want to get a taste of the life of a scientist. In September, the selected students will carry out their proposed experiments at CERN together with professional researchers. Overall, the competition involved more than 1500 students from 42 countries, from which 30 teams were shortlisted. Each will receive a cosmic-ray detector known as Cosmic Pi.

Cryptic Ontics

A screenshot of the application video of one of the winning teams.

The Filipino team, "Beamcats", consisting of three boys and three girls, proposed using pions for cancer therapy. They will simulate human tissues using materials that are similar in composition to the human body, and measure the energy lost by the beam while travelling through it. The Indian team,"Cryptic Ontics", comprises nine boys and nine girls and aims to study the deflection of protons and electrons in a magnetic field to learn about anomalies in the Earth's magnetic field.

APPOINTMENT

Larry Gladney named dean of diversity at Yale

Experimental particle physicist Larry Gladney of the University of Pennsylvania in the US has been appointed dean of diversity and faculty development for the Yale Faculty of Arts and Sciences – a new role intended to promote equity and inclusion.

Gladney's research career has focused on the study of weak interactions of heavy quarks and the experimental examination of dark energy. He is currently working on the planning and simulation of the Large Synoptic Survey Telescope, an observatory under construction in Chile that is designed to measure the expansion history of the universe. Gladney will continue to carry out research and teach once he takes up the new role in January 2019.

New York Academy of Sciences

Larry Gladney aims to improve inclusion and diversity.

MEETINGS

Science for development in Vietnam

The international workshop Science for Development was held at the International Centre for Interdisciplinary Science and Education (ICISE) in Quy Nhơn, Vietnam, on May 9–10. The second in a new series of Les Rencontres du Vietnam that kicked off two years ago, the event brought together scientists, policy makers, economics experts, entrepreneurs and industry managers to design a common roadmap for development based on science and technology.

M Gaulié

The ICISE conference center in Quy Nhơn,Vietnam.

Based on past experience, scientists have been able to construct an effective "micro-society" that is based on a collaborative – yet competitive – approach to problem solving. They have built multifaceted laboratories in which a new generation of scientists is trained in a border-free environment. One good example is CERN. Born from the ashes of the Second World War, CERN has grown to become the world's largest laboratory for fundamental physics. Today, the Organization is recognised as a powerful model for peaceful and harmonious development.

In July 2016, motivated by a new proactive approach to positively impact society, scientists connected to the Les Rencontres de Moriond launched the Les Rencontres du Vietnam series on science and society. The workshop is led by the founder of Les Rencontres de Moriond, physicist Jean Trân Thanh Vân, and is organised in conjunction with CERN, the International Solvay Institutes and UNESCO.

The goal of this year's event was to gather valuable input from all of the different stakeholders to eventually design a roadmap. This would have the twofold goal of raising the awareness of scientists regarding their potential role in society and, at the same time, helping society look at scientists as powerful allies for development. Designed to trigger stimulating questions, the conference sought to identify the most urgent societal issues that would benefit from a clearer and deeper involvement of scientists. These include the sharing of information (such as open-access publishing and open hardware); strengthening ties with politicians, governments and parliaments; and more evidence-based policy when dealing with open societal issues.

The day after the conference, participants were addressed by the President of the Socialist Republic of Vietnam, Trần Đại Quang, and by many high-level dignitaries from the government, parliament and the communist party.

Our main messages to them included: one, that Vietnam should increase its participation to international scientific unions or organisations, such as CERN and IUPAP (the International Union of Pure and Applied Physics), and take a lead in pushing a proposal for an International Year of Basic Sciences for Development that has been made in the context of the United Nations 2030 Agenda for Sustainable Development; and two, that Vietnam and other countries should promote basic, applied and social sciences for their development. Vietnam is a "young" country, full of dynamism, competencies and ready to develop in a respectful and sustainable way.

The outcome of the conference will be summarised in a report that will be added to the collection Science and Society in a CERN perspective, which already includes reports from the previous conference as well as other documents that focus on the role of CERN and fundamental science in society. The scope is to allow scientists, stakeholders and members of the public to access information about the efforts being done to put these themes under the spotlight.

● *Michel Spiro, president designate of IUPAP.*

Weighing options for better ion-therapy systems

Sixty experts from all over the world met on 19–21 June at the European Scientific Institute (ESI) in Archamps, France, to explore future medical accelerators for treating cancer with ions. The workshop, jointly organised by CERN, ESI and GSI in Darmstadt, Germany, focused on designs for a next-generation medical and research facility for ion therapy in Europe. The event was the second in the series "Ions for cancer therapy, space research and material science", which was initiated by GSI to highlight the increasingly important interface between physics and its applications.

Particle therapy, also known as hadron therapy, is an advanced form of radiotherapy that uses protons, carbon and other ions to precisely target tumour cells while sparing the surrounding healthy tissues. While commercial proton-therapy equipment is now available, there are only a few bespoke facilities providing treatment with heavier ions such as carbon. Ions are effective with tumours that are resistant to photon irradiation, and their action on DNA is fundamentally different, resulting in the release of more complex DNA fragments from destroyed cells. These, in turn, could also trigger the immune system to attack unirradiated metastases across the body, particularly if combined with the right immune-modulating agents. However, the cost, complexity and size of ion-therapy facilities are hampering the widespread adoption of this treatment modality (see *CERN Courier* January 2018 p25 and p32).

Nymus3D

A virtual particle therapy centre.

The availability of technically still-challenging gantry systems for ions is one of the elements that would lead to faster, more efficient and flexible therapy systems for the routine treatment of "big killers" such as lung cancer. Two approaches for a next-generation therapy system were discussed at the Archamps event: one, relying on proven delivery schemes, could be based on a superconducting synchrotron; another involves novel approaches such as linacs with a high pulse-repetition rate.

Compared to the situation for state-of-the-art photon therapy, where 3D imaging is seamlessly integrated in virtually every setup to guide the treatment, new options for image-guided therapy must be accommodated into ion-therapy systems. As pointed out at the conference, the pinnacle of this development could be fast, adaptive particle therapy combined with online magnetic resonance imaging and monitoring of prompt emissions to assess the particle-beam range. This would finally enable the precise elimination of tumours in complex anatomical locations or moving organs.

During the closing discussion session, it was made clear that the community is eager to establish a dedicated collaboration resulting in a proposal to the European Commission for a new European facility for ion therapy and research. Discussions about a possible R&D programme raised the need to compare the linac- and synchrotron-based designs, for example, and a dedicated meeting is proposed in the autumn to define how best to proceed.

● *Maurizio Vretenar, CERN, Yiota Foka, GSI, Louis Rinolfi, ESI.*

SHiP collaboration meets in Russia

The 14th international meeting of CERN's Search for Hidden Particles (SHiP) collaboration took place on 6–8 June at the National University of Science and Technology (NUST) MISIS in Moscow. During the event, more than 50 specialists from 12 countries discussed current projects and plans.

Proposed in 2013, SHiP would explore the domain of very weakly interacting particles, which may make up dark matter, and study the properties of tau neutrinos. The experiment is designed to be installed at a new beam-dump facility at the Super Proton Synchrotron (SPS) at CERN (see *CERN Courier* March 2016 p25). The SHiP collaboration comprises 52 institutions from 17 countries, including nine Russian institutions, and is part of CERN's Physics Beyond Colliders programme.

Participants at the SHiP collaboration meeting in Moscow.

During the meeting, the main topic discussed was the detector and instrumentation challenges associated with the search for weakly interacting particles such as heavy neutral leptons from the decays of heavy hadrons. The discovery of these particles would constitute proof for physics beyond the Standard Model. Likewise, the absence of the particles would place limits on a wide range of models describing dark matter and its properties.

NUST MISIS, which officially joined the SHiP experiment in 2015, is heavily involved in the development of a prototype of a tungsten–molybdenum target, one of the central nodes of the experiment. CERN is currently testing the prototype at SPS and the results will be published later this year.

● *Dina Moiseeva, NUST MISIS.*

HEPTech exposes young researchers to the business world

ELI-ALPS

The HEPTech-symposium participants at the ELI-ALPS research institute in Hungary.

For a fifth consecutive year, the annual symposium of the High-Energy Physics Technology Transfer Network (HEPTech), fostered by CERN, brought together early-stage researchers in high-energy physics and related scientific domains to help them transform their research ideas into marketable innovations. The symposium took place on 11–15 June, and was hosted by the brand-new ELI-ALPS research institute in Szeged, Hungary. Sixteen young researchers from 10 European countries had the chance to meet six experienced professionals, entrepreneurs and technology-transfer experts from the business world to learn how science can impact society.

Along with the traditional topics, such as entrepreneurship in physics, negotiation skills, intellectual-property protection and investor readiness, several new topics were introduced this year. These included the specifics of "open innovation" in a knowledge-based economy and how to conduct research in a scientifically responsible way.

A special session was dedicated to the creation and funding of spin-offs, during which delegates were introduced to the principles of entrepreneurship as well as to grant schemes for financing start-ups and to the importance of the geographical definition of their potential markets.

The story of the creation and growth of Raspberry Pi – an affordable, credit-card-sized computer designed to be used in educational environments – revealed how developments in research were transformed into successful marketable products. The story also addressed issues concerning the development of a commercially sustainable product, such as the role of competition and improvement of the product to meet users' needs.

Topics relating to intellectual property and patent applications triggered lively discussions, with special attention paid to intellectual-property rights in an open-innovation system. The exposure to win–win negotiation techniques allowed delegates to discover their own negotiation styles, and a great challenge for participants was the preparation of five-minute pitches of research projects to attract investors' attention. The last day of the symposium saw the early-stage researchers delivering their pitches before a panel of experts who gave them constructive feedback.

This year's HEPTech-symposium participants qualified their experience as "a high-quality environment for developing business skills", "a perfect place for networking and learning", and "an outstanding opportunity for bridging the gap between science and business".

● *Eleonora Getsova, HEPTech.*

CERN openlab goes to Europe's premier computing event

From 24 to 28 June, more than 3400 members of the scientific computing community gathered in Frankfurt, Germany, for the annual ISC High Performance conference. The event showcases the latest developments in a host of fields related to high-performance computing (HPC) and features a significant industry show, with more than 150 companies and research organisations exhibiting. It also plays host to the biannual announcement of the "TOP500" list of the world's fastest supercomputers, with Oak Ridge National Laboratory's Summit supercomputer taking this year's top spot following a five-year period of domination by the Chinese machines Tianhe-2 and Sunway TaihuLight.

Maria Girone, CTO of CERN openlab, gave the keynote talk for this year's conference. CERN openlab is a unique public–private partnership between CERN and leading companies such as Intel, Oracle, Siemens and Huawei to make research carried out at CERN and other laboratories possible. Girone's talk, titled "tackling tomorrow's computing challenges today at CERN", discussed the schedule of upgrades for the LHC – which will culminate in the operation of the High-Luminosity LHC (HL-LHC) in around 2026 – and how this will result in a host of new challenges (*CERN Courier* November 2017 p5). Using current software, hardware and analysis techniques, the required computing capacity when the HL-LHC comes online ▷

R Maggi

Maria Girone, CTO of CERN openlab, speaking at the ISC High Performance conference in Frankfurt.

is likely to be roughly 50–100 times higher than today, with data storage expected to enter the exabyte (10^{18} bytes) regime. Girone ended her talk by highlighting a range of specific areas – such as machine learning and data analytics – where collaborative R&D efforts with industry are either already taking place or hold significant future potential, and social-media posts about the talk reached an audience of more than 100,000.

Members of CERN openlab's management team, which is led by Alberto Di Meglio, held meetings with a range of existing and potential partner companies, including D-Wave, Google and Cray. The event also saw Sofia Vallecorsa of the CERN IT department awarded the prize for best research poster in the category "programming models and systems software". Her poster presented work carried out through a CERN openlab project with Intel to explore the feasibility of using deep-learning algorithms for the simulation of particle transport in the LHC experiments.

● *Andrew Purcell, CERN.*

PhD training programme for southeastern European students

Since its foundation in 2003, the Southeastern European Network in Mathematical and Theoretical Physics (SEENET-MTP) has organised scientific training and research activities in the Balkan and neighbouring regions. The fifth and "closing" school of the first cycle of one such activity, High Energy and Particle Physics: Theory and Phenomenology – BS2018, was held in Niš, Serbia on 3–9 June.

In 2015, CERN and SEENET-MTP launched a joint PhD training programme aimed at students from southeastern European countries (*CERN Courier* April 2018 p52). The main part of the programme consisted of a series of one-week schools for PhD and advanced MSc students in high-energy physics, and in 2017 the programme became part of a general agreement of cooperation between CERN and SEENET-MTP.

M Milošević

The participants of the BS2018 School in Niš in Serbia.

At BS2018, Sergey Sibiryakov (CERN) gave an introduction to cosmic-structure formation and Kyriakos Papadodimas (CERN) introduced the AdS/CFT correspondence and black holes. Paolo Creminelli (ICTP) taught cosmology and inflation, and Lasha Berezhiani (LMU/MPI) gave an introduction to supersymmetry. The organisers owe a special gratitude to Emilian Dudas (CPHT), who agreed to cover the Standard Model course and gave a brief introduction to string phenomenology, and also to Ignatios Antoniadis (AEC/LPTHE), who completed the latter course. Alexei Starobinsky (Landau Institute) was a special guest lecturer and gave the closing lecture on inflation and its present status.

Around 40 students from 10 countries attended the school and each had the opportunity to present their work through oral and poster sessions. The school was followed by the seventh edition of the Balkan Workshop, BW2018 – Field Theory and the Early Universe, on June 10–14, which was attended by 51 scientists from 15 countries and comprised around 30 lectures.

The EPS and SEENET-MTP jointly marked their anniversaries: 50 years of the EPS (for the SEE region) and 15 years of the network.

The next cycle of the joint PhD training programme is expected to start in Ioannina in Greece in the spring of 2019.

● *Goran S Djordjević and Danilo Delibašić, University of Niš.*

Obituaries

Homer Neal 1942–2018

Homer Neal, a prominent leader in particle physics who helped to shape US science policy and develop educational opportunities for undergraduate students nationwide, passed away on 23 May.

Homer Alfred Neal was born on 13 July 1942, and grew up in the small town of Franklin, Kentucky, US. As a teenager, Neal entered the world of research as an amateur radio operator. Unfortunately, some were unhappy that he, an African-American in the segregated South, was working together with a white boy on amateur radio projects, and brought an end to their collaboration. According to Neal, this only served as an impetus in his later efforts to improve scientific diversity: "…it did teach me that basically when individuals are working on a scientific project together, the colour of one's skin doesn't matter."

As a researcher, Neal participated in experiments at Stanford Linear Accelerator Laboratory, Fermilab and CERN, and was considered a world expert in studies of particle spin and polarisation. In 1987, while chairing the University of Michigan physics department, his group contributed to key research on the Tevatron's D0 experiment, including the discovery of the top quark, and the Ξ_b and Ω_b baryons.

More recently, Neal led a team of 40 Michigan faculty members, research scientists and students on the ATLAS experiment at CERN. The team played an important role in the construction of the experiment's muon spectrometer and contributed to vital software and analysis efforts, including studies leading to the discovery of the Higgs boson in 2012.

APS

Homer Neal helped to shape science policy in the US.

In the 1980s, Neal led a committee to examine undergraduate science, mathematics and engineering programmes for the National Science Board, which sets policies for the National Science Foundation (NSF). The committee found that science education was so poor that it posed "a grave long-term threat" to the nation and, among other recommendations, it asked that the foundation provide undergraduate students with opportunities to participate in current, cutting-edge research. This led to the creation of the Research Experiences for Undergraduates (REU) and the Research Experiences for Teachers (RET) programmes, which serve thousands of students and high-school teachers across the US. The NSF has also incorporated REU and RET into the official CERN summer student and high school teacher programmes, and the Richard Lounsbery foundation sponsors a CERN semester abroad programme, following the recommendations.

Neal held a variety of important academic leadership positions at Michigan and elsewhere, including provost of the State University of New York at Stony Brook on Long Island and dean of research and graduate development at Indiana University. He was a recipient of a Sloan Foundation Fellowship, a Guggenheim Fellowship, the Stony Brook Medal and the Indiana University Distinguished Alumni Service Award. He was a fellow of the American Physical Society, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences. He also held honorary doctorates from Indiana University, Notre Dame University and Michigan State University.

Outside of academia, Neal served as president of the American Physical Society, board member of the Ford Motor Company, council member of the National Museum of African American History and Culture, member of the US National Research Council Board on Physics and Astronomy, director of the Richard Lounsbery Foundation, and regent of the Smithsonian Institution. He also co-authored a widely used science-policy textbook titled *Beyond Sputnik*.

Neal is survived by his wife, Donna Jean Neal; their children, Sharon-Denise Neal, who trained as an archaeologist, and Homer A Neal Jr, a physicist and staff scientist at SLAC; and four grandchildren.

● *Steven Goldfarb, CERN.*

Mike Pennington 1946–2018

Mike Pennington, a distinguished theoretical physicist and leader, passed away on 23 May after a relatively brief illness. He will be sorely missed by his colleagues, who extend their heartfelt condolences to his widow, Pat Pennington, and to his close family.

Mike received a bachelor's degree in mathematical physics in 1968 from the University of Edinburgh and a PhD in theoretical physics in 1971 from Westfield College, University of London, under the supervision of Elliot Leader. He then completed three two-year postdoc positions, one of which was at CERN. His research focus was in the theoretical and phenomenological study of quantum chromodynamics, and he published more than 200 scientific articles.

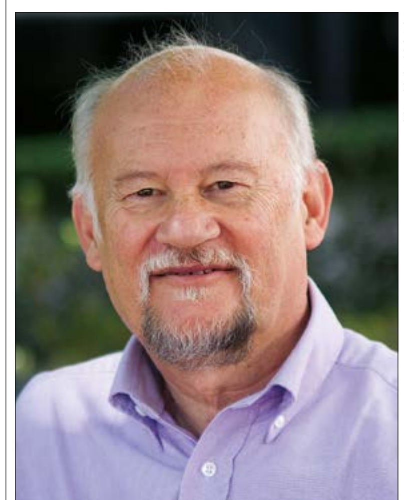
Mike spent much of his career at the University of Durham, where he held many leadership positions, including head of the physics department from 1999 to 2003. As department head, Mike played a key role in developing the department as it is today, through the establishment of the Ogden Centre for Fundamental Physics and the creation of the world-leading Institute for Particle Physics Phenomenology and the Institute for Computational Cosmology.

Mike's influence on Durham's physics department remains very visible. During his tenure, the department grew considerably ▷

in staff and student numbers, size and range of research. None of this came about by accident. He had analysed which areas needed to change or to improve, and he developed a plan for how best to facilitate the changes. Most importantly, he was one of those rare academics who are also gifted leaders, able to communicate his vision to other members of the senior management team and to bring them on board to effect the necessary transition.

Mike was a born educator and worked tirelessly to improve learning for all students. He was a legendary lecturer, meticulous in his preparation and writing clearly with his distinctive and transparent style on the board. For many years he taught the first-year classes in classical mechanics and special relativity, and frequently his exam questions would reflect the personalities of the day. His conference talks were equally memorable and often the highlight of the conference. He communicated as he did most things, with style and panache.

In his career, Mike served on a variety of international science groups, including participation as a member of the CERN SPS committee and as a member of the DAΦNE physics working group in Frascati, Italy. In addition, he was a visiting academic at the University of Adelaide in Australia and the Brookhaven National Laboratory in the US. Mike was also an elected fellow of the UK Institute of Physics and the American Physical Society.



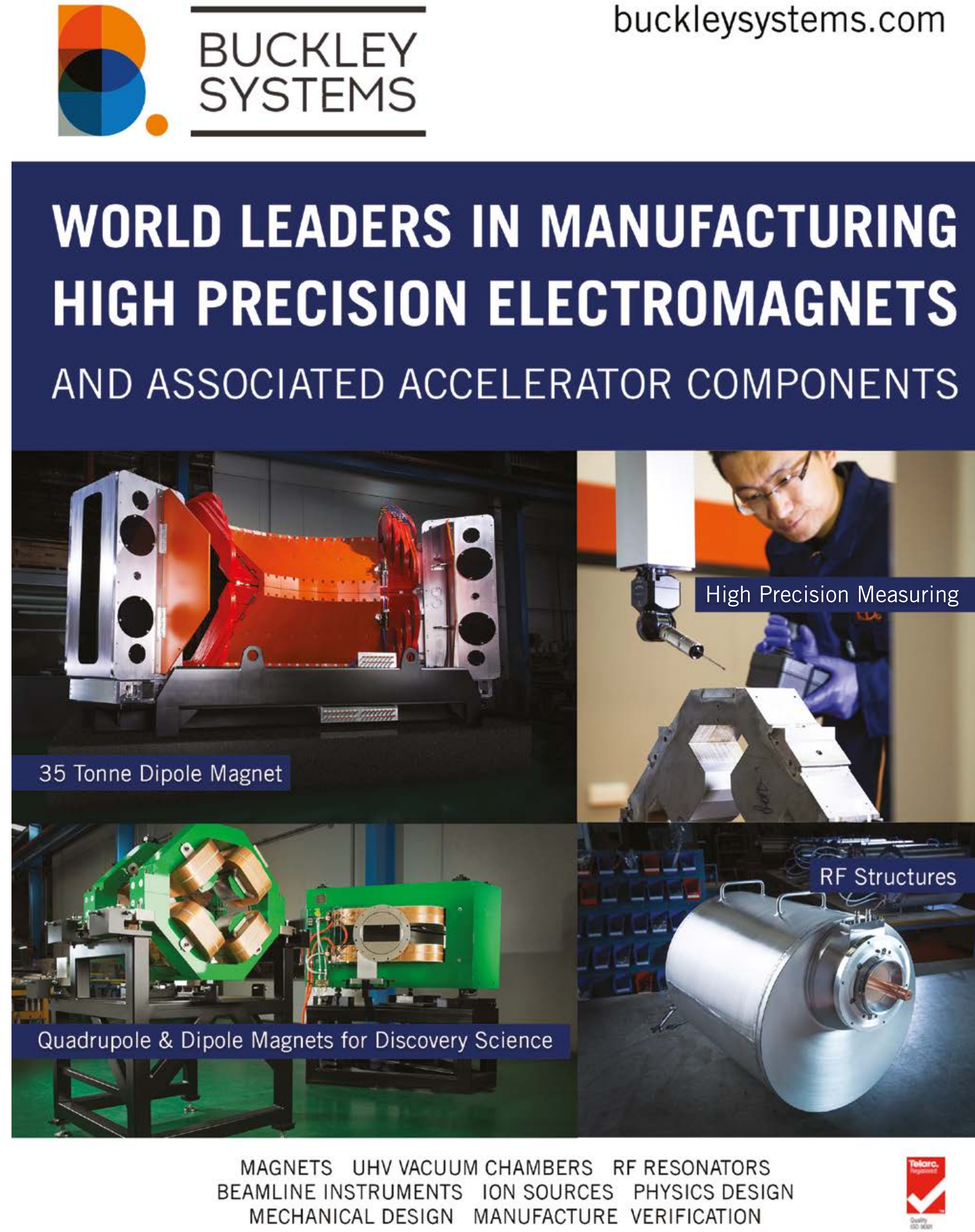
DOE's Jefferson Lab

Mike Pennington's research focus was quantum chromodynamics.

From 2010 to 2016, Mike was associate director of the Jefferson Lab for Theoretical and Computational Physics and professor at the College of William & Mary. His influence on Jefferson Lab also rested on his ability to communicate. He enjoyed collaborations with most of the experiments across the world that played roles in spectroscopy, and we would joke that he was creating a Jefferson Lab hegemony by stealth.

Mike's professional legacy stands as a testament to his leadership, his vision, his ability to mentor rising colleagues, and his determination to make a difference. There is no doubt that his numerous contributions to our institutions, to the field of nuclear and particle physics, and to humanity, will last far into the future.

● *His friends and colleagues.*



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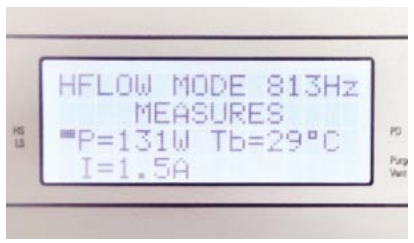

The "three-dimensional" pump control algorithm provides maximum flexibility and simplicity to optimize throughput and compression ratio in every application and working condition, thanks to the dynamic tuning of output power and rotational speed, which are directly linked to the load applied on the rotor.

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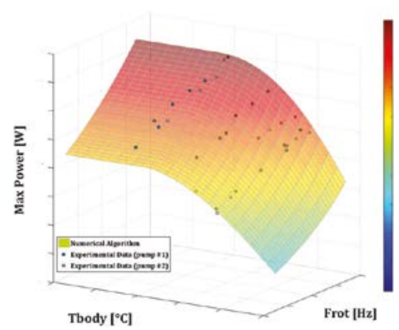
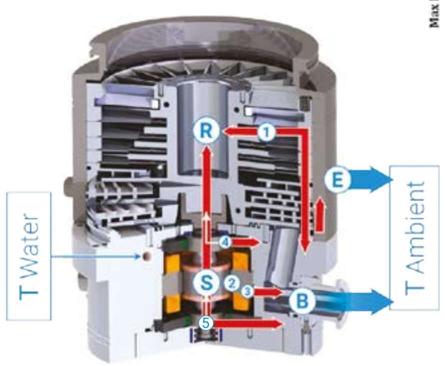


Simulation result



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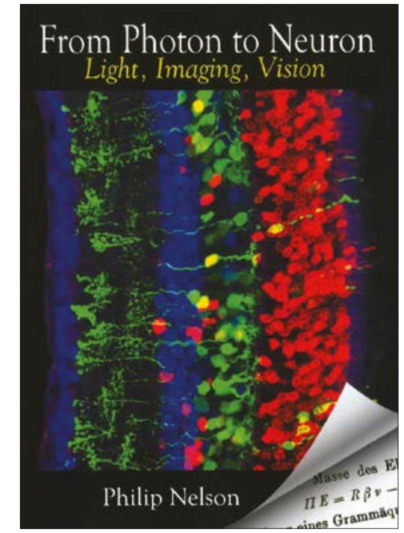
Bookshelf

Compiled by Virginia Greco, CERN

From Photon to Neuron: Light, Imaging, Vision
By Philip Nelson
Princeton University Press 2017



This book is as elegant as it is deep. A masterful tour of the science of light and vision. It goes beyond artificial boundaries between disciplines and presents all aspects of light as it appears in physics, chemistry, biology and the neural sciences.

The text is addressed to undergraduate students, an added challenge to the author, which is met brilliantly. Since many of the biological phenomena involved in our perception of light (in photosynthesis, image formation and image interpretation) happen ultimately at the molecular level, one is introduced rather early to the quantum treatment of the particles that form light: photons. And when they are complemented with the particle-wave duality characteristic of quantum mechanics, it is much easier to understand a large palette of natural phenomena without relying on the classical theory of light, embodied by Maxwell's equations, whose mathematical structure is far more advanced than what is required. This classical approach has the problem that eventually one needs the quantisation of the electromagnetic field to bring photons into the picture. This would make the text rather unwieldy, and not accessible to a majority of undergraduates or biologists working in the field.

In the same way that the author instructs non-physics students in some basic physics concepts and tools, he also provides physicists with accessible and very clear presentations of many biological phenomena involving light. This is a textbook, not an encyclopaedia, hence a selection of such phenomena is necessary to illustrate the concepts and methods needed to develop the material. There are sections at the end of most chapters containing more advanced topics, and also suggestions for further reading to gain additional insight, or to follow some of the threads left open in the main text of the chapter.

A cursory perusal of the table of contents at the beginning will give the reader an idea of the breadth and depth of material covered. There is a very accessible presentation of the theory of colour, from a physical and biological point of view, and its psychophysical effects. The evolution of the eye and of vision at different stages of animal complexity, imaging, the mechanism of visual transduction and many more topics are elegantly covered in this remarkable book.

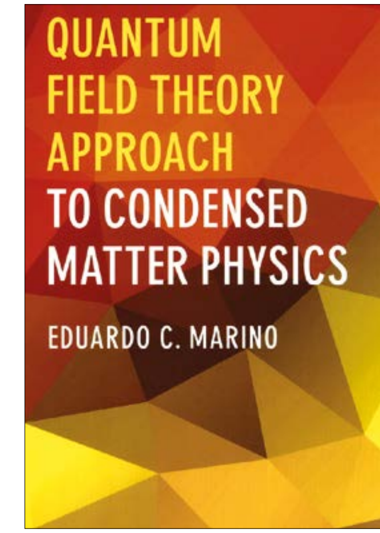
The final chapters contain some advanced topics in physics, namely, the treatment of light in the theory of quantum electrodynamics. This is our bread and butter in particle physics, but the presentation is more demanding on the reader than any of the previous chapters.

Unlike chapter zero, which explains the rudiments of probability theory in the standard frequentist and Bayesian approaches that can be understood basically by anyone familiar with high-school mathematics, chapters 12 and 13 require a more substantial background in advanced physics and mathematics.

The gestalt approach advocated by this book provides one of the most insightful, cross-disciplinary texts I have read in many years. It is mesmerising and highly recommendable, and will become a landmark in rigorous, but highly accessible interdisciplinary literature.

● *Luis Álvarez-Gaumé, Stony Brook University, US.*

Quantum Field Theory Approach to Condensed Matter Physics
By Eduardo C Marino
Cambridge University Press



This book provides an excellent overview of the state of the art of quantum field theory (QFT) applications to condensed-matter physics (CMP). Nevertheless, it is probably not the best choice for a first approach to this wonderful discipline.

QFT is used to describe particles in the relativistic (high-energy intensity) regime, but, as is well known, its methods can also be applied to problems involving many interacting particles – typically electrons. The conventional way of studying solid-state physics and, in particular, silicon devices does not make use of QFT methods due to the success of models in which independent electrons move in a crystalline substrate. Currently, though, we deal with various condensed-matter systems that are impervious to that simple model and could instead profit from QFT tools. Among them: superconductivity beyond the Bardeen–Cooper–Schrieffer approach (high-temperature superconducting cuprates and iron-based superconductors), the quantum Hall effect, conducting polymers, graphene and silicene.

The author, as he himself states, aims to offer a unified picture of condensed-matter theory and QFT. Thus, he highlights the interplay between these two theories in many examples to show how similar mechanisms operate in different systems, despite being separated by several orders of magnitude in energy. He discusses, for example, the comparison between the Landau–Ginzburg field of a superconductor with the Anderson–Higgs field in the Standard Model. He also explains the not-so-well-known relation between the Yukawa mechanism for mass generation of leptons and quarks, and the Peierls mechanism of gap generation in polyacetylene: the same trilinear interaction between a Dirac field, its conjugate and a scalar field that explains why polyacetylene is an insulator, is responsible for the mass of elementary particles.

The book is structured into three parts. The first covers conventional CMP (at advanced undergraduate level). The second provides a brief review of QFT, with emphasis on the mathematical analysis and methods appropriate for non-trivial many-body systems (as, in particular, in chapters eight and nine, where a classical and a quantum description of topological excitations are given). I found the pages devoted to renormalisation remarkable, in which the author clearly exposes that the renormalisation procedure is a necessity due to the presence of interactions in any QFT, not to that of divergences in a perturbative approach. The heart of the book is part three, composed of 18 chapters where the author discusses the state of the art of condensed-matter systems, such as topological insulators and even quantum computation.

The last chapter is a clear example of the non-conventional approach proposed by the author: going straight to the point, he does not explain the basics of quantum computation, but rather discusses how to preserve the coherence of the quantum states storing information, in order to maintain the unitary evolution of quantum data-processing algorithms. In his words, "the main method of coherence protection involves excitation, having the so-called non-abelian statistics", which, going back to CMP, takes us to the realm of anyons and Majorana qubits. In my opinion, this book is not suitable for undergraduate or first-year graduate students (for whom I see as more appropriate, the classic *Condensed Matter Field Theory* by Altland and Simons). Instead, I would keenly recommend this to advanced graduate students and researchers in the field, who will find, in part three, plenty of hot topics that are very well explained and accompanied by complete references.

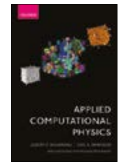
● *Rogelio Palomo, University of Sevilla, Spain.*

Books received

Applied Computational Physics

By Joseph Boudreau and Eric Swanson

Oxford University Press



This book aims to provide physical sciences students with the computational skills that they will need in their careers and expose them to applications of programming to problems relevant to their field of study. The authors, who are professors of physics at the University of Pittsburgh, decided to write this text to fill a gap in the current scientific literature that they noticed while teaching and training young researchers. Often, graduate students have only basic knowledge of coding, so they have to learn on the fly when asked to solve "real world" problems, like those involved in physics research. Since this way of learning is not optimal and sometimes slow, the authors propose this guide for a more structured study.

Over almost 900 pages, this book introduces readers to modern computational environments, starting from the foundation of object-oriented computing. Parallel computation concepts, protocols and methods are also discussed early in the text, as they are considered essential tools.

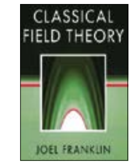
The book covers various important topics, including Monte Carlo methods, simulations, graphics for physicists and data modelling, and gives large space to algorithmic techniques. Many chapters are also dedicated to specific physics applications, such as Hamiltonian systems, chaotic systems, percolation, critical phenomena, few-body and multi-body quantum systems, quantum field theory, etc. Nearly 400 exercises of varying difficulty complete the text.

Even though most of the examples come from experimental and theoretical physics, this book could also be very useful for students in chemistry, biology, atmospheric science and engineering. Since the numerical methods and applications are sometimes technical, it is particularly appropriate for graduate students.

Classical Field Theory

By Joel Franklin

Cambridge University Press



This book provides a comprehensive introduction to classic field theory, which concerns the generation and interaction of fields and is the logical precursor of quantum field theory. But, while in most university physics programmes students are taught classical mechanics first and then quantum mechanics, quantum field theory is normally not preceded by dedicated classic field theory classes. The author, though, claims that it would be worth giving more room to classical field theory, since it can offer a good way to think about modern physical model building.

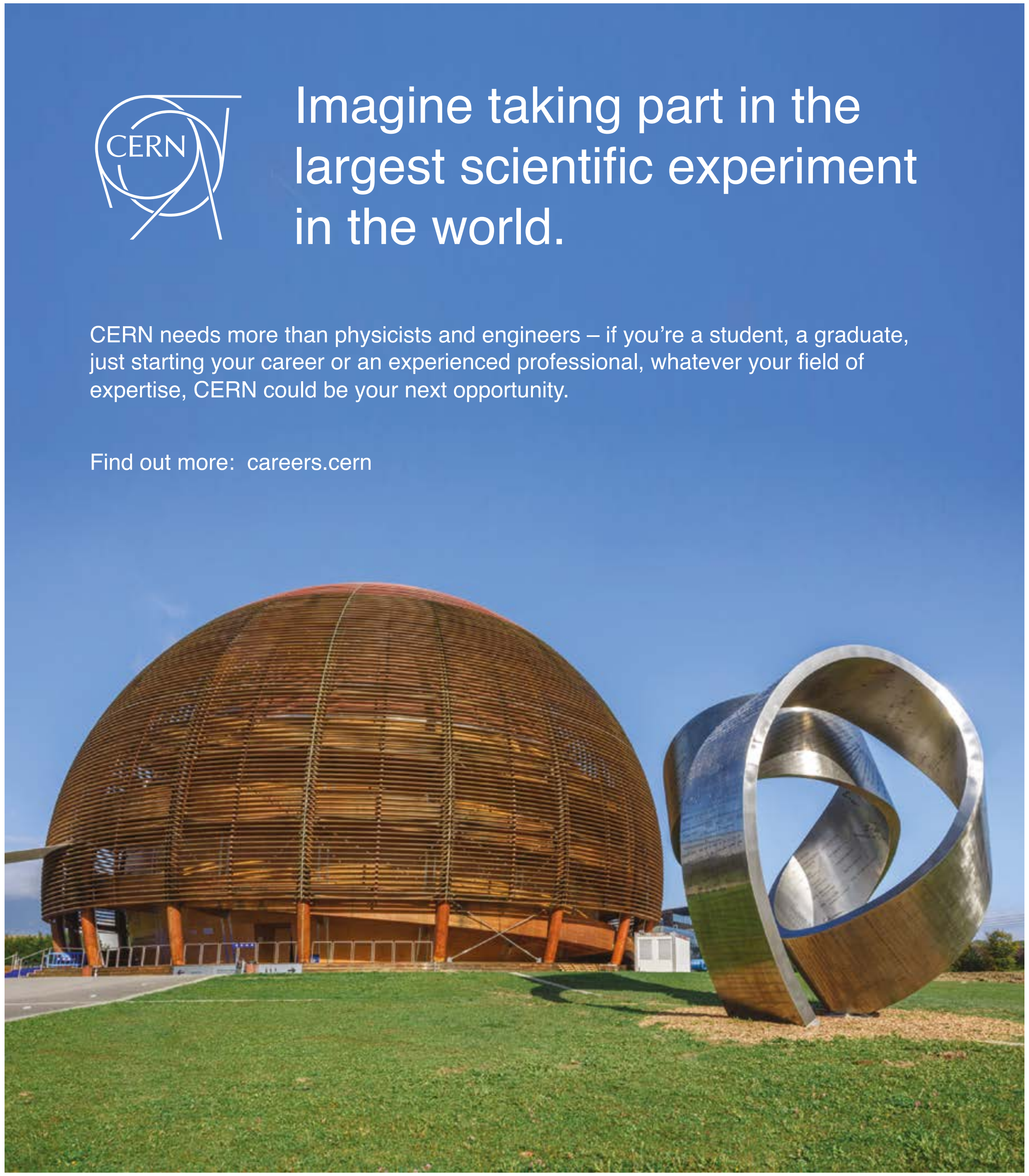
The focus is on the relativistic structural elements of field theories, which enable a deeper understanding of Maxwell's equations and of the electromagnetic field theory. The same also stands for other areas of physics, such as gravity.

The book comprises four chapters and is completed by three appendices. The first chapter provides a review of special relativity, with some in-depth discussion of transformations and invariants. Chapter two focuses on Green's functions and their role as integral building blocks, offering as examples static problems in electricity and the full wave equation of electromagnetism. In chapter three, Lagrangian mechanics is introduced, together with the notions of a field Lagrangian and of action. The last chapter is dedicated to gravity, another classic field theory. The appendices include mathematical and numerical methods useful for field theories and a short essay on how one can take a compact action and from it develop all the physics known from EM.

Written for advanced-undergraduate and graduate students, this book is meant for dedicated courses on classical field theory, but could also be used in combination with other texts for advanced classes on EM or a course on quantum field theory. It could also be used as a reference text for self-study.

Recruitment

For advertising enquiries, contact *CERN Courier* recruitment/classified, IOP Publishing, Temple Circus, Temple Way, Bristol BS1 6HG, UK.
Tel +44 (0)117 930 1264 Fax +44 (0)117 930 1178 E-mail sales@cerncourier.com
Please contact us for information about rates, colour options, publication dates and deadlines.



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Requirements

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DESY-Fellowships are awarded for a duration of 2 years with the possibility of prolongation by one additional year.

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Human Resources Department | Code: FHFE003/2018
Notkestraße 85 | 22607 Hamburg | Germany | Phone: +49 40 8998-3392
Email: recruitment@desy.de
Deadline for applications: 30 September 2018
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PROFESSOR

SCIENCE AND PLASMAS APPLICATION (AP 18-05)

INSTITUT NATIONAL DE LA RECHERCHE SCIENTIFIQUE (tenure-track position)

CONTEXT AND SUMMARY

Institut national de la recherche scientifique (INRS) is the only institution in Québec (Canada) dedicated exclusively to graduate level university research and training. The influence of our faculty and students extends around the world. In partnership with the community and with industry, we are proud to contribute to the development of society through our discoveries and through the training of young scientists.

INRS would like to fill a new faculty position in the area of science and application of plasmas. The successful candidate will collaborate with the multidisciplinary research program at the INRS Énergie Matériaux Télécommunications Research Centre by contributing recognized expertise in plasma physics applied to materials synthesis, characterization and treatment.

MAIN DUTIES AND RESPONSIBILITIES

- Develop an original and innovative program of applied and fundamental research in plasma physics preferably (but not exclusively) oriented towards the following research areas:
  - Plasma interaction with organic matter (complex molecules, cells, tissues, cell treatment or destruction, reconstructive surgery, etc.)
  - Plasma for nanomaterials synthesis related to various fields of application (catalysis, energy conversion, photonic, 3D impressions, etc.)
- Secure external funding from a variety of funding agencies, both provincial and federal, also involving various partners from the public and private sectors whenever needed/pertinent.
- Participate in teaching and training at the graduate level (both M.Sc. and Ph.D. students), as well as supervising post-doctoral fellows and research personnel.

REQUIREMENTS

- Doctorate in physics, chemistry, materials science, engineering physics, chemical engineering or related fields, with specialization in experimental plasmas or assisted plasma processes.
- Relevant postdoctoral research experience would be an asset.
- Strong scientific publishing record illustrating originality and innovation.
- Ability to work in multidisciplinary teams and networks as well as in collaboration with representatives of various agencies.
- Aptitude for basic and applied research, as well as multidisciplinary teaching and mentoring at the masters and doctorate levels.
- Entrepreneurial qualities and demonstrated ability to secure external research funding.
- Preference will be given to junior candidates. However, outstanding senior candidates will also be considered.

WORKING LANGUAGE

French is the official language at INRS. Fluency in English is required. Candidates whose native language is not French are encouraged to apply. The Centre will provide them with all the resources necessary to facilitate their learning of the French language.

WORKPLACE

Institut national de la recherche scientifique (INRS)
Centre Énergie Matériaux Télécommunications
1650, boulevard Lionel-Boulet, Varennes (Québec) J3X 1S2 CANADA
Varennes is located on the South Shore of Montreal.

SALARY

In accordance with the collective agreement in effect at INRS.

HOW TO APPLY

Interested applicants should send their application including a complete curriculum vitæ, a copy of their three most significant publications, a three page summary of their research interests, a statement of teaching experience and philosophy, and the names and contact information of three referees, before **October 15th 2018** indicating position number AP 18-05 by e-mail at **concours@emt.inrs.ca** or by mail to:

Director
Institut national de la recherche scientifique (INRS)
Centre Énergie Matériaux Télécommunications
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The Institute invites women, visible minorities, ethnic minorities, natives and people with disabilities to apply.
Priority will be given to candidates with Canadian citizenship or permanent resident.

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PROFESSOR

ULTRAFAST CHARACTERIZATION OF MATERIALS (AP 18-06)

INSTITUT NATIONAL DE LA RECHERCHE SCIENTIFIQUE (tenure-track position)

CONTEXT AND SUMMARY

Institut national de la recherche scientifique (INRS) is the only institution in Québec (Canada) dedicated exclusively to graduate level university research and training. The influence of our faculty and students extends around the world. In partnership with the community and with industry, we are proud to contribute to the development of society through our discoveries and through the training of young scientists. INRS would like to fill a new faculty position in the area of Ultrafast Materials Characterization. The areas of expertise aimed at, but not limited to, are: time-resolved electron microscopy, electron microscopy, ultrafast electron diffraction, ultrafast characterization of materials, microscopy of irreversible phenomena, ultra-fast lasers and photonics and their applications in materials and biological sciences for various areas such as, for example, biomedical and energy.

MAIN DUTIES AND RESPONSIBILITIES

- The candidate is expected to establish collaborations with research teams already in place, while developing or maintaining partnerships with groups outside the EMT research center. The ability to develop partnerships with the private sector is particularly valuable.
- This position is incorporated within an environment where about forty professors-researchers undertake leading-edge research and training in diverse fields of sustainable energy, advanced materials, ultrafast photonics, telecommunication systems and nanobiotechnology.
- The Centre hosts unique major research infrastructure including the Advanced Laser Light Source and the Laboratory of Micro and Nanofabrication, comprising the Infrastructure of Nanostructures and Femtoscience (http://lmn.emt.inrs.ca/EN/inf.htm).
- This new position is intended to build a critical mass of expertise around a major $15M addition, the Infrastructure for Advanced Imaging (IAI), awarded by the Canada Foundation for Innovation (CFI) in the 2012 competition. This infrastructure houses two time-resolved electron microscopes (for irreversible and reversible dynamics) and several sample preparation equipment, including a focused ion beam. As a whole, with the range of dynamic phenomena it can access, the IAI is a unique infrastructure worldwide.
- Secure external funding from a variety of funding agencies, both provincial and federal, also involving various partners from the public and private sectors whenever needed/pertinent. Potential sources of funding include the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Fonds québécois de la recherche sur la nature et les technologies (FQRNT).
- Participate in teaching and training at the graduate level (both M.Sc. and Ph.D. students), as well as supervising post-doctoral fellows and research personnel.

REQUIREMENTS

- A doctoral degree in a relevant discipline (physics, materials science, engineering, chemistry, biology).
- An outstanding record of research accomplishments that will enable her/him to successfully develop a strong independent research program.
- Academic and technical expertise that are complementary to the existing faculty at EMT (http://www.emt.inrs.ca/les-professeurs/mosaique/6)
- The aptitude for teaching and supervising graduate students and other trainees.
- The ability to work in a multidisciplinary team and within research networks.
- The ability to collaborate with industrial partners.

WORKING LANGUAGE

French is the official language at INRS. Fluency in English is required. Candidates whose native language is not French are encouraged to apply. The Centre will provide them with all the resources necessary to facilitate their learning of the French language.

WORKPLACE

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1650, boulevard Lionel-Boulet, Varennes (Québec) J3X 1S2 CANADA
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SALARY

Salary and benefits are in accordance with the current collective agreement at INRS.

HOW TO APPLY

Interested applicants should send their application including a complete curriculum vitæ, a copy of their three most significant publications, a three page summary of their research interests, a statement of teaching experience and philosophy, and the names and contact information of three referees, before **October 15th 2018** indicating position number AP 18-06 by e-mail at **concours@emt.inrs.ca** or by mail to:

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Priority will be given to candidates with Canadian citizenship or permanent resident.

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BlueYonder Data Scientist (m/f) in Karlsruhe

Blue Yonder enables retailers to take a transformative approach to their core processes, automating complex decisions that deliver higher profits and customer value using AI.

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Blue Yonder was founded in 2008 in Karlsruhe, Germany, by former CERN scientist Professor Michael Feindt. The company has been awarded the Experton Big Data Leader Award 2016, the BT Retail Week Technology Award and the IGD Award 2017 for Supply Chain Innovation.

To support our team in Karlsruhe, we are looking for a Data Scientist (m/f).

Every day, our teams work enthusiastically with our customers on innovative AI-based solutions and sophisticated optimization for the retail industry. Working with us means you can look forward to coworkers who use creativity to collectively develop ideas and appreciate each other's expertise.

Mutual respect, friendly relationships and results-oriented work are an important part of our environment. We strive to be a family-friendly business and are open to modern working structures.

We believe that the individuality and diversity of our employees make a decisive contribution to our success. Our hiring process is based on qualifications and career profile. We welcome applications from all motivated candidates, regardless of age, gender, disability, sexual orientation, origin or religion.

Want to join our team?

Please email your application and references, preferably also from the open source sector, stating the job title to jobs@blue-yonder.com.

What you will do

» Develop and operate solutions that optimize and automate business decisions using large data sets and algorithms
» Work with complex data analysis, data preparation and developing prognostic models based on modern statistical methods
» Develop a deep understanding of retail and supply chain problems
» Write productive software that generates value for our customers
» Take ownership of onboarding new customers and continuously improve our existing solutions
» Work as part of a highly motivated, interdisciplinary and agile team

Your experience

» In-depth knowledge of data analysis and multivariate statistics, preferably in the Python data ecosystem
» Passion for writing software with emphasis on quality, testability and automation
» Expertise in working with SQL
» Experience in building machine learning models or optimization software to solve business problems
» Ability to communicate results clearly to both colleagues and less technically versed audiences

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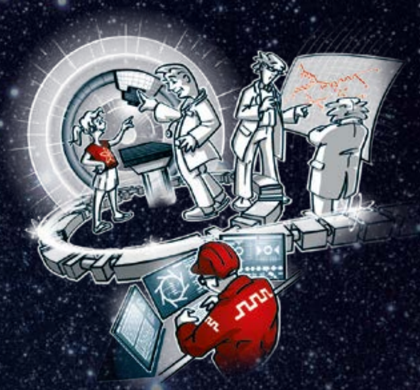

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1 National "Thousand Talents Program" (full time & part time programs) for established scientists
2 National "Thousand Young Talents Program" for outstanding junior scientists
3 Pioneer "Hundred Talents Program" of CAS for outstanding junior scientists, excellent junior detector or accelerator experts
4 "Outstanding Talents Program" of IHEP for scientific research or technical talents

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Contact:

Office of Human Resources, Institute of High Energy Physics, Chinese Academy of Sciences
E-mail: lianggj@ihep.ac.cn **Tel:** (86)010-88233157 **Fax:** (86)010-88233102
Address: No. 19 (B), Yuquan Road, Shijingshan District, Beijing (Postcode: 100049)

Applications should include a CV, an outline of academic accomplishments, description of current research and plan for future research, 3 – 5 published papers representative of your work, and a record of citations for your work. You should arrange for 3 letters of reference from experts in your field to be sent by post or email (established scientists are not requested).

For detailed information, please visit **http://english.ihep.cas.cn/doc/2649.html**

CERN Courier Archive: 1975

A look back to CERN Courier vol. 15, September 1975, compiled by Peggie Rimmer

News

Magnetic monopole

Monopoles, the basic units of magnetism, were first suggested by P A M Dirac in 1931, as the magnetic counterparts of electrons, the basic units of electricity. He predicted that the monopole charge would be at least 68.5 times that of the electron.

In a lecture at CERN at the end of August, E K Shirk described evidence that a Berkeley/Houston group have detected a monopole. Two years ago the team dangled a balloon over Iowa loaded with a stack of plastic (Lexan) plates, nuclear emulsion layers and a Cherenkov counter. They were looking for heavy nuclei in cosmic rays, particularly for 'super-heavy' nuclei around atomic number 114.

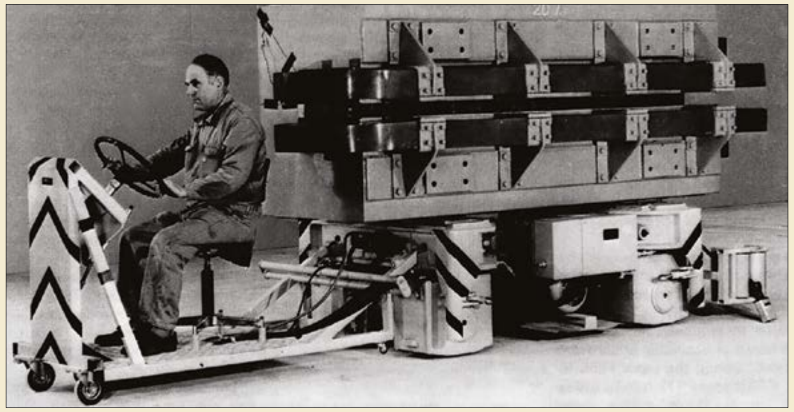
The nuclear emulsion, scanned at Houston, gave data suggesting the passage of a particle with atomic number around 80 and a velocity about half that of light, 0.5 c. The depth and rate of chemical etching in the Lexan stack, measured at Berkeley, gave as best estimate a particle of charge around 137 and a velocity about equal to that of light, contradicting the nuclear emulsion data. Fast film from the Cherenkov counter showed no evidence of a particle with a velocity higher than 0.7 c, in line with the nuclear emulsion data for a low velocity particle.

How then was it possible to explain the etching of the Lexan sheets which indicated a highly ionizing, high velocity particle? A magnetic monopole is predicted to cause ionization at a rate proportional to its charge, g, and its velocity. The etch rate seemed consistent with a monopole with g = 137 and a velocity sufficient to penetrate all the plates. This means that it must have an energy over 32 GeV and a mass more than 200 times that of the proton.

It was perhaps the estimate of the particle charge at 137, twice the Dirac prediction, which lent extra weight to the monopole interpretation. Since the result was first announced, a recalibration has taken the charge to 121 and a lot of credulity with it. Nevertheless, it is an intriguing observation which has served to give the high-energy physics world another stir and to bring magnetic monopoles onto the front pages of the newspapers.

● Compiled from text on p261.

Around CERN

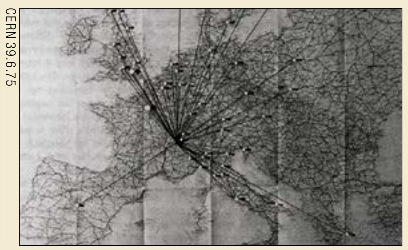


CERN 290.10.68

The versatile transporter which was used to convey the precisely assembled and measured magnets of the Intersecting Storage Rings to their positions in the tunnel. Vehicles of this type are now in common use in the ship building industry.

CERN 39.6.75

An inflatable mirror made from an aluminised mylar membrane 25 μm thick, which has been developed at the CERN West Workshop. By varying the pressure applied to the membrane the mirror takes up varying quasi-spherical forms. The focal length can thus be varied for use in a Cherenkov counter.

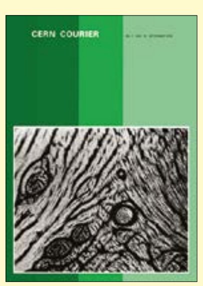


CERN 39.6.75

A map of Europe with lines radiating out from CERN to the national centres, which draw some of their research material from the bubble chamber experimental programme.

● Compiled from texts on pp 263, 265 and 266.

Compiler's note



The faith, hope and endurance of physicists were seriously tested during the 48 years between the three illustrious papers on spontaneous symmetry breaking in 1964 and the discovery of the Higgs boson in 2012. This patience is already surpassed by a dogged determination to capture a magnetic monopole, predicted by Dirac in 1931. The latest search with the Monopole and Exotics Detector, MoEDAL, at the LHC has found none, so far. If monopoles are too heavy to be produced by accelerators, a future MoEDAL could be located on a mountaintop to look, once again, for any that might be spattering in from space.

A comparison of the distribution of data from CERN bubble-chamber experiments in the 1970s with that of data generated by the LHC experiments today – the former by land, sea and air, the latter by networks over the Worldwide LHC Computing Grid – shows CERN's evolution from its eurocentric beginnings to become a source of material for multicontinental high-energy physics research (wlcg-public.web.cern.ch).

Sydney IEEE NSS/MIC 2018

IEEE NPSS Nuclear & Plasma Sciences Society

2018 IEEE Nuclear Science Symposium and Medical Imaging Conference

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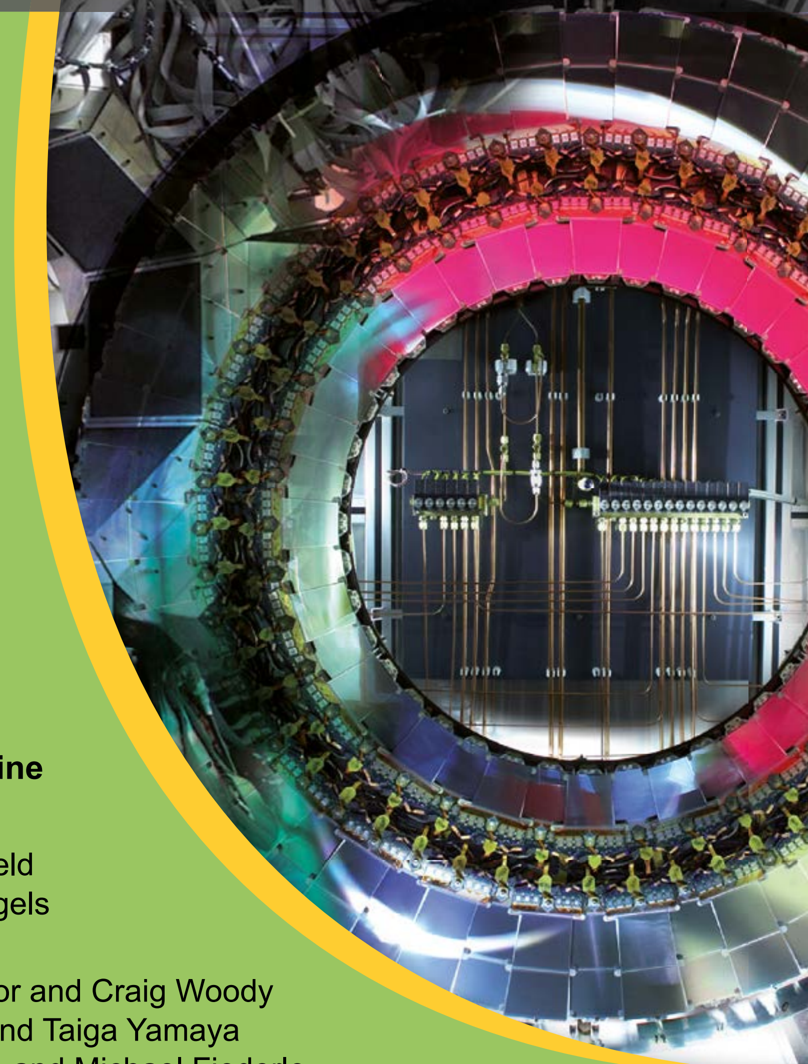

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9th May 2018

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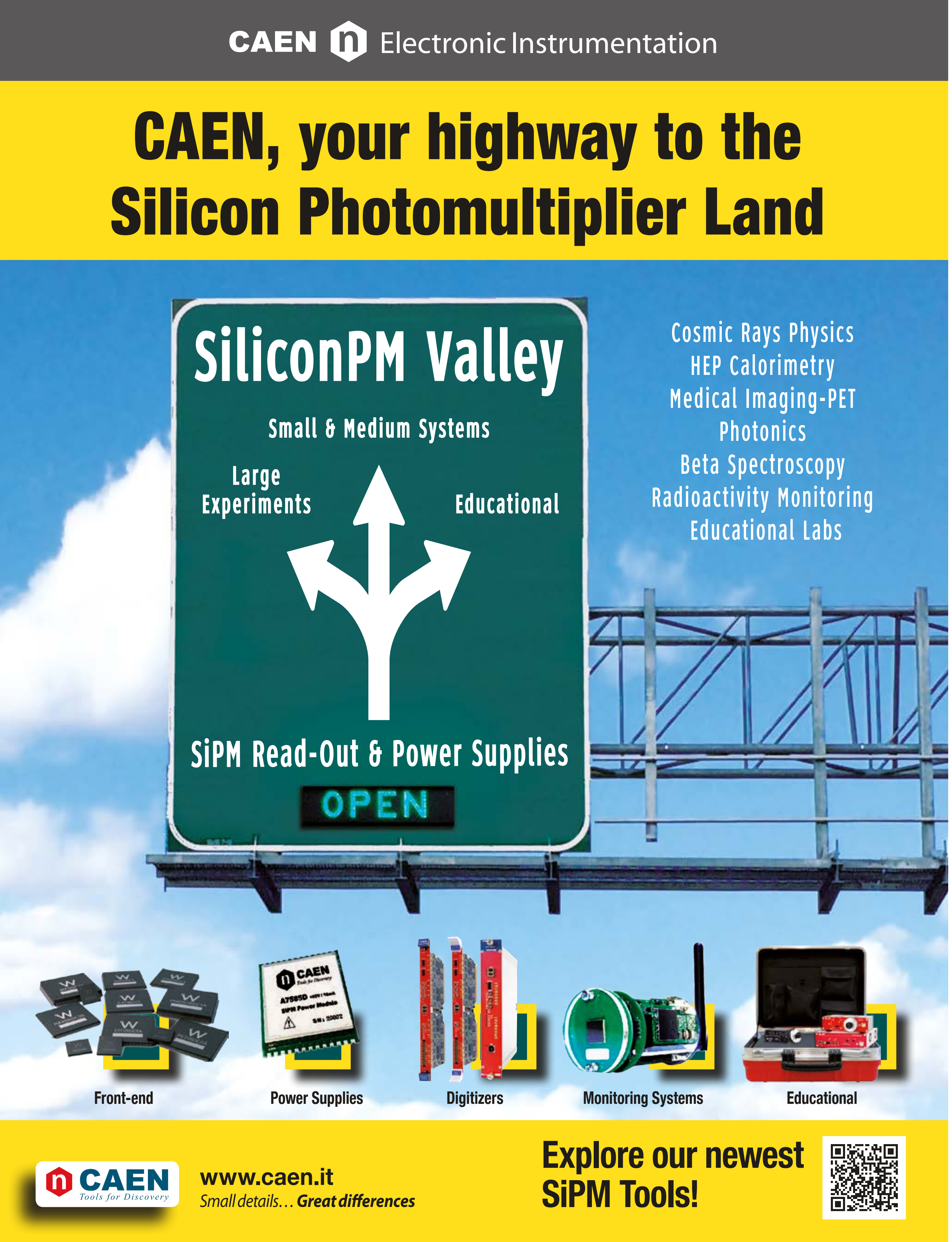
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