WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the March/April 2020 issue of *CERN Courier*.

This issue of the *Courier* looks at the monumental impact of the LHC's first 10 years of physics at the high-energy frontier (p40), and hears from those who have been at the sharp end of the machine (p49) and the experiments (p33) during this period. The LHC's story has a long way to go, and it has parallels with LIGO and its quest to detect gravitational waves. In 1987, when a planning group set up by the CERN Council recommended a high-luminosity proton–proton collider with a centre-of-mass energy of 13–15 TeV, LIGO had just been founded as a Caltech/MIT project. Site construction for LIGO began in 1994, the year the LHC was approved, and, two decades later, these two infrastructures made history with the direct discoveries of the Higgs boson and gravitational waves. Now, with the high-luminosity LHC upgrade and an enhanced Advanced LIGO "Plus" under way, physicists are vying to build a Higgs factory and a third-generation gravitational-wave interferometer to exploit these epochal discoveries to the full. Plans for the former have been at the centre of discussions of the European strategy update, which is about to conclude, while, as we report on p53, two sites in Europe are bidding to host the Einstein Telescope (ET). Interferometers might be cheaper than colliders, but, as former LIGO director Barry Barish explains in our interview on p61, a project like the ET requires professional management, tough decisions and a healthy appetite for risk.

Also in this issue: MICE reports results on muon-ionisation cooling (p7); AMS emerges from repair (p9); protons treat heart arrhythmia (p11); particle physics turns green (p59); machine-learning talks (p70); news briefs (p15); meeting reports (p23); reviews (p67); and much more.

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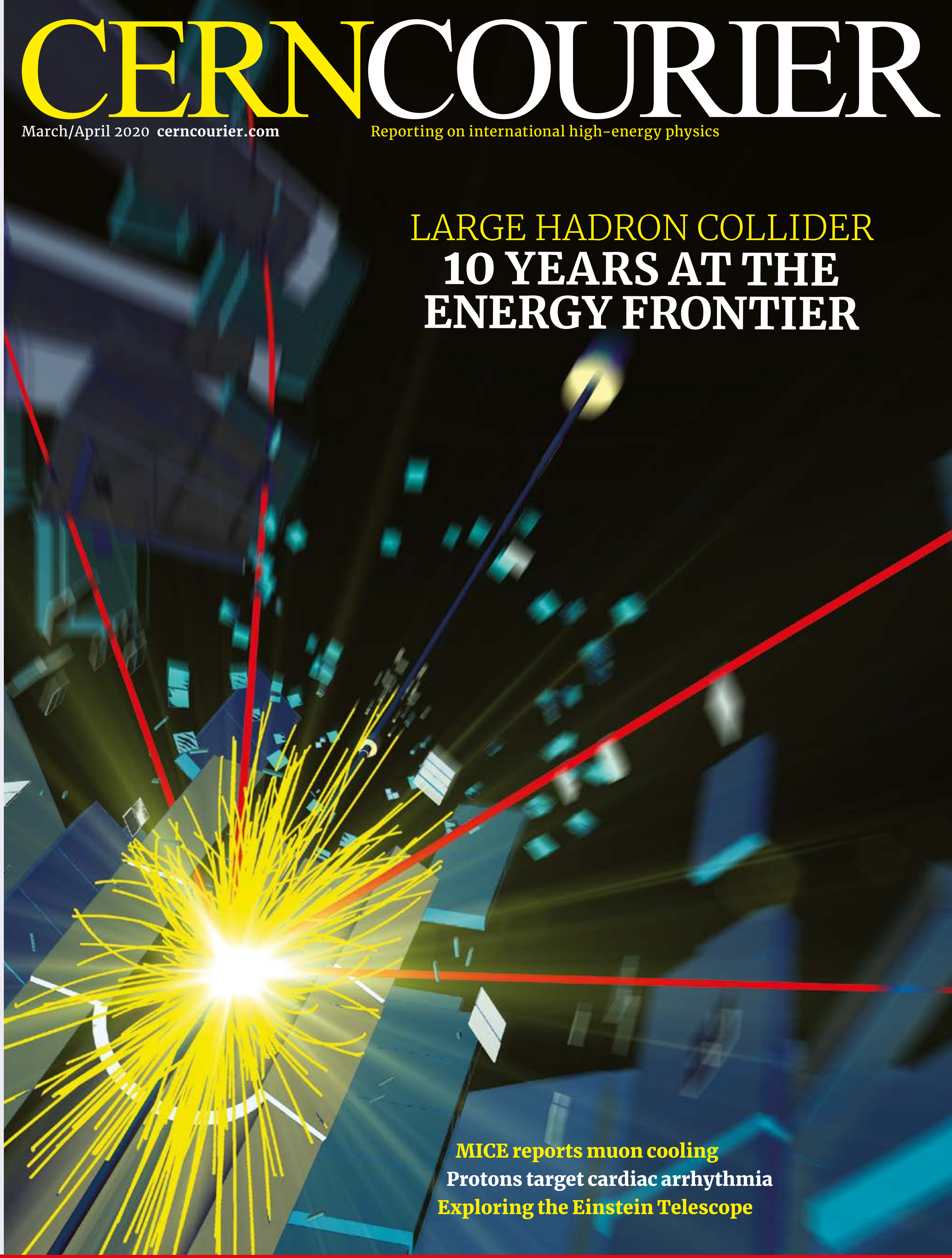

CERNCOURIER

March/April 2020 cerncourier.com

Reporting on international high-energy physics

LARGE HADRON COLLIDER
10 YEARS AT THE
ENERGY FRONTIER

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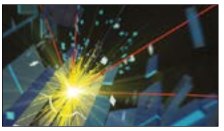

On the cover: *Treated image of a candidate H → ZZ* → 4μ decay recorded by ATLAS on 10 June 2012.* 40

FROM THE EDITOR

Big physics, monumental returns

Matthew Chalmers
Editor

When, 10 years ago, debris from the LHC's first high-energy proton–proton collisions sprayed through the four main detectors, the atmosphere at CERN was one of elation. After a tortuous wait, physicists had their first glimpse of nature at an uncharted energy. This issue of the *Courier* looks at the monumental impact of the LHC's first 10 years of physics at the high-energy frontier (p40), which has already unearthed a new elementary boson, enriched our understanding of the Standard Model and transformed ideas about the capabilities of hadron colliders. Hearing from those who have been at the sharp end of the machine (p49) and the experiments (p33) during this period, it is incredible that these colossal and complex instruments work as well as they do.

The LHC's story has strong parallels with LIGO and its quest to detect gravitational waves. Either project could have come up short, or failed technologically. Their successes are testament to bold decisions, careful long-term planning and the dedication and ingenuity of thousands of people, in particular, in the LHC's case, those who have undertaken vital applied work in accelerators, detectors and computing.

It was 1987 when a planning group, set up by the CERN Council and chaired by Carlo Rubbia, recommended that CERN's next major facility should be a high-luminosity proton–proton collider with a centre-of-mass energy of 13–15 TeV. At that time, LIGO had just been founded as a Caltech/MIT project. Site construction for LIGO began in 1994, the year the LHC was approved, and, two decades later, within a few years of one another, these two infrastructures made history with the direct discoveries of the Higgs boson and gravitational waves – 50 and 100 years after their respective theoretical predictions.

The LHC's story has strong parallels with LIGO and its quest to detect gravitational waves

The next generation

Now, with the LHC in the process of its high-luminosity upgrade (due to operate from 2027) and with work underway for an enhanced Advanced LIGO "Plus" (due to come online in 2024), both communities are vying to build the facilities that will exploit these epochal discoveries to the full: a Higgs factory and a third-generation gravitational-wave interferometer at least 10 times more sensitive than existing facilities, both of which could come online in the 2030s. Proposals for the former have been at the centre of discussions of the European strategy update, which is about to conclude (p10), while, as we report on p53, two sites in Europe are bidding to host the Einstein Telescope (ET). Interferometers might be cheaper than colliders, but, as former LIGO director Barry Barish explains in our interview on p61, a project like the ET requires professional management, tough decisions to build the right teams, and a healthy appetite for risk among well-informed funding agencies. Technological R&D and design efforts for the ET also have interesting overlaps with particle-physics capabilities, as demonstrated recently by the use at Advanced Virgo in Italy of a precision laser inclinometer developed by CERN and JINR to monitor the motion of underground structures.

Also in this issue: the MICE collaboration has reported its results on muon-ionisation cooling (p7); AMS stands ready for further cosmic-ray scrutiny (p9); ideas to make particle physics greener (p59); applying machine-learning to language (p70); meeting reports (p23); news briefs (p15); reviews (p67); and more.

M Struik/CERN

Particle fever *The LHCb control room on 30 March 2010, when first collisions at 7 TeV were established at the LHC.*

Reporting on international high-energy physics

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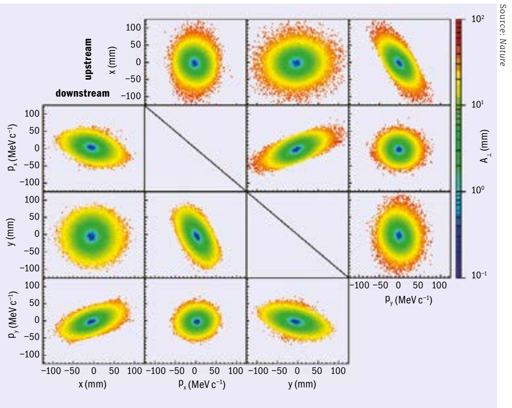
NEWS ANALYSIS

Accelerators

MICE reports muon–ionisation cooling

Particle physicists have long coveted the advantages of a muon collider, which could offer the precision of a LEP-style electron–positron collider without the energy limitations imposed by synchrotron-radiation losses. The clean neutrino beams that could be produced by bright and well-controlled muon beams could also drive a neutrino factory. In a step towards demonstrating the technical feasibility of such machines, the Muon Ionisation Cooling Experiment (MICE) collaboration has published results showing that muon beams can be "cooled" in phase space.



Source: *Nature*

Phase space *Measured phase-space distributions upstream and downstream of the low-Z target. The muons are coloured according to their transverse amplitude, a measure of their "single-particle emittance".*

Muon colliders can in principle reach very high centre-of-mass energies and luminosities, allowing unprecedented direct searches of new heavy particles and high-precision tests of standard phenomena, explains accelerator physicist Lenny Rivkin of the Paul Scherrer Institute in Switzerland, who was not involved in the work. "Production of bright beams of muons is crucial for the feasibility of these colliders and MICE has delivered a detailed characterisation of the ionisation-cooling process – one of the proposed methods to achieve such muon beams," he says. "Additional R&D is required to demonstrate the feasibility of such colliders."

Force feeding

The potential benefits of a muon collider come at a price, as muons are unstable and much harder to produce than electrons. This imposes major technical challenges and, not least, a $2.2\,\mu s$ stopwatch on accelerator physicists seeking to accelerate muons to longer lifetimes in the relativistic regime. MICE has demonstrated the essence of a technique called ionisation cooling, which squeezes the watermelon-sized muon bunches created by smashing protons into targets into a form that can be fed into the accelerating structures of a neutrino factory or the more advanced subsequent cooling stage required for a muon collider – all on a time frame that is short compared to the muon lifetime.

An alternative path to a muon collider or neutrino factory is the recently proposed Low Emittance Muon Accelerator (LEMMA) scheme, whereby a naturally cool muon beam would be obtained by capturing muon–antimuon pairs created in electron–positron annihilations.

Based at the Rutherford Appleton Laboratory (RAL) in the UK, and two decades in the making (*CERN Courier* July/August 2018 p19), MICE set out to reduce the spatial extent, or more precisely the otherwise approximately conserved phase-space volume, of a muon beam by passing it through a low-Z (atomic number) material while tightly focused, and then restoring the lost longitudinal momentum in such a way that the beam remains bunched and matched. This is only possible in low-Z materials where multiple scattering is small compared to energy loss via ionisation. The few-metre-long MICE facility, which precisely measured the phase-space coordinates of individual muons upstream and downstream of the absorber (see figure), received muons generated by intercepting the proton beam from the ISIS facility with a cylindrical titanium target. The absorber was either liquid hydrogen in a tank with thin windows or solid lithium hydride, in both cases surrounded by coils to achieve the necessary tight focus and maximise transverse cooling.

A full muon-ionisation cooling channel would work by progressively damping the transverse momentum of muons over multiple cooling cells while restoring lost longitudinal momentum in radio-frequency cavities. However, due to issues with the spectrometer solenoids and the challenges of integrating the four-cavity linac module with the coupling coil, explains spokesperson Ken Long of Imperial College London, MICE adopted a simplified design without cavities. "MICE has demonstrated ionisation cooling," says Long. The next issues to be addressed, he says, are the engineering integration of an appropriate demonstrator system, cooling down to the lower emittances needed at a muon collider, and investigations into the effect of bulk ionisation on absorber materials. "The execution of a 6D cooling experiment is feasible – and is being discussed in the context of the Muon Collider Working Group."

The execution of a 6D cooling experiment is feasible

Extraordinary challenges

The MICE result was obtained with data collected in 2017 and the collaboration confirmed muon cooling by observing an increased number of "low-amplitude" muons after the passage of the muon beam through an absorber. In this context, the amplitude is an additive contribution to the overall emittance of the beam, with a lower emittance corresponding to a higher density of muons in transverse phase space. The feat presented some extraordinary challenges, and the team says that instrumentation developed for MICE made a single-particle analysis possible for the first time in an accelerator-physics experiment.

"We started MICE in 2000 with great enthusiasm and a strong team from all continents," says MICE founding spokesperson Alain Blondel of the University of Geneva. "It has been a long and difficult road, with many practical novelties to solve. However, the collaboration has held together with exceptional resilience and the host institution never failed us. It is a great pride to see the demonstration achieved, just at a time when it becomes evident to many new people that we must include muon machines in the future of particle physics."

Further reading

MICE Collaboration 2020 *Nature* **578** 53.

Cosmic rays

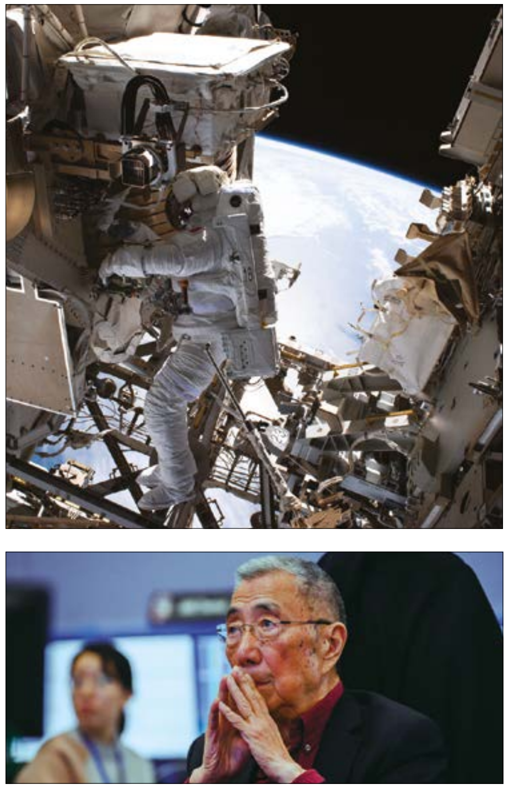
AMS detector given a new lease of life

On 25 January, European Space Agency astronaut Luca Parmitano stepped outside a half-million-kilogramme structure travelling at tens of thousands of kilometres per hour, hundreds of kilometres above Earth, and, tethered by a thin cord, ventured into the vacuum of space to check for a leak. It was the fourth such extravehicular activity (EVA) he'd been on in two months. All things considered, the task ahead was relatively straightforward: to make sure that a newly installed cooling system for the Alpha Magnetic Spectrometer (AMS), the cosmic-ray detector that has been attached to the International Space Station (ISS) since 2011, had been properly plumbed in.

Heart-stopping spacewalks

The first EVA on 15 November saw Parmitano and fellow astronaut, NASA's Drew Morgan, remove and jettison the AMS debris shield, which is currently still spiralling its way to Earth, to allow access to the experiment's cooling system. The CO_2 pumps, needed to keep the 200,000-channel tracker electronics at a temperature of 10 ± 3 °C, had started to fail in 2014 – which was no surprise, as AMS was initially only supposed to operate for three years. During the second EVA on 22 November, the astronauts cut through the cooling system's eight stainless-steel lines to isolate and prepare it for removal, and a critical EVA3 on 2 December saw Morgan and Parmitano successfully connect the new pump system, which had been transported to the ISS by an Antares rocket the previous month. Then came a long wait until January to find out if the repair had been successful.

"EVA4 was the heart-stopping EVA because that's where we did the leak tests on all those tubes," says Ken Bollweg, NASA's AMS project manager. The success of the previous EVAs suggested that the connections were going to be fine. But Parmitano arrived at the first tube, attached one of 29 bespoke tools developed specially for the AMS repair, and saw that the instrument had issued a warning signal. "I see red," he reported to anxious teams at NASA's Johnson Space Center's Mission Control Center and the AMS Payload Operations Control Centre (POCC) at CERN's Prévessin site, from where spokesperson Sam Ting and his colleagues were monitoring proceedings closely. Though not huge, the leak was serious enough not to guarantee that the system would work, jeopardising four years of preparation involving hundreds of astronauts, engineers and scientists. Following procedures put in place to deal with such a situation, Parmitano tightened the connection and waited for about an hour before checking the tube again. A leak was still present. Then, after re-tightening the troublesome connection again, while the team was preparing a risky "jumper" manoeuvre to bypass the leak and make a new connection, he checked a third time: "No red!" Happy faces lit up the POCC.


NASA

N Caraban/CERN

Out of this world *(Top) Luca Parmitano checking the installation of the Upgraded Tracker Thermal Pump System for AMS (seen above his head), while AMS spokesperson Sam Ting monitors proceedings from CERN.*

AMS was never designed to be serviceable, and the repair, unprecedented in complexity for a space intervention, required the avoidance of sharp edges and other hazards in order to bring it back to full operational capacity. The chances of something going wrong were high, says Bollweg. "NASA has learned a lot of new things from this. We really pushed the envelope. It showed that we have the capabilities to do even more than we have done in the past." EVA4 lasted almost six hours. Five hours and two minutes into it, Parmitano, who returned safely to Earth on 6 February, broke the European record for the most time spent spacewalking (33 hours and nine minutes). It's not a job for the faint-hearted. During a spacewalk in 2013, while wedged into a confined space outside the ISS, a malfunction in Parmitano's spacesuit caused his helmet to start filling with water and he almost drowned.

NASA has learned a lot of new things from this

"Building and operating AMS in space has been an incredible journey through engineering and physics, but today it is thanks to the NASA group that in AMS we can continue this journey and this is amazing. An enormous thanks to the EVA crew," said AMS integration engineer Corrado Gargiulo of CERN. The day after EVA4, the POCC team spent about 10 hours refilling the new AMS cooling system with 1.3 kg of CO_2 and started to power up the detector. At noon on 27 January, all the detector's subsystems were sending data back, marking a new chapter for AMS that will see it operate for the lifetime of the ISS.

Unexpected behaviours

The 7.5 tonne AMS apparatus has so far recorded almost 150 billion charged cosmic rays with energies up to the multi-TeV range, and its percent-level results show unexpected behaviour of cosmic-ray events at high energies (*CERN Courier* December 2016 p26). A further 10 years of operation will allow AMS to make conclusive statements on the origin of these unexpected observations, says Ting. "NASA is to be congratulated on seeing this difficult project through over a period of many years. AMS has observed unique features in cosmic-ray spectra that defy traditional explanations. We're entering into a region where nobody has been before."

The first major result from AMS came in 2013 (*CERN Courier* October 2013 p22), when measurements of the cosmic positron fraction (the ratio of the positron flux to the flux of electrons and positrons) up to an energy of 350 GeV showed that the spectrum fits well to dark-matter models. The following year, AMS published the positron and electron fluxes, which showed that neither can be fitted with the single-power-law assumption underpinning ▷

AMS has observed unique features in cosmic-ray spectra that defy traditional explanations

the traditional understanding of cosmic rays. The collaboration has continued to find previously unobserved features in the measured fluxes and flux ratio of electrons and positrons.

Last year, AMS reaffirmed the complex energy dependence exhibited by the positron flux: a significant excess starting from 25 GeV, a sharp drop-off above 284 GeV and a finite energy cutoff at 810 GeV. "In the entire energy range the positron flux is well described by the sum of a term associated with the positrons produced in the collision of cosmic rays, which dominates at low energies, and a new source term of positrons, which dominates at high energies," says Ting. "These experimental data on cosmic-ray positrons show that, at high energies, they predominantly originate either from dark-matter annihilation or from other astrophysical sources." Although dark-matter models predict such a cut off, the AMS data cannot yet rule out astrophysical sources, in particular pulsars. Further intrigue comes from the latest, to-be-published, AMS result on antiprotons, which, although rare at high energies, exhibit similar functional behaviour as the positron spectrum. "This indicates that the excess of positrons may not come from pulsars due to the similarity of the two spectra and the high mass of antiprotons," says Ting.

Novelties in nuclei

Unexpected results continue to appear in data from cosmic nuclei, which make up the bulk of cosmic rays travelling through space. Helium, carbon and oxygen nuclei are thought to be mainly produced and accelerated in astrophysical sources and are known as primary cosmic rays, while lithium, beryllium and boron nuclei are produced by the collision of heavier nuclei with nuclei of the interstellar matter and are known as secondary cosmic rays. New properties of primary cosmic rays – helium, carbon and oxygen – have been observed in the rigidity range 2 GV to 3 TV; at high energies these three spectra also have identical rigidity dependence, all deviating from a single power law above 200 GV. Similar oddities have appeared in measurements of secondary cosmic rays – lithium, beryllium and boron – in the range 1.9 GV to 3.3 TV; the lithium and boron fluxes have an identical rigidity dependence above 7 GV, all three fluxes have an identical rigidity dependence above 30 GV, and, unexpectedly, above 30 GV the Li/Be flux ratio is approximately equal to two.

The ratio of secondary fluxes to primary fluxes is particularly interesting because it directly measures the amount and properties of the interstellar medium. The latest AMS results on secondary-to-primary flux ratios show a significantly different power-law behaviour between the two rigidity ranges $60 < R < 200$ GV and $200 < R < 3300$ GV. By 2028, says Ting, AMS will extend its measurements of cosmic nuclei up to $Z = 30$ (zinc) with sufficient statistics to get to the bottom of these and other mysteries. "We have measured many particles, electrons, positrons, antiprotons and many nuclei, and they all have distributions and none agree with current theoretical models. So we will begin to create a new field."

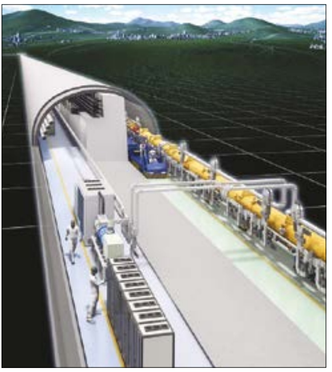
- *A full report on the latest results from AMS is available at cerncourier.com/c/astrophysics-cosmology/.*

Further reading

AMS Collab. 2019 *Phys. Rev. Lett.* **122** 041102.
AMS Collab. 2018 *Phys. Rev. Lett.* **120** 021101.

POLICY

Japan identifies priorities


R Hori/KEK

Long view *An International Linear Collider in Japan has been on the table since 2012.*

The International Linear Collider (ILC), currently being considered to be hosted in the Tohoku region of Japan, has not been selected as a high-priority project in the country's 2020 "master plan" for large research projects. The master plan, which is compiled every three years, was announced on 30 January by the Science Council of Japan. Among 31 projects that did make it onto the high-priority list were the Super-B factory at KEK, the KAGRA gravitational-wave laboratory and an upgrade of the J-PARC facility. The recently approved Hyper-Kamiokande experiment (see p15) was a top priority in the 2017 master plan and therefore is not listed in the latest report.

At a press conference held on 31 January, member of the Japanese government's cabinet office, Naokazu Takemoto, who is minister of state for science and technology policy, said: "To put it simply, the project made it through the first round of evaluations, and there were about 60 such projects. In the second round, 31 projects were selected, and the ILC was not among them. However, this is a viewpoint of the Science Council. When considering the possibilities going forward, MEXT [Ministry of Education, Culture, Sports, Science and Technology] will look at high-priority research topics, and I hear that the ILC will be included in the list of these topics."

Director of the Linear Collider Collaboration, Lyn Evans, says it is no surprise that the ILC is not on the Science Council's list. "It is of a different order of magnitude to any other project the committee considered. It also requires broad international collaboration. The important thing is that discussions on how to share the burden start soon."

Strategy drafting session concludes


Wikicommons/Birds-eye

From 20 to 25 January, senior figures in European particle physics gathered in Physikzentrum Bad Honnef, Germany (pictured), for the "drafting session" of the update of the European Strategy for Particle Physics. Convened by the European Strategy Group (ESG), which includes a scientific delegate from each of CERN's member and associate-member states, directors and representatives of major European laboratories and organisations, and invitees from outside Europe, the 60 or so attendees were tasked with identifying a set of priorities and recommendations to the CERN Council.

Following the week-long discussions, the ESG released a statement reporting that convergence had been achieved. The ESG recommendations will be presented to the CERN Council in March and are currently scheduled to be made public at an event in Budapest, Hungary, on 25 May.

OUTREACH

Ascent commemorates cosmic-ray pioneers

On 25 January, a muon detector, a particle physicist and a prizewinning pilot ascended 4000 m above the Swiss countryside in a hot-air balloon to commemorate the discovery of cosmic rays. The event was the highlight of the opening ceremony of the 42nd Château-d'Oex International Balloon Festival, attended by an estimated 30,000 people, and attracted significant media coverage.

In the early 1900s, following Becquerel's discovery of radioactivity, studying radiation was all the rage. Portable electrometers were used to measure the ionisation of air in a variety of terrestrial environments, from fields and lakes to caves and mountains. With the idea that ionisation should decrease with altitude, pioneers adventured in balloon flights as early as 1909 to count the number of ions per cm^3 of air as a function of altitude. First results indeed indicated a decrease up to 1300 m, but a subsequent ascent to 4500 m by Albert Gockel, professor of physics at Fribourg, concluded that ionisation does not decrease and possibly *increases* with altitude. Gockel, however, who later would coin the term "cosmic radiation", was unable to obtain the hydrogen needed to go to higher altitudes. And so it fell to Austrian physicist Victor Hess to settle the case. Ascending to 5300 m in 1912, Hess clearly identified an increase, and went on to share the 1936 Nobel Prize in Physics for the discovery of cosmic rays. Gockel, who died in 1927, could not be awarded, and for that reason is almost forgotten by history.


M Hoch


M Hoch

For the love of physics *Left: the balloon shortly after taking off, showing CAEN's Cosmic Hunter inside a heated box attached to the basket and passenger Hans Peter Beck with pilot Nicolas Tièche. Top: the view from above.*

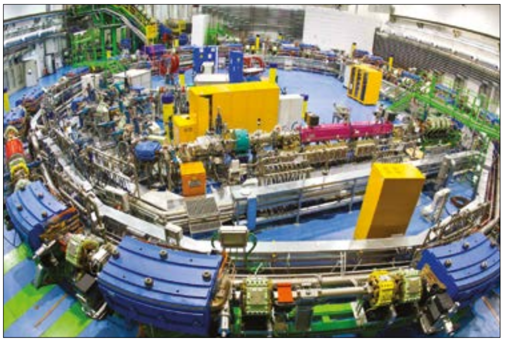
ATLAS experimentalist Hans Peter Beck of the University of Bern, and a visiting professor at the University of Fribourg, along with two students from the University of Fribourg, reenacted Gockel's and Hess's pioneering flights using 21st-century technology: a muon telescope called the Cosmic Hunter, newly developed by instrumentation firm CAEN. The educational device, which counts coincidences in two scintillating-fibre tiles of 15×15 cm^2 separated by 15 cm, verified that the flux of cosmic rays increases as a function of altitude. Within two hours of landing, including a one-hour drive back to the starting point, Beck was able to present the data plots during a public talk attended by more than 250 people. A second flight up to 6000 m is planned, with oxygen supplies for passengers, when weather conditions permit.

"Relating balloons with particle physics was an easy task, given the role balloons played in the early days for the discovery of cosmic rays," says Beck. "It is a narrative that works and that touches people enormously, as the many reactions at the festival have shown."

The event – a collaboration with the universities of Bern and Fribourg, the Swiss Physical Society, and the Jungfraujoch research station – ran in parallel to a special exhibition about cosmic rays at the local balloon museum, organised by Beck and Michael Hoch from CMS, which was the inspiration for festival organisers to make physics a focus of the event, says Beck: "Without this, the festival would never have had the idea to bring 'adventure, science and freedom' as this year's theme. It's really exceptional."

APPLICATIONS

Protons herald new cardiac treatment


CNAO

Striking application *The 80 m-circumference synchrotron at CNAO, which is isolated from the treatment rooms by reinforced concrete shielding.*

In a clinical world-first, a proton beam has been used to treat a patient with a ventricular tachycardia, which causes unsynchronised electrical impulses that prevent the heart from pumping blood. On 13 December, a 150 MeV beam of protons was directed at a portion of tissue in the heart of a 73-year-old male patient at the National Center of Oncological Hadrontherapy (CNAO) in Italy – a facility set out 25 years ago by the TERA Foundation and rooted in accelerator technologies developed in conjunction with CERN via the Proton Ion Medical Machine Study (PIMMS). The successful procedure had a minimal impact on the delicate surrounding tissues, and marks a new path in the rapidly evolving field of hadron therapy.

The use of proton beams in radiation oncology, first proposed in 1946 by founding director of Fermilab Robert Wilson, allows a large dose to be deposited in a small and well-targeted volume, reducing damage to healthy tissue surrounding a tumour and thereby ▷

reducing side effects. Upwards of 170,000 cancer patients have benefitted from proton therapy at almost 100 centres worldwide, and demand continues to grow (*CERN Courier* January/February 2018 p32).

The choice by clinicians in Italy to use protons to treat a cardiac pathology was born out of necessity to fight an aggressive form of ventricular tachycardia that had not responded effectively to traditional treatments. The idea is that the Bragg peak typical of light charged ions (by which a beam can deposit a large amount of energy in a small region) can produce small scars in the heart tissues similar to the ones caused by the standard invasive technique of RF cardiac ablation. "To date, the use of heavy particles (protons, carbon ions) in this area has been documented in the international scientific literature only on animal models," said Roberto Rordorf, head of arrhythmology at San Matteo Hospital, in a press release on 22 January. "The Pavia procedure appears to be the first in the world to be performed on humans and the first results are truly encouraging. For this reason, together with CNAO we are evaluating the feasibility of an experimental clinical study."

I think that in 20 years' time cardiac arrhythmias will be mostly treated with light-ion accelerators

Hadron therapy for all

CNAO is one of just six next-generation particle-therapy centres in the world capable of generating beams of protons and carbon ions, which are biologically more effective than protons in the treatment of radioresistant tumours. The PIMMS programme from which the accelerator design emerged, carried out at CERN from 1996 to 2000, aimed to design a synchrotron optimised for ion therapy (*CERN Courier* January/February 2018 p25). The first dual-ion treatment centre in Europe was the Heidelberg Ion-Beam Therapy Centre (HIT) in Germany, designed by GSI, which treated its first patient in 2009. CNAO followed in 2011 and then the Marburg Ion-Beam Therapy Centre in Germany (built by Siemens and operated by Heidelberg University Hospital since 2015). Finally, MedAustron in Austria, based on the PIMMS design, has been operational since 2016. Last year, CERN launched the Next Ion Medical Machine Study (NIMMS) as a continuation of PIMMS to carry out R&D into the superconducting magnets, linacs and gantries for advanced hadron therapy. NIMMS will also explore ways to reduce the cost and footprint of hadron therapy centres, allowing more people in different regions to benefit from the treatment (*CERN Courier* March 2017 p31).

"When I decided to leave the spokesmanship of the DELPHI collaboration to devote my time to cancer therapy with light-ion beams I could not imagine that, 30 years later, I would have witnessed the treatment of a ventricular tachycardia with a proton beam and, moreover, that this event would have taken place at CNAO, a facility that has its roots at CERN," says TERA founder Ugo Amaldi. "The proton treatment recently announced, proposed to CNAO by cardiologists of the close-by San Matteo Hospital to save the life of a seriously ill patient, is a turning point. Since light-ion ablation is non-invasive and less expensive than the standard catheter ablation, I think that in 20 years' time cardiac arrhythmias will be mostly treated with light-ion accelerators. For this reason, TERA has secured a patent on the use of ion linacs for heart treatments."

ASTROWATCH

Renewed doubt cast on origin of fast radio bursts

Fast radio bursts (FRBs), intense few-millisecond bursts of radio waves, are a relatively new mystery within astrophysics. Around 100 of these objects have been spotted since the first detection in 2007, but hardly anything is known about their origin. Thanks to close collaboration between different radio facilities and lessons learned from the study of previous astrophysical mysteries such as quasars, our understanding of these phenomena is evolving rapidly. During the past year or so, several FRBs have been localised in different galaxies, strongly suggesting that they are extra-galactic. A newly published FRB measurement, however, casts doubts about their underlying origin.

On the hunt *The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is one of several radio telescopes scouring the sky for fast radio bursts.*

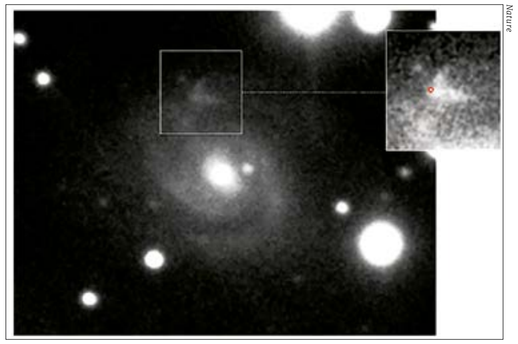
CHIME collaboration

The repeater

As recently as one year ago, only a few tens of FRBs had been measured. One of these FRBs was of particular interest because, unlike the single-event nature of all other known FRBs, it produced several radio signals within a short time scale – earning it the nickname "the repeater" (*CERN Courier* January/February 2019 p13). This could imply that while all other FRBs were a result of some type of cataclysmic event, the repeater was an altogether different source that just happened to produce a similar signal. Adding to the intrigue, measurements also showed it to be in a rather peculiar high-metallicity dwarf galaxy close to the supermassive black hole within this host galaxy.

Much has happened in the field of FRBs since then, mainly thanks to data from new facilities such as ASKAP in Australia, CHIME in Canada (pictured), and FAST in China. A number of new FRBs have been detected including nine more repeaters. Additionally, the new range of facilities has allowed for more detailed location measurements, including some for non-repeating FRBs, which are more challenging due to their unpredictable occurrence. Since non-repeating bursts were found to be in more conventional galaxies than that of the original repeater, a fully different origin of the two types of FRBs seemed the more likely explanation.

The latest localisation measurement of an FRB, using data from CHIME and subsequent triangulation via eight radio telescopes from the European VLBI network, throws this theory into question.



Radio star *The new, repeating FRB (red circle) was traced to a star-forming-region of a fairly ordinary spiral galaxy.*

Nature

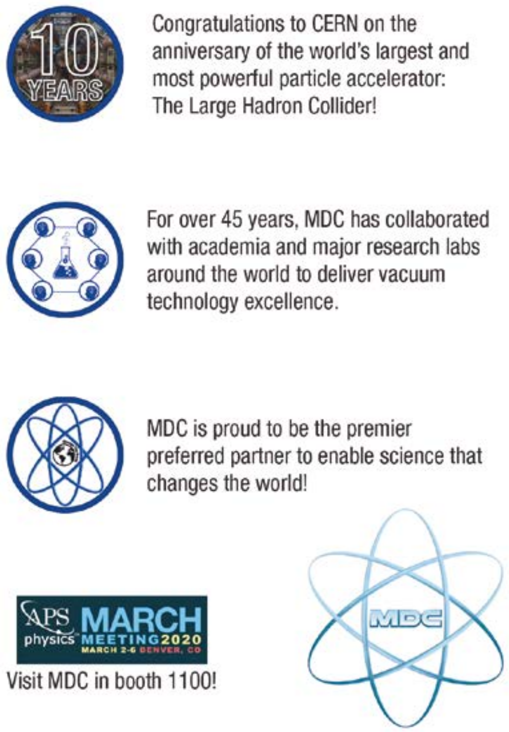
Writing in *Nature*, the international team found that another repeater was not only the closest FRB found to date (at a distance of 500 million light years), it was found in a star-forming region of a galaxy not that different from the Milky Way and therefore very different from the other localised repeating FRB. This precise localisation measurement, which allowed astronomers to pinpoint the location within an area just seven light years across, indicates that extreme environments are not required for repeater FRBs. Additionally, some of the repeated signals from this source were not strong enough to have come from any of the non-repeating FRBs as these are all at a larger distance. The latter finding casts doubt on the idea of two distinct classes of FRBs as the non-repeaters could just simply be too far away for some of their signal to reach us.

New insights

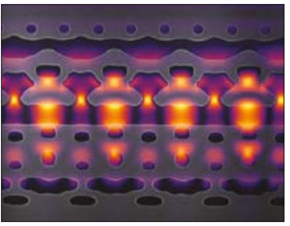
Although these latest findings give new insights into the quickly evolving field of FRBs, it is clear that more measurements are required. The new radio facilities will soon make population studies possible. Such studies have previously answered many questions for the fields of gamma-ray bursts and quasars, which, in their early stages, showed large similarities with the state in which FRB studies are now. They could show, for instance, if one of the two vastly differing environments in which the two repeaters are found is simply a peculiarity or if FRBs can be produced in a range of different environments. Additionally, studies of the burst intensities and the distances of their origin will be able to prove if repeaters and non-repeaters are only different because of their distance.

Further reading

K W Bannister *et al.* 2019 *Science* **365** 565.
B Marcote *et al.* 2020 *Nature* **577** 190.



NEWS DIGEST


N Sapra

An SEM image of the few-micron-wide chip, with its electric field overlaid.

Accelerator integrated on a chip
Physicists at Stanford University and SLAC National Accelerator Laboratory have used lasers to accelerate electrons along an etched channel on a silicon chip. A bunch of 80 keV electrons gained 915 eV over a span of 30 microns – an accelerating gradient of 30.5 MV/m – having been driven through the nanostructured channel by a pulsed laser. Dielectric laser accelerators (DLAs) potentially offer radical miniaturisation compared with traditional radio-frequency technology, but previous designs required separate devices to generate the electrons. In a step towards a completely integrated MeV-scale device, the US team used a photonic inverse-design approach to demonstrate a waveguide-integrated DLA (*Science* **367** 6473).

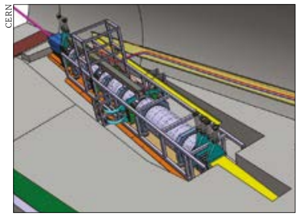
Brookhaven to host EIC
Brookhaven National Laboratory (BNL) has been selected as the site for the planned Electron–Ion Collider (EIC), edging out competition from the Thomas Jefferson National Accelerator Facility (JLab). The decision, announced by the US Department of Energy on 9 January, will see BNL's Relativistic Heavy-Ion Collider reconfigured to include a new electron storage ring to facilitate electron–ion collisions. Scheduled to enter operation at the end of the decade, the EIC will pivot BNL's physics focus from the study of the quark–gluon plasma to nuclear femtography (*CERN Courier* October 2018 p31).

Double first for ISOLDE
The atomic nucleus possesses certain magic numbers (2, 8, 20, 28, 50, 82, 126) of either protons or neutrons after which the next proton or neutron to be added has a noticeably lower binding energy. A high-precision measurement of the nuclear mass of ^{132}Cd from CERN's radioactive-beam facility, ISOLDE, has allowed researchers to probe the $N = 82$ neutron binding below the $Z = 50$ (proton) magic number for the first time (arXiv:2001.05075, accepted in *Phys. Rev. Lett.*). Another recently published paper from ISOLDE offers the first exploration of the neutron shell structure beyond $N = 126$ and below the doubly magic ^{208}Pb, by probing neutron excitations in ^{207}Hg (*Phys. Rev. Lett.* **124** 062502). These neutron-rich nuclides are crucial for understanding the rapid neutron-capture process that is responsible for the creation of approximately half of the atomic nuclei heavier than iron. The ^{207}Hg result was obtained with the new post-accelerated beams of HIE-ISOLDE, complementing the low-energy result on ^{132}Cd.

Hyper-K approved
The University of Tokyo, KEK and J-PARC announced on 12 February that the Hyper-Kamiokande (HK) project has been officially approved by the Japanese parliament. With a first-year construction budget of 3.5 billion Yen ($32 million), HK will have a fiducial mass 8.4 times larger than its predecessor, Super-Kamiokande, conferring sensitivity to proton decay, astrophysical neutrinos and leptonic CP violation via the detection of accelerator neutrinos from the soon-to-be-upgraded J-PARC accelerator facility on the opposite coast (p25). Operations are due to begin in 2027.

The shape of the future
In a preprint posted on 31 December, 53 physicists, among them previous CERN Council presidents, former CERN Directors-General and leading members of the LHC experiments, argue that the next major European project after the LHC should be a 100 km-circumference circular collider (arXiv:1912.13466). The authors advocate for the sequential electron–positron and hadron–hadron programme of the Future Circular Collider, labelling it "a visionary programme for the future of CERN". On 15 January, leading members of the Compact Linear Collider (CLIC) collaboration countered that choosing CLIC would allow an energy frontier programme to be maintained while leaving the choice of the following machine to be guided by new results and technology (arXiv:2001.05373).

FASER sets new target
The LHC's Forward Search Experiment (FASER), currently under construction 480 m downstream of ATLAS, will be complemented by a newly approved neutrino detector now expected to observe collider neutrinos for the first time. A 25 × 25 cm stack of emulsion films and tungsten plates, "FASERν", will be placed at the front of the experiment's main detector, which will be tasked with searching for light and weakly interacting particles such as dark photons. Weighing in at 1.2 tonnes, FASERν is expected to detect approximately 20,000 muon neutrinos, 1300 electron neutrinos and 20 tau neutrinos, with energies beyond 1 TeV (arXiv.org:1908.02310).


CERN

FASERν (yellow, right) aspires to observe the first "collider neutrino".

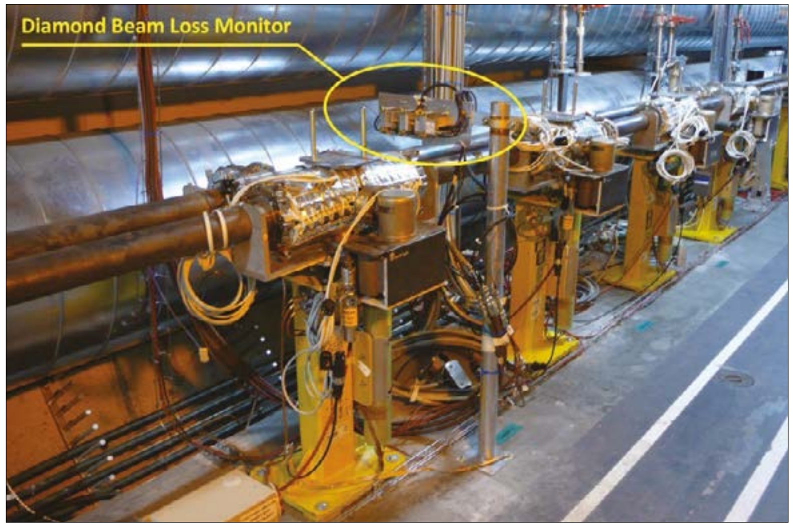
ORCA is in the deep
The first six strings of the Oscillation Research with Cosmics in the Abyss (ORCA) detector have been deployed at the bottom of the Mediterranean Sea and are collecting data. Each string is equipped with 18 clusters of photomultiplier tubes that watch for Cherenkov light from charged particles in the seawater. Located 40 km off the coast of Toulon, France, ORCA will observe atmospheric neutrinos in the few-GeV range to measure the neutrino-mass hierarchy. Its sister experiment in the KM3NeT programme, ARCA, which will have more widely spaced light sensors and be deployed off the coast of Italy, will observe TeV–PeV neutrinos from galactic astrophysical sources.

Gene editing safe to fight cancer
The first clinical trial of the revolutionary CRISPR gene-editing procedure has found it to be safe, feasible and ripe for development, after three cancer patients in their 60s received injections of CRISPR-altered versions of their own T cells, edited to be better at identifying and killing tumours, without serious side effects (*Science* 10.1126/science.aba7365). The cells successfully integrated with the patients' immune systems, and were still found in their blood nine months later. Discovered in 1987 by Yoshizumi Ishino and co-workers, Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) are found in the DNA of bacteria and archaea. CRISPR gene editing, which took off rapidly amid some controversy in the past decade, is inspired by the way bacteria destroy the DNA of invading viruses, and allows researchers to edit DNA at precise locations.

ADVERTISING FEATURE

What's next for the 'small but brilliant'?

Ten years of LHC results and the confirmation of the existence of the Higgs particle are the successful outcomes of a unique challenge to build and operate the CERN LHC and its experiments. CIVIDEC is proud to have been able to contribute to some of the breathtaking developments in this challenge by way of its radiation diagnostic equipment based on CVD diamond detectors and their related electronics. A short summary is given below.



LHC, Collimation Area Point 7, Scraper and Diamond Beam Loss Monitor.

First developments for the LHC

CIVIDEC Instrumentation was founded after the first year of operation of the LHC, stimulated by the BE-BI-BL group at CERN, which decided to develop fast beam-loss monitors for beam diagnostics and machine protection purposes.

After a one-year-long study in the SPS accelerator at CERN, a new type of solid-state ionisation detector device for single-particle detection was developed on the basis of CVD diamond, together with radiation-hard electronics for the direct amplification of the detector signals at the measurement position of these point beam-loss detectors.

The devices provide nano-second time resolution, are sensitive to single MIP particles and have a linear response to high power losses.

Today, several units are installed at the LHC in points 2, 4, 6, 7 and 8, where the time structures of the beam losses are measured over individual LHC cycles and integrated over time. The data is used for beam diagnostics, machine protection and machine performance improvement. Several devices are also in use at the SPS, the PS and the Booster.

Follow-up at SLAC

As a follow-up project, in 2019 CIVIDEC equipped the new 4 GeV superconducting linac at SLAC with CVD diamond point beam-loss monitors (PBLMs), which will be placed at likely loss sites to prevent damage to collimators, stoppers and dumps. The PBLMs are used to integrate bunched losses generated by an electron beam with a 1 MHz repetition rate. They are complementary to long beam-loss monitors (LBLMs) made of radiation-hard optical fibres. The system will serve three functions:

1. Beam containment system, which stops the machine if the beam goes outside its intended location or power.
2. Machine protection system, which halts or rate-limits a beam path if losses exceed the threshold for machine damage.
3. Diagnostics, which helps operators to tune the machine, display losses, indicate loss locations, reduce radiation on beamline components and detect loss signals from fast wire scanners.

More to come

After the LHC beam-loss monitors, CIVIDEC contributed to several developments, such as:

1. Diamond strip detectors for the emittance monitor at the LINAC4.
2. Cryogenic diamond detectors, which are being installed in the interconnect of the quadrupole and the 11 T magnet.
3. Spectroscopic detectors at the ISOLDE facility for particle energy measurements.
4. Neutron monitors for the n_TOF experiment, for the detection of fast and thermal neutrons.
5. A timing detector system for the TOTEM experiment with excellent time resolution.
6. A dedicated detector installation at the CNGS experiment for measuring the departure time of muon neutrinos to Gran Sasso, where the "faster-than-light neutrino anomaly" was refuted.
7. High-radiation diamond beam-position monitors for the HiRadMat facility for extreme ionisation levels.

What's next?

In the near future, new investigations into detector systems for cancer treatment in the field of particle therapy will be launched.

In the longer term, we will continue searching for new technologies for the 'small but brilliant' diamond detectors, and the solutions they offer.

Erich Griesmayer is CEO of CIVIDEC Instrumentation. He has been working at CERN for more than 25 years. As an associated professor at the Vienna University of Technology, he is a member of the ATLAS and n_TOF collaborations at CERN.

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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

ATLAS extends search for top squark

Supersymmetry is an attractive extension of the Standard Model, and aims to answer some of the most fundamental open questions in modern particle physics. For example: why is the Higgs boson so light? What is dark matter and how does it fit in with our understanding of the universe? Do electroweak and strong forces unify at smaller distances?

Supersymmetry predicts a new partner for each elementary particle, including the heaviest particle ever observed – the top quark. If the partner of the top quark (the top squark, or "stop") were not too heavy, the quantum corrections to the Higgs boson mass would largely cancel, thereby stabilising its small value of 125 GeV. Moreover, the lightest supersymmetric particle (LSP) may be stable and weakly interacting, providing a dark-matter candidate. Signs of the top squark, and thus supersymmetry, may yet be lurking in the enormous number of proton–proton collisions provided by the LHC.

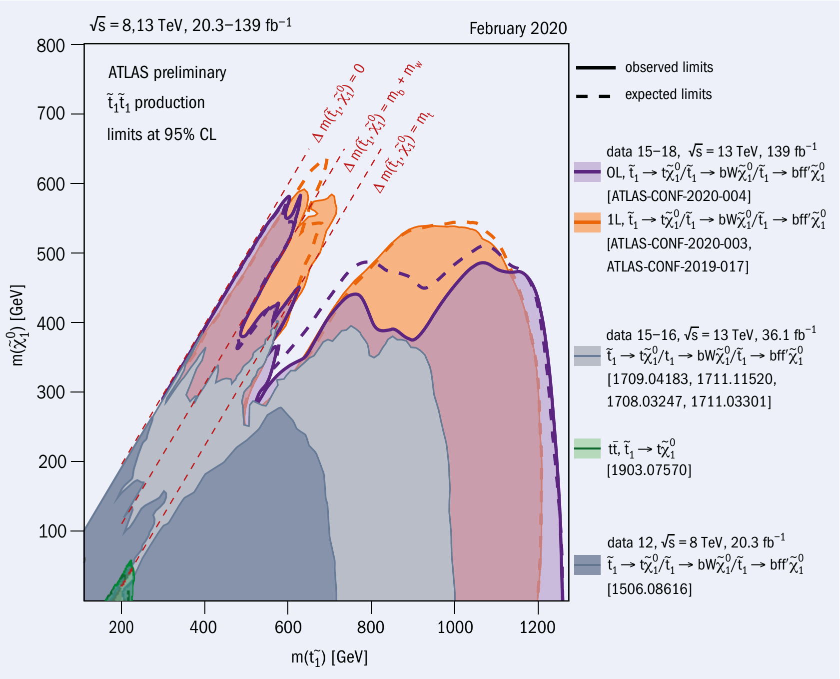


Fig. 1. *The regions of the lightest supersymmetric particle (LSP; here: the lightest neutralino) versus the lightest stop mass excluded by ATLAS in an interpretation using simplified models. The colours demonstrate the extended reach of the new analyses compared to previous ATLAS results using a smaller dataset (grey colours). In the central non-excluded region, close to the kinematic boundary of the stop decay to an on-shell top and the LSP, stop pair production is difficult to distinguish from the top–antitop background.*

Two new searches

The ATLAS collaboration recently released two new searches, each looking to detect pairs of top squarks by exploring the full LHC dataset corresponding to an integrated luminosity of 139 fb^{-1} recorded during Run 2. Each top squark decays to a top quark and an LSP that escapes the detector without interacting. Thus, our experimental signature is an event that is energetically unbalanced, with two sets of top-quark remnants and a large amount of missing energy.

A challenge for such searches is that the masses of the supersymmetric particles are unknown, leaving a large range of possibilities to explore. Depending on the mass difference between the top squark and the LSP, the final decay products can be (very) soft or (very) energetic, calling for different reconstruction techniques and sparking the development of new approaches. For example, novel "soft b-tagging" techniques, based on either pure secondary-vertex information or jets built from tracks, were implemented for the first time in these analyses to extend the sensitivity to lower kinematic regimes. This allowed the searches to probe small top squark–LSP mass differences down to 5 GeV for the first time.

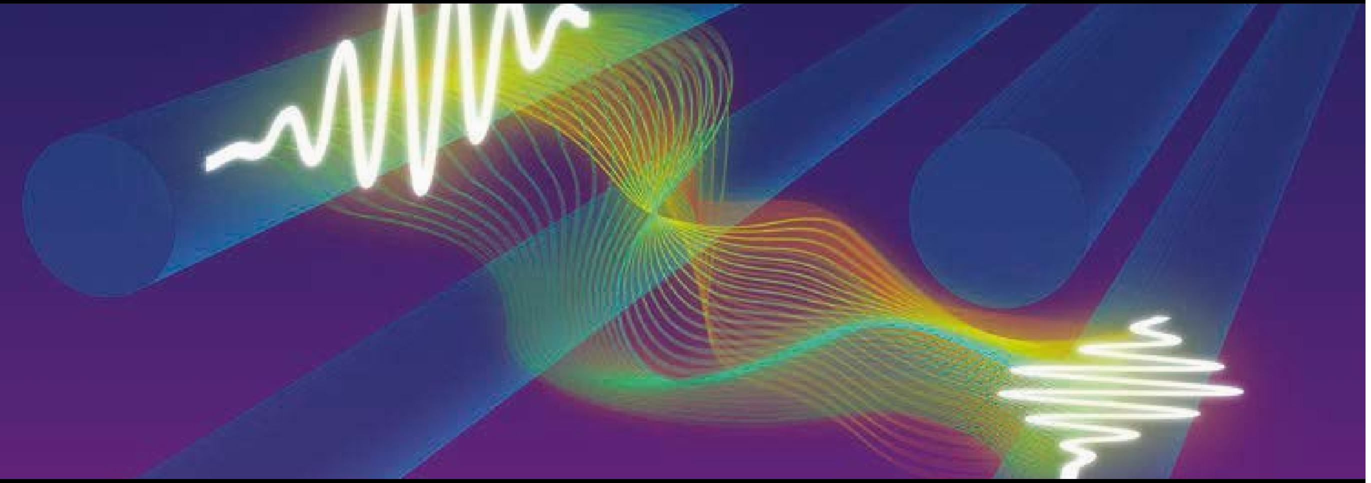
These searches greatly extend the reach in the top squark mass versus LSP mass plane

Other sophisticated analysis strategies, including the use of machine-learning techniques, improved the discrimination between the signal and Standard-Model background and maximised the sensitivity of the analysis. Furthermore, these two searches are designed in such a way as to fully complement one another. Together they greatly extend the reach in the top squark mass versus LSP mass plane, including the challenging region where the top squark masses are very close to the top mass (figure 1). No evidence of new physics was found in any of these searches.

Beyond supersymmetry, these search results are intriguing for other new-physics scenarios. For example, the decay of a hypothetical top quark–neutrino hybrid, called a leptoquark, would exhibit a similar experimental signature to a top-squark decay. The results also constrain models predicting dark matter produced with a pair of top quarks that do not originate from supersymmetry.

Further reading

ATLAS Collaboration 2020 ATLAS-CONF-2020-004.
ATLAS Collaboration 2020 ATLAS-CONF-2020-003.
ATLAS Collaboration 2019 ATLAS-CONF-2019-017.



ALICE

Plasma polarised by spin–orbit effect

Spin–orbit coupling causes fine structure in atomic physics and shell structure in nuclear physics, and is a key ingredient in the field of spintronics in materials sciences. It is also expected to affect the development of the quickly rotating quark–gluon plasma (QGP) created in non-central collisions of lead nuclei at LHC energies. As such, plasmas are created by the collisions of lead nuclei that almost miss each other. They have very high angular momenta of the order of $10^7\hbar$ – equivalent to the order of 10^{21} revolutions per second. While the extreme magnetic fields generated by spectating nucleons (of the order of 10^{14}T, *CERN Courier* Jan/Feb 2020 p17) quickly decay as the spectator nucleons pass by, the plasma's angular momentum is sustained throughout the evolution of the system as it is a conserved quantity. These extreme angular momenta are expected to lead to spin–orbit interactions that polarise the quarks in the plasma along the direction of the angular momentum of the plasma's rotation. This should in turn cause the spins of vector (spin-1) mesons to align if hadronisation proceeds via the recombination of partons or by fragmentation. To study this effect, the ALICE collaboration recently measured the spin alignment of the decay products of neutral K^* and ϕ vector mesons produced in non-central Pb–Pb collisions.

Spin alignment can be studied by measuring the angular distribution of the decay products of the vector mesons. It is quantified by the probability ρ_{00} of finding a vector meson in a spin state 0 with respect to the direction of the angular momentum of the rotating QGP, which is approximately perpendicular to the plane of the beam direction and the impact parameter of the two colliding nuclei. In the absence of spin-alignment effects, the probability of finding a vector meson in any of the three spin states (–1, 0, 1) should be equal, with $\rho_{00} = 1/3$.

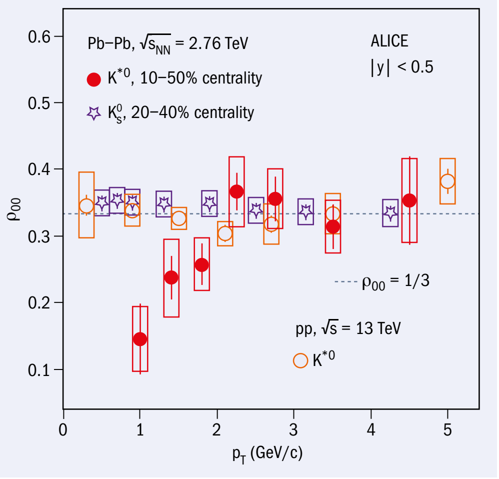


Fig. 1. *The spin alignment of (spin-1) K^{*0} mesons (red circles) can be characterised by deviations from $\rho_{00} = 1/3$, which is estimated here versus their transverse momenta, p_T. The same variable was estimated for (spin-0) K_0^S mesons (magenta stars), and K^{*0} mesons produced in proton–proton collisions with negligible angular momentum (hollow orange circles), as systematic tests.*

The ALICE collaboration measured the angular distributions of neutral K^* and ϕ vector mesons via their hadronic decays to $K\pi$ and KK pairs, respectively. ρ_{00} was found to deviate from 1/3 for low-p_T and mid-central collisions at a level of 3σ (figure 1). The corresponding results for ϕ mesons show a deviation of ρ_{00} values from 1/3 at a level of 2σ. The observed p_T dependence of ρ_{00} is expected if quark polarisation via spin–orbit coupling is subsequently transferred to the vector mesons by hadronisation, via the recombination of a quark and an antiquark from the quark–gluon plasma. The data are also consistent with the initial angular momentum of the hot and dense matter being highest for mid-central collisions and decreasing towards zero for central and peripheral collisions.

The results are surprising, however, as corresponding quark-polarisation values obtained from studies with Λ hyperons are compatible with zero. A number of systematic tests have been carried out to verify these surprising results. K^0_S mesons do indeed yield $\rho_{00} = 1/3$, indicating no spin alignment, as must be true for a spin-zero particle. For proton–proton collisions, the absence of initial angular momentum also leads to $\rho_{00} = 1/3$, consistent with the observed neutral K^* spin alignment being the result of spin–orbit coupling.

The present measurements are a step towards experimentally establishing possible spin–orbit interactions in the relativistic-QCD matter of the quark–gluon plasma. In the future, higher statistics measurements in Run 3 will significantly improve the precision, and studies with the charged K^*, which has a magnetic moment seven times larger than neutral K^*, may even allow a direct observation of the effect of the strong magnetic fields initially experienced by the quark–gluon plasma.

Further reading

ALICE Collab. 2019 arXiv:1910.14408.
ALICE Collab. 2019 arXiv:1909.01281.

CMS

Boosting top-quark measurements

Measuring at high momenta enables detailed studies of a compelling kinematic regime that has not been accessible before

Weighing in at 180 times the mass of the proton, the top quark is the heaviest elementary particle discovered so far. Because of its large mass, it is the only quark that does not form bound states with other quarks but decays immediately after it has been produced. Despite its short lifetime, its existence has far-reaching consequences. It governs the stability of the electroweak vacuum, gives large contributions to the mass of the W boson, and influences many other important observables through quantum-loop corrections. An accurate knowledge of its mass is important for our understanding of fundamental interactions.

The LHC's high centre-of-mass energy makes it an ideal laboratory to study the properties of the top quark with unprecedented precision. Such studies demand that jets originating from light and bottom quarks are measured very accurately, however, subtleties remain even then, as exact calculations are not possible for low-energy quarks and gluons once they start to form bound states. In this regime, our approximations become inaccurate, because the mass of the bound states becomes as large as the energy of the underlying process. An exciting way to overcome these difficulties is to measure top quarks that have been produced with very high transverse momenta and thus large Lorentz boosts. In these topologies, the decay products are highly collimated, and can be clearly assigned to a decaying top quark. Effects from the formation of hadrons play a minor effect in boosted topologies as the top quarks, which were originally produced in quark–antiquark pairs, move apart from each other fast enough that their decays can be considered to happen independently.

By reconstructing a boosted top quark in a single jet, a measurement of the jet mass can be translated into one of the top-quark mass. The CMS collaboration has carried out such a measurement ▷

using the $\sqrt{s} = 13$ TeV data collected in 2016, reconstructing the top-quark jets with the novel XCone algorithm to obtain a top quark mass of 172.6 ± 2.5 GeV (figure 1). Due to this new way of reconstructing jets, an improvement of more than a factor of three relative to an earlier measurement at $\sqrt{s} = 8$ TeV has been achieved. Although the uncertainty is larger than for direct measurements, where top quarks are reconstructed from multiple jets or leptons and missing transverse momentum (which currently yield a world average of 172.9 ± 0.4 GeV from a combination of CMS, ATLAS and Tevatron measurements), this new result shows for the first time the potential of using boosted top quarks for precision measurements.

Measuring the properties of the top quark at high momenta enables detailed studies of a theoretically compelling kinematic regime that has not been accessible before. Different effects, such as the collinear radiation of gluons and quarks, govern its dynamics compared to top-quark production at low energies. Exploiting the full Run-2 dataset should allow CMS to extend this measurement to higher boosts, and establish the boosted regime for a number of precision measurements in the top-quark sector in Run 3 and at the high-luminosity LHC.

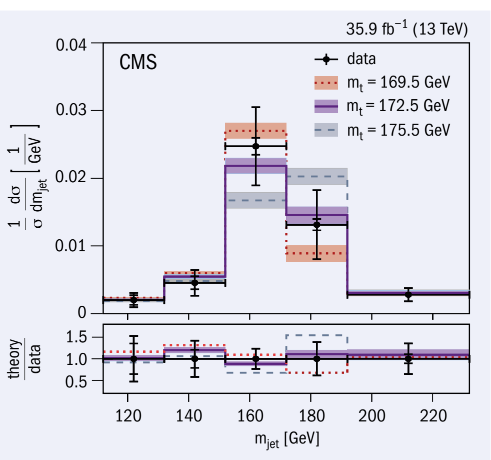


Fig. 1. *Normalised differential top-quark pair-production cross section as a function of jet mass. The peak position is sensitive to the value of the top quark mass (coloured lines).*

Further reading

CMS Collab. 2019 arXiv:1911.03800.

LHCb

Beauty baryons strike again

The LHCb experiment has observed new beauty-baryon states, consistent with theoretical expectations for excited Ω_b^- (bss) baryons. The Ω_b^- (first observed a decade ago at the Tevatron) is a higher mass partner of the Ω^- (sss), the 1964 discovery of which famously validated the quark model of hadrons. The new LHCb finding will help to test models of hadronic states, including some that predict exotic structures such as pentaquarks.

The LHCb collaboration has uncovered many new baryons and mesons during the past eight years, bringing a wealth of information to the field of hadron spectroscopy. Critical to the search for new hadrons is the unique capability of the experiment to trigger on fully hadronic beauty and charm decays of b baryons, distinguish protons, kaons and pions from one another using ring-imaging Cherenkov detectors, and reconstruct secondary and tertiary decay vertices with a silicon vertex detector.

LHCb physicists searched for excited Ω_b^- states via strong decays to $\Xi_b^0 K^-$, where the Ξ_b^0 (bsu), in turn, decays weakly through $\Xi_b^0 \to \Xi_c^+ \pi^-$ and $\Xi_c^+ \to pK^- \pi^+$. Using the full data sample collected during LHC Runs 1 and 2, a large and clean sample of about 19,000 Ξ_b^0 signal decays was collected. Those Ξ_b^0 candidates were then combined with a K^- candidate from the same primary interaction. Combinations with the wrong sign ($\Xi_b^0 K^+$), where no Ω_b^- states are expected, were used to study the background. This control sample was used to tune particle-identification requirements to reject misidentified pions, reducing the background by a factor of 2.5 while keeping an efficiency of 85% on simulated signal decays.

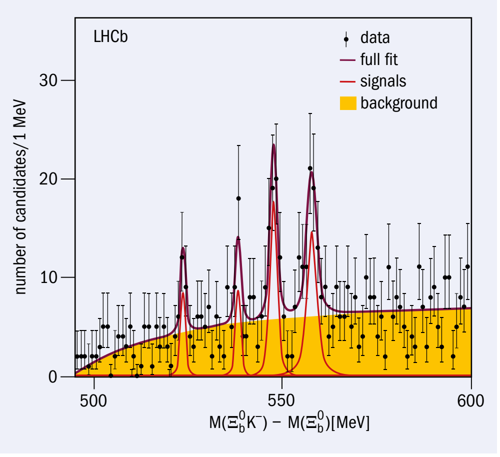


Fig. 1. *The spectrum of the difference in invariant mass between the $\Xi_b^0 K^-$ combination and the Ξ_b^0 candidate. The fitted masses of the four peaks are: 6315.64 ± 0.31 ± 0.07 ± 0.50 MeV, 6330.30 ± 0.28 ± 0.07 ± 0.50 MeV, 6339.71 ± 0.26 ± 0.05 ± 0.50 MeV and 6349.88 ± 0.35 ± 0.05 ± 0.50 MeV, where the uncertainties are statistical, systematic, and due to the uncertainty on the world-average Ξ_b^0 mass of 5791.9 ± 0.5 MeV.*

The width of the $\Omega_b(6350)^-$ shows the most significant deviation from zero

The search used the difference in invariant mass, $\delta M = M(\Xi_b^0 K^-) - M(\Xi_b^0)$, determining the δM resolution to be approximately 0.7 MeV using simulated signal decays. (For comparison, the resolution is about 15 MeV for the Ξ_b^0 decay.) Several peaks can be seen by eye (figure 1), but to measure their properties a fit is needed. To help constrain the background shape, the wrong-sign δM spectrum (not shown) is fitted simultaneously with the signal mode. The peaks are each described by a relativistic Breit–Wigner convolved with a resolution function.

Four peaks, corresponding to four excited Ω_b^- states, were included in the fit. Following the usual convention, the new states were named according to their approximate mass: $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$ and $\Omega_b(6350)^-$. Each mass was measured with a precision of well below 1 MeV, and the errors are dominated by the uncertainty on the world-average Ξ_b^0 mass. All four peaks are narrow. The width of the $\Omega_b(6350)^-$ shows the most significant deviation from zero, with a central value of $1.4^{+1.0}_{-0.8} \pm 0.1$ MeV. The two lower-mass peaks have significances below three standard deviations (2.1σ and 2.6σ) and so are not considered conclusive observations. But the two higher-mass peaks have significances of 6.7σ and 6.2σ, above the 5σ threshold for discovery.

The new states seen by LHCb follow a similar pattern to the five narrow peaks observed in the $\Xi_c^+ K^-$ invariant mass spectrum by the collaboration in 2017. It has proven difficult to obtain a satisfactory explanation of all five as excited Ω_c^0(css) states, raising the possibility that at least one of the $\Xi_c^+ K^-$ peaks is a pentaquark or molecular state. Since the $\Xi_c^+ K^-$ and $\Xi_b^0 K^-$ final states differ only by replacing a c quark with a b quark, the two analyses together should provide strong constraints on any models that aim to explain the structures in these mass spectra.

Further reading

LHCb Collab. 2020 arXiv:2001.00851.
LHCb Collab. 2017 *Phys. Rev. Lett.* **118** 182001.

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."

For more information, visit **www.uhvdesign.com/products/push-pull-devices**

UHVD

Web www.uhvdesign.com
Email sales@uhvdesign.com

FIELD NOTES

Reports from events, conferences and meetings

TeVPA

Astroparticle physicists head down under

Despite the thick haze of bushfire smoke hanging over the skyline, 200 delegates gathered in Sydney from 2 to 6 December for the 14th edition of the TeV Particle-Astrophysics conference (TeVPA) to discuss the status and future of astroparticle physics.

The week began with a varied series of talks on dark matter. Luca Grandi (Chicago) and Tom Thorpe (LNGS) updated delegates on progress towards the next generation of xenon- and argon-based experiments: these massive underground detectors are now approaching total masses in the multiton-scale. Experiments like XENON, LZ and DarkSide are poised to be so sensitive to rare signals that they will even be able to detect coherent elastic neutrino–nucleus scattering – the ultimate background to direct dark-matter searches.

Irreconcilable tension

Meanwhile, Greg Lane (Australian National University) brought us news of exciting developments in Australian dark-matter research. The Stawell Underground Laboratory – the first deep underground site in the southern hemisphere – will host part of the SABRE experiment, which aims to test the annually modulating event rate seen by the DAMA experiment. This highly controversial, dark-matter-like signal has been observed for two decades by DAMA, but remains in irreconcilable tension with null results from many other experiments. Excavation at Stawell is underway as of October last year. The site will form a central component of the Centre of Excellence for Dark Matter Particle Physics, recently awarded by the Australian Research Council.

Eminent astrophysicist Joe Silk (IAP) reviewed the many ways in which galaxies can be used as laboratories for particle physics. One of the most persistent hints of dark-matter particle interactions in astrophysical data is the notorious excess of GeV gamma rays coming from the galactic centre. Recent analyses of the excess using improved statistical techniques and better models for the Milky Way's central bulge were detailed by Shunsaku Horiuchi (Virginia Tech). While dark-matter-related explanations remain tempting, there is growing evidence in support of millisecond pulsars being responsible, given the spatial morphology of the excess. Francesca Calore (LAPTh) told us that multi-wavelength probes of the excess will be possible in the near future, and may finally allow us to conclusively determine the origin of the signal.

S Hickey

Cosmic *Yvonne Wong tells TeVPA delegates how cosmological data can be used as a test of neutrino physics – and vice versa.*

A host of upcoming experiments will hopefully allow us to peer back to the birth of the first stars at "cosmic dawn"

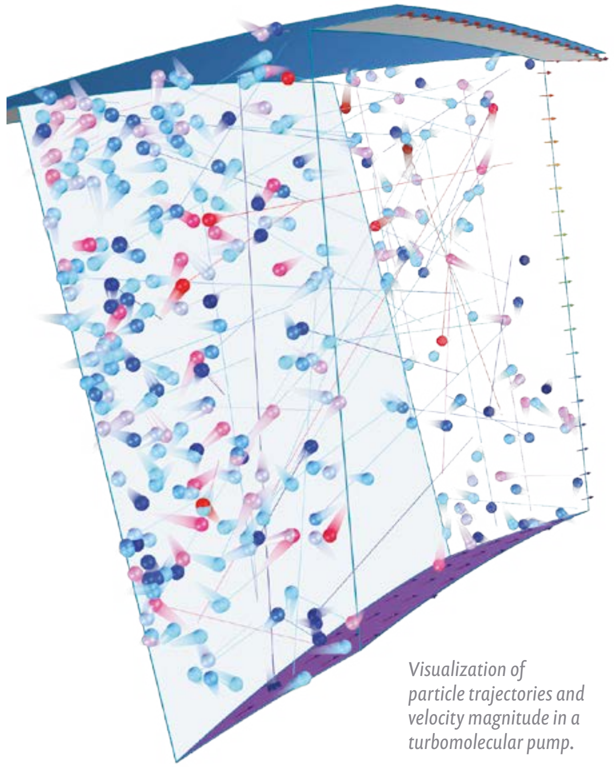
Probing the cosmos

Delegates enjoyed a stirring series of talks on the ever-increasing number of probes of cosmology. Following a review of the post-Planck status of cosmology by Jan Hamaan (UNSW), Xuelei Chen (CAS) explained how the unique 21 cm radio line can be used to map neutral hydrogen throughout the universe and across cosmic time. A host of upcoming ground- and space-based experiments attempting to observe the sky-averaged 21 cm line will hopefully allow us to peer back to the birth of the first stars at "cosmic dawn". We also heard from Yvonne Wong (UNSW) about how cosmological data can be used as a test of neutrino physics and how neutrino physics may in turn be a means to alleviate tensions between cosmological datasets. For example, strong self-interactions between neutrinos could bring the two increasingly divergent measurements of the Hubble constant, from the cosmic microwave background and type-1a supernovae, respectively, into agreement.

Much of the week's schedule was devoted to cosmic-ray research, gamma rays and indirect searches for dark matter. The antimatter cosmic-ray detector AMS, mounted on the International Space Station, is making measurements of cosmic-ray spectra to within 1% accuracy. Weiwei Xu (Shandong) summarised an impressive array of physics results made over almost a decade by AMS, including the most recent measurement of the positron flux, which has a clear high-energy component with a well-defined cutoff at 810 GeV – just as expected for galactic dark-matter annihilations. As with the GeV gamma-ray excess, however, pulsars represent a possible natural astrophysical explanation. The mystery could be resolved by the fact that, unlike pulsars, dark-matter annihilations are expected to produce antiprotons. While current antiproton data show a tantalisingly similar trend to the positron spectrum, more data is needed to identify the origin of the high-energy positrons.

Many ongoing and upcoming observatories in the fields of cosmic-ray and gamma-ray research were also introduced to us, such as DAMPE (Jingjing Zang, CAS), the Cherenkov Telescope Array (Roberta Zanin, CTAO), the Pierre Auger Observatory (Bruce Dawson, University of Adelaide) and LHAASO (Zhen Cao, CAS). We are entering an exciting time, when many of the enticing but ambiguous anomalies in cosmic-ray spectra will be definitively tested, potentially identifying a signal of dark matter in the process.

Gamma-ray bursts (GRBs) generated much enthusiasm this year, with Edna Ruiz-Velasco (MPIK) and Elena Moretti (IFAF) talking about brand-new observations of GRBs from the H.E.S.S. and ▷



MAGIC collaborations, including the first detection of a GRB afterglow at very high energies (> 100 GeV) by H.E.S.S. These observations have helped resolve the long-standing mysteries surrounding the complex array of processes that are needed to produce the phenomenal energies of GRB emissions. An important contribution is now known to be "synchrotron self-Compton" – an emission in which a synchrotron photon generated from an electron spiralling around a magnetic field line is Compton up-scattered by the same electron that produced it.

Finally, the subject of gravitational waves continues to surge in popularity within this community. We were first given a summary by Susan Scott (Australian National University) of more than 50 confirmed gravitational-wave discoveries made by Advanced LIGO and Advanced Virgo to date, and from Tara Murphy (Sydney), about the intense work involved in rapidly following-up luminous gravitational-wave events with radio observations. LIGO's discoveries of neutron-star and black-hole mergers are a window into one of the strongest regimes of gravity we have ever been able to see. With general relativity still holding up as robustly as ever, many well-motivated theories of modified gravity are now finding little room to hide.

The subject of gravitational waves continues to surge in popularity

The next TeVPA will take place in late October 2020 in Chengdu, China.

Ciaran O'Hare *University of Sydney.*

NuPhys19

Hyper-active neutrino physicists visit London

The sixth edition of Prospects in Neutrino Physics (NuPhys19) attracted almost 100 participants to the Cavendish Conference Centre in London from 16 to 18 December. Jointly organised by King's College London and the Institute for Particle Physics Phenomenology at Durham University, the conference provides a much-needed snapshot of the fast-moving field of neutrino physics.

The neutrino community's current challenge is to understand the origin of neutrino masses and lepton mixing. This means establishing whether neutrinos are Dirac or Majorana fermions, their absolute mass scale, the order of the measured mass splittings (the neutrino mass ordering), whether there is leptonic CP violation, the precise value of other parameters in the neutrino mixing matrix, and, finally, whether there is an indication of physics beyond the standard three-neutrino paradigm, for example through the detection of sterile neutrinos.


NuPhys19

Green light *Nobel laureate Takaaki Kajita opened NuPhys19 by confirming that the construction of Hyper-Kamiokande will begin this year.*

Budget boost

2015 Nobel laureate Takaaki Kajita (University of Tokyo) opened the conference by confirming that construction of the Hyper-Kamiokande experiment will begin in 2020, following the allocation by the Japanese government of a supplementary budget on 13 December. Hyper-Kamiokande will be a water-Cherenkov detector with a total mass of 260 kton – almost an order of magnitude larger than its famous predecessor Super-Kamiokande, where atmospheric neutrino oscillations were discovered, and far larger than KamiokaNDE, which observed solar neutrinos and supernova SN1987A. Hyper-Kamiokande will eventually replace Super-Kamiokande as the far detector for the upgraded J-PARC neutrino beam, which is situated on the far side of Japan (essentially a comprehensive upgrade of the T2K experiment), with the aim of measuring CP violation in the leptonic sector. It will also provide high statistics for proton-decay searches, supernova-neutrino bursts, atmospheric and solar neutrinos, and indirect searches for dark matter. Hyper-Kamiokande will therefore soon join DUNE in the US as a next-generation long-baseline neutrino-oscillation experiment under construction. Together, the detectors will provide a far wider coverage of physics signals than either could manage alone.

Critical mass

News of KATRIN's record-breaking new upper limit on the electron–antineutrino mass was complemented by a report from Joseph Formaggio (MIT) on the successful "Project 8" demonstration in the US of a new approach to directly measuring neutrino masses, wherein the energies of beta-decay electrons are determined from the frequency of cyclotron radiation as the electrons spiral in a magnetic field. This work will be complemented by the JUNO experiment in China, which will begin to constrain the ordering of the neutrino-mass eigenvalues in 2021.

The search for neutrinoless double-beta decay also has the potential to provide information on neutrino masses. A potentially unambiguous indication of lepton-number violation and the postulated Majorana nature of neutrinos, it is being pursued aggressively as experiments compete to reduce backgrounds and increase detector masses to the tonne-scale. Several talks emphasised the complementary progress by the theory community to better estimate nuclear effects, and reduce the errors arising from the discrepancies between different nuclear models and different isotopes. These calculations are equally important for NOvA and T2K, which is now beginning to probe leptonic CP conservation at the 3σ level.

Current and future cosmological constraints of neutrino properties were reviewed by Eleonora Di Valentino (Manchester), whose recent work with Alessandro Melchiorri and Joe Silk reinterprets Planck-satellite data to favour a closed universe at more than 99% significance – an inference that could lead to the current cosmological upper limit on the sum of neutrino masses being relaxed upwards if it is accepted by the community. Conversely, astrophysical neutrinos are also powerful tools for studying astrophysical objects. One key development in this field is the doping of Super-Kamiokande with gadolinium, currently underway in Japan. This will soon give the detector sensitivity to the diffuse supernova-neutrino background.

The next edition of NuPhys will take place in London from 16 to 18 December 2020.

Francesca Di Lodovico *and* **Teppei Katori** *King's College London, and* **Silvia Pascoli** *Durham University.*

50 YEARS OF THE GLASHOW–ILIOPOULOS–MAIANI MECHANISM

Shanghai plays host to GIM celebration

In 1969 many weak amplitudes could be accurately calculated with a model of just three quarks, and Fermi's constant and the Cabibbo angle to couple them. One exception was the remarkable suppression of strangeness-changing neutral currents. John Iliopoulos, Sheldon Lee Glashow and Luciano Maiani boldly solved the mystery using loop diagrams featuring the recently hypothesised charm quark, making its existence a solid prediction in the process. To celebrate the 50th anniversary of their insight, the trio were guests of honour at an international symposium at the T. D. Lee Institute at Shanghai Jiao Tong University on 29 October 2019.


J Liu

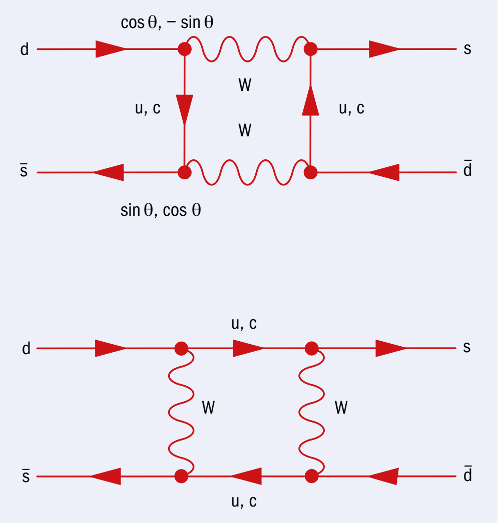
Happy anniversary *Hong-Jian He, John Ellis, John Iliopoulos, Sheldon Lee Glashow, Verónica Riquer and Luciano Maiani at a celebration of 50 years of the GIM mechanism in Shanghai.*

The Glashow–Iliopoulos–Maiani (GIM) mechanism was conceived in 1969, submitted to *Physical Review D* on 5 March 1970, and published on 1 October of that year, after several developments had defined a conceptual framework for electroweak unification. These included Yang–Mills theory, the universal V–A weak interaction, Schwinger's suggestion of electroweak unification, Glashow's definition of the electroweak group $SU(2)_L \times U(1)_Y$, Cabibbo's theory of semileptonic hadron decays and the formulation of the leptonic electroweak gauge theory by Weinberg and Salam, with spontaneous symmetry breaking induced by the vacuum expectation value of new scalar fields.

The GIM mechanism then called for a fourth quark, charm, in addition to the three introduced by Gell-Mann, such that the first two blocks of the electroweak theory are made each by one lepton and one quark doublet, $[(\nu_e, e), (u, d)]$ and $[(\nu_\mu, \mu), (c, s)]$. Quarks u and c are coupled by the weak interaction to two superpositions of the quarks d and s: $u \leftrightarrow d_C$, with d_C the Cabibbo combination $d_C = \cos\theta_C\, d + \sin\theta_C\, s$, and $c \leftrightarrow s_C$, with s_C the orthogonal combination. In subsequent years, a third generation, $[(\nu_\tau, \tau), (t, b)]$ was predicted to describe CP violation. No further generations have been observed yet.

Charming prediction

The GIM mechanism was the solution to a problem arising in the simplest weak interaction theory with one charged vector boson coupled to the Cabibbo currents. As pointed out in 1968, strangeness-changing neutral-current processes, such as $K_L \to \mu^+\mu^-$ and $K^0 - \bar{K}^0$ mixing, are generated at one loop with amplitudes of order $G \sin\theta_C \cos\theta_C\, (G\Lambda^2)$, where G is the Fermi constant, Λ is an ultraviolet cutoff and $G\Lambda^2$ (dimensionless) is the first term in a perturbative expansion that could be continued to take higher order diagrams into account. To comply with the strict limits existing at the time, one had to require a surprisingly small value of the cutoff, Λ, of 2–3 GeV, to be compared with the naturally expected value: $\Lambda = G^{-1/2} \approx 300$ GeV. This problem was taken seriously by the GIM authors, who wrote that "It appears necessary to depart from the original phenomenological model of weak interactions."



In the loop *One-loop quark diagrams for $K^0 - \bar{K}^0$ mixing in the light of the GIM mechanism. The charm-quark amplitudes have the same magnitude but opposite sign as for up-quark lines, leading to a perfect cancellation, $\cos\theta \sin\theta + (-\sin\theta)\cos\theta = 0$, in the case where $m_c = m_u$, suggesting an explanation for the suppression of processes with strangeness-changing neutral currents.*

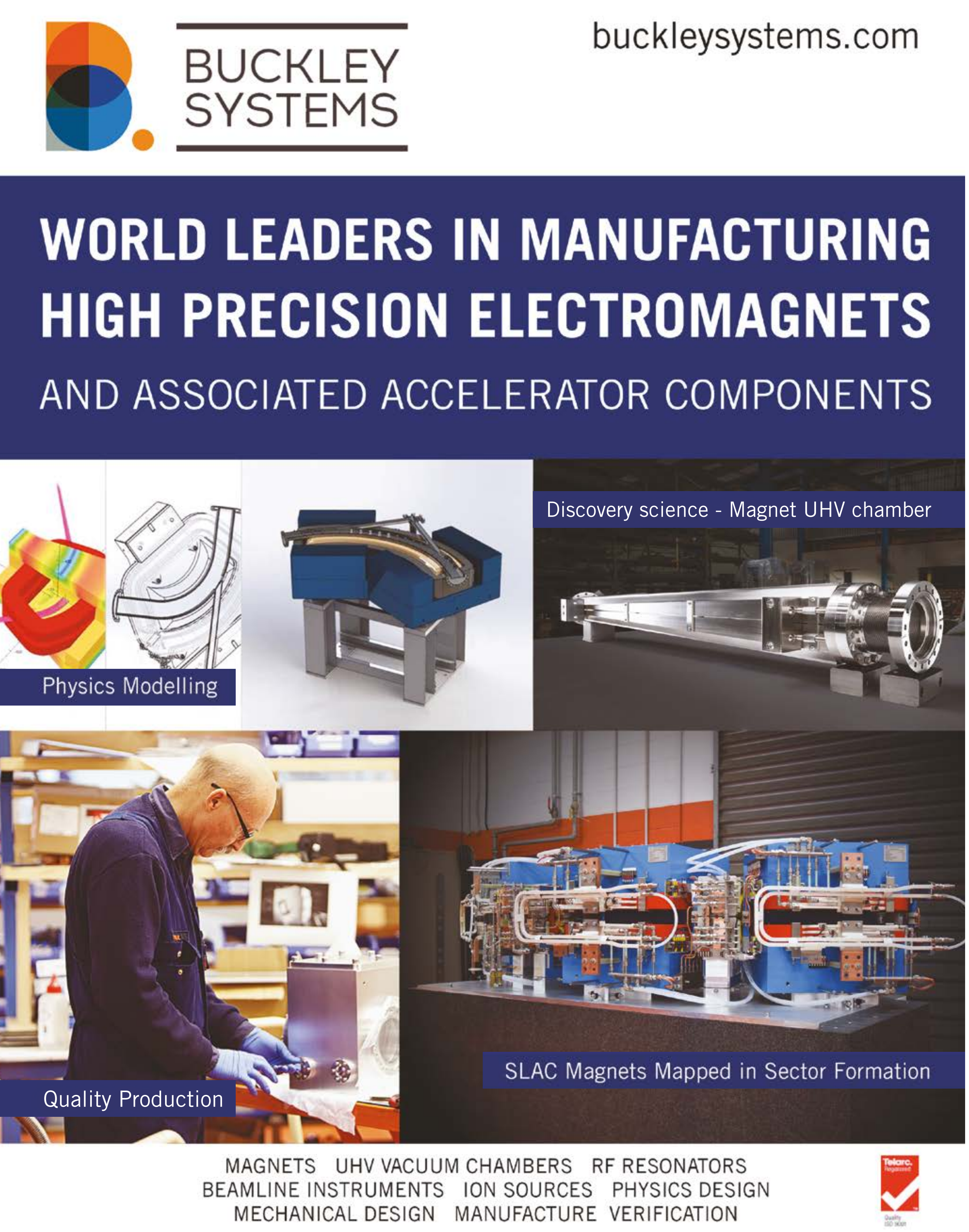
To sidestep this problem, Glashow, Iliopoulos and Maiani brought in the fourth "charm" quark, already introduced by Bjorken, Glashow and others, with its typical coupling to the quark combination left alone in the Cabibbo theory: $c \leftrightarrow s_C = -\sin\theta_C\, d + \cos\theta_C\, s$. Amplitudes for $s \to d$ with u or c on the same fermion line would cancel exactly for $m_c = m_u$, suggesting a more natural means to suppress strangeness-changing neutral-current processes to measured levels. For $m_c \gg m_u$, a residual neutral-current effect would remain, which, by inspection, and for dimensional reasons, is of order $G \sin\theta_C \cos\theta_C\, (Gm_c^2)$. This was a real surprise: the "small" UV cutoff needed in the simple three-quark theory became an estimate of the mass of the fourth quark, which was indeed sufficiently large to have escaped detection in the unsuccessful searches for charmed mesons that had been conducted in the 1960s.

Embarrassment averted

With the two quark doublets included, a detailed study of strangeness changing neutral current processes gave $m_c \approx 1.5$ GeV, a value consistent with more recent data on the masses of charmed mesons and baryons. Another aspect of the GIM cancellation is that the weak charged currents make an SU(2) algebra together with a neutral component that has no strangeness-changing terms. Thus, there is no difficulty in including the two quark doublets in the unified electroweak group $SU(2)_L \times U(1)_Y$ of Glashow, Weinberg and Salam. The 1970 GIM paper noted that "In contradistinction to the conventional (three-quark) model, the couplings of the neutral intermediary – now hypercharge conserving – cause no embarrassment."

The GIM mechanism has become a cornerstone of the Standard Model, and gives a precise description of the observed flavour-changing neutral-current processes for s and b quarks. For this reason, flavour-changing neutral currents are still an important benchmark and give strong constraints on theories that go beyond the Standard Model in the TeV region.

Hong-Jian He *T. D. Lee Institute, Shanghai Jiao Tong University and*
Luciano Maiani *T. D. Lee Institute and Università di Roma.*



Beauty 2019

Flavour heavyweights converge on Ljubljana

Exciting times *Beauty 2019 delegates looked forward to important developments in the coming year.*

Beauty 2019

The international conference devoted to b-hadron physics at frontier machines, Beauty 2019, was held in Ljubljana, Slovenia, from 30 September to 4 October. The aims of the conference series are to review the latest results in heavy-flavour physics and discuss future directions. This year's edition, the 18th in the series, attracted around 80 scientists and 65 invited talks, of which 13 were theory-based.

Bubbling anomalies

The study of hadrons containing beauty quarks, and other heavy flavours, offers a powerful way to probe for physics beyond the Standard Model, as highlighted in the inspiring opening talk by Chris Quigg (Fermilab). In the last few years much attention has been focused on b-physics results that do not show perfect agreement with the predictions of the theory. In particular, studies by Belle, BaBar and LHCb of the processes $B^- \to K^- \ell^+ \ell^-$ and $B^0 \to K^* \ell^+ \ell^-$ (where $\ell^\pm$ indicates a lepton) in specific kinematic regions have yielded different decay rates for muon pairs and electron pairs, apparently violating lepton universality. For both processes the significance of the effect is around 2.5σ. Popular models to explain this and related effects include leptoquarks and new Z' bosons, however, no firm conclusions can be drawn until more precise measurements are available, which should be the case when the next Beauty meeting occurs.

The B system is an ideal laboratory for the study of CP violation, and recent results were presented by the LHC experiments for ϕ_s – the phase associated with time-dependent measurements of B_s meson decays to CP eigenstates. Indications that ϕ_s is nonzero are starting to emerge, which is remarkable given that its magnitude in the Standard Model is less than 0.1 radians. This is great encouragement for Run 3 of the LHC, and beyond.

Heavy-flavour experiments are also well suited to the study of hadron spectroscopy. Many very recent results were shown at the conference, including the discovery of the X(3842), which is a charmonium resonance above the open charm threshold, and new excited resonances seen in the $\Lambda_b \pi\pi$ final state, which help map out the relatively unexplored world of b-baryons. The ATLAS collaboration presented, for the first time, an analysis of $\Lambda_b \to J/\psi pK$ decays in which a structure is observed that is compatible with that of the LHCb pentaquark discovery of 2015, providing the first confirmation by another experiment of these highly exotic states.

The Beauty conference welcomes reports on flavour studies beyond b-physics, and a highlight of the week was the first presentation at a conference of new results on the measurement of the branching ratio of the ultra-rare decay $K^+ \to \pi^+ \nu \bar{\nu}$, by the NA62 collaboration. The impressive background suppression that the experiment has achieved left the audience in no doubt as to the sensitivity of the result that can be expected when the full data set is accumulated and analysed. Comparing the measurement with the predicted branching fraction of $\sim 10^{-10}$ will be a critical test of the Standard Model in the flavour domain.

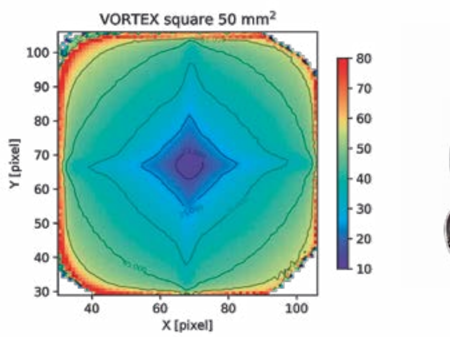
The study of hadrons containing beauty quarks offers a powerful way to probe for physics beyond the Standard Model

Bright future

Flavour physics has a bright future. Several talks presented the first signals and results from the early running of the Belle II experiment, and precise and exciting measurements can be expected when the next meeting in the Beauty series takes place. In parallel, studies with increasing sensitivity will continue to emerge from the LHC. The meeting was updated about progress on the LHCb upgrade, which is currently being installed ready for Run 3, and will allow for an order of magnitude increase in b-hadron samples. The conference was summarised by Patrick Koppenburg (Nikhef), who emphasised the enormous potential of b-hadron studies for uncovering signs of new physics beyond the Standard Model.

The next edition of Beauty will take place in Japan, hosted by Kavli IPMU at the University of Tokyo, in autumn 2020.

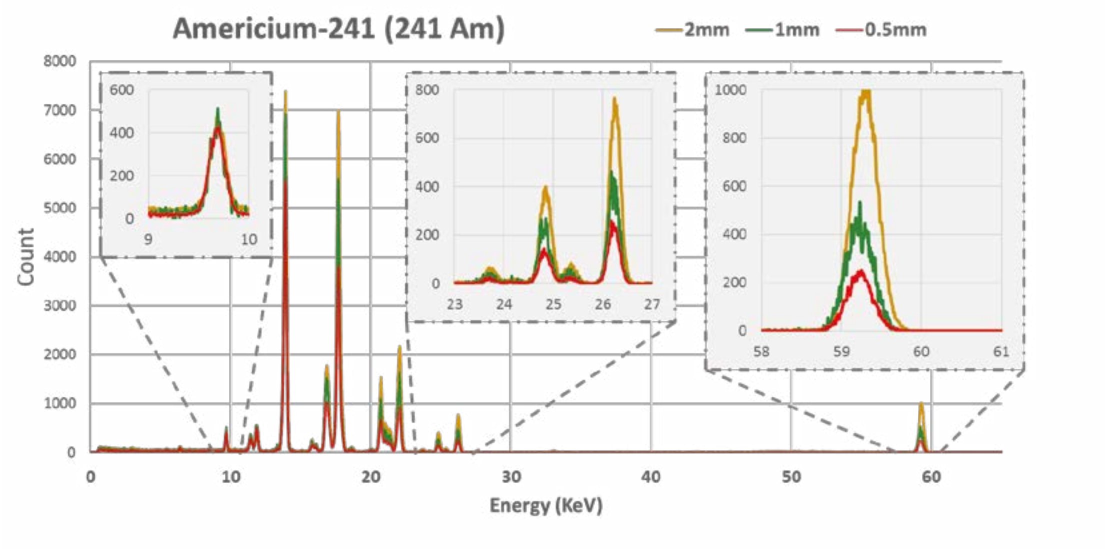
Robert Fleischer *Nikhef and Vrije Universiteit Amsterdam,*
Guy Wilkinson *University of Oxford,*
and **Bostjan Golob** *University of Ljubljana and Jožef Stefan Institute.*



VORTEX ME-7 SDD Rise Time Mapping

VORTEX ME-7 SDD— 38 mm diameter Detector - the same as the current VORTEX ME-4 SDD

38 mm



HG2019

Linacs pushed to the limit in Chamonix

HG2019

High-tech *Delegates at the 2019 International High-Gradient Linac Technology Workshop.*

This past June in Chamonix, CERN hosted the 12th edition of an international workshop dedicated to the development and application of high-gradient and high-frequency linac technology. These technologies are making accelerators more compact, less expensive and more efficient, and broadening their range of applications. The workshop brought together more than 70 scientists and engineers involved in a wide range of accelerator applications, with a common interest in the use and development of normal-conducting radio-frequency cavities with very high accelerating gradients ranging from around 5 MV/m to above 100 MV/m.

Applications for high-performance linacs such as these include the Compact Linear Collider (CLIC), compact XFELs and inverse-Compton-scattering photon sources, medical accelerators, and specialised devices such as radio-frequency quadrupoles, transverse deflectors and energy-spread linearisers. In recent years the latter two devices have become essential to achieving low emittances and short bunch lengths in high-performance electron linacs of many types, including superconducting linacs. In the coming years, developments from the high-gradient community will increase the energy of beams in existing facilities through retrofit programmes, for example in an energy upgrade of the FERMI free-electron laser. In the medium term, a number of new high-gradient linacs are being proposed, such as the room-scale X-ray-source SMART*LIGHT, the linac for the advanced accelerator concept research accelerator EUPRAXIA, and a linac to inject electrons into CERN's Super Proton Synchrotron for a dark-matter search. The workshop also covered fundamental studies of the very complex physical effects that limit the achievable high gradients, such as vacuum arcing, which is one of the main limitations for future technological advances.

Originated by the CLIC study, the focus of the workshop has grown to encompass high-gradient radio-frequency design, precision manufacture, assembly, power sources, high-power operation and prototype testing. It is also notable for strong industrial participation, and plays an important role in broadening the applications of linac technology by highlighting upcoming hardware to companies. The next in the series will be hosted jointly by SLAC and Los Alamos and take place on the shore of Lake Tahoe from 8 to 12 June.

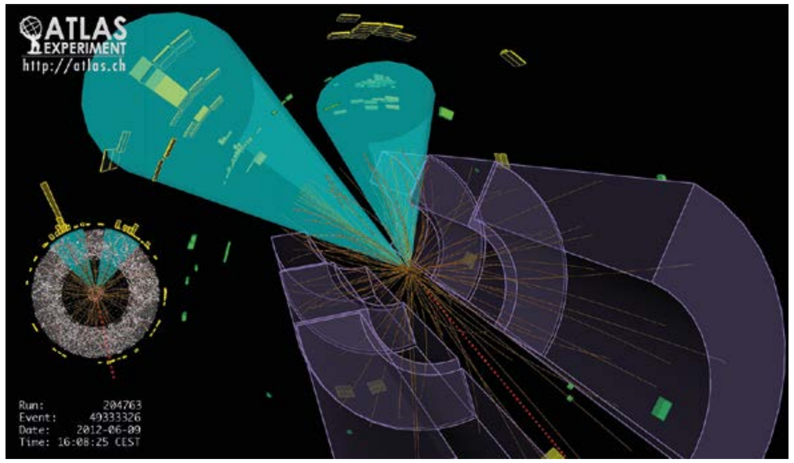
Walter Wuensch *CERN.*

At the crossroads of space, LHC experiments and high-tech entrepreneurship

We sat down with Diego Casadei from Cosylab Switzerland and asked how it all comes together, especially concerning space, CERN and high-tech companies.

While developing instrumentation systems for space, you also had connections to CERN. You designed the Time-of-Flight (TOF) system of the AMS-02 space experiment, and you organised and coordinated two beam tests of the AMS-02 TOF and RICH (Ring Imaging CHerenkov) prototypes. Could you describe for our readers how the coordination of a beam test runs at CERN?
These have been my first tasks in management and I must admit I felt inadequate all the time. Still, with a bit of luck, we were able to perform all of the activities successfully.
I had underestimated the complexity of managing access to a restricted area (because of the radiation). This takes effort and preparation. There are a multitude of rules to follow, many documents to fill in and get approved, as well as safety procedures to learn and ensure other people are following, among other things.

From 2007 to 2012 you were part of the large ATLAS team at CERN. You played an essential role in the development of the ATLAS missing transverse momentum (aka "missing transverse-energy" or MET) trigger and coordinating the corresponding experimental group. Could you – in layman's terms – explain what role MET triggers play in beyond-Standard Model physics experiments? What were your most significant challenges in this project?
In a collision, the total momentum is conserved. However, measuring the longitudinal component (along the beams that carry proton bunches circulating the LHC to the interaction point) is subject to extreme fluctuations and in practice it is unfeasible. Hence one focuses on the projection of the momentum on the transverse plane, which is orthogonal to the incoming beams. MET triggers detect the imbalance in the vector sum of all transverse-momenta. When this is bigger than the measurement uncertainty, this implies that an undetected particle escaped from the interaction point.
Apart from neutrinos and the charged particles passing through un-instrumented regions of the detector, one might also detect neutralinos, predicted by supersymmetric models. But the challenge is that the measured quantity is non-null: one always measures some transverse momentum. The problem is to isolate interesting events among so many fake events, which are due to instrumental effects, statistical fluctuations, and multiple interactions in the same bunch crossing. Finally, the MET trigger rate increases exponentially with the LHC instantaneous luminosity (the collision rate), which was difficult during the early operation of LHC, when the rate increased by several orders of magnitude.



An ATLAS event with two jets and a lot of missing energy (Image: ATLAS Experiment/CERN)

What do you see as the next big opportunity for cooperation between the private-sector and CERN's 14 areas of operation in developing custom ICT solutions for the research community, for example through the CERN openlab?
CERN pays a lot of attention to the transfer of technology to society. However, the flow is mainly one-way: from CERN outwards. Industrial contributions to research activities are not so numerous. What I've learned after moving to Cosylab is that there are many companies developing high-tech solutions, which can help research enormously. Nevertheless, many researchers do not realise this. Many people spend incredible effort re-inventing things and solutions that already exist, which diverts energy away from striving towards what is truly new.
At times it can be apparent how research institutions value people's time differently to commercial companies.

You are also the head of space R&D. What are the main challenges you face in this role?
I have two key roles in Cosylab. One is the management of the Swiss branch and the other is the differentiation of the business. Having worked for almost 20 years on space research, the management asked me to find new projects in this domain, while allowing me to follow also other roads. Space is a very risk-averse domain and the entry threshold for new companies is very high. Many failures in space can be traced to a failure in the control system, hence the main challenge is to demonstrate reliability. This is a typical chicken or egg problem: one needs to get into space to show reliability, but it's hard to get a chance to do so before demonstrating a successful record. We are addressing the problem in small steps: small projects are the best way to show results, and in five to 10 years the space market will be much more open to Cosylab.

Diego Casadei is the general manager of Cosylab Switzerland, which is the Swiss daughter organisation of Cosylab d.d., where he is also the head of space research and development. Cosylab provides and integrates state-of-the-art software and electronics for cancer-therapy systems, high-tech startups and complex big physics machines, such as particle accelerators, optical and radio telescopes and nuclear fusion reactors.
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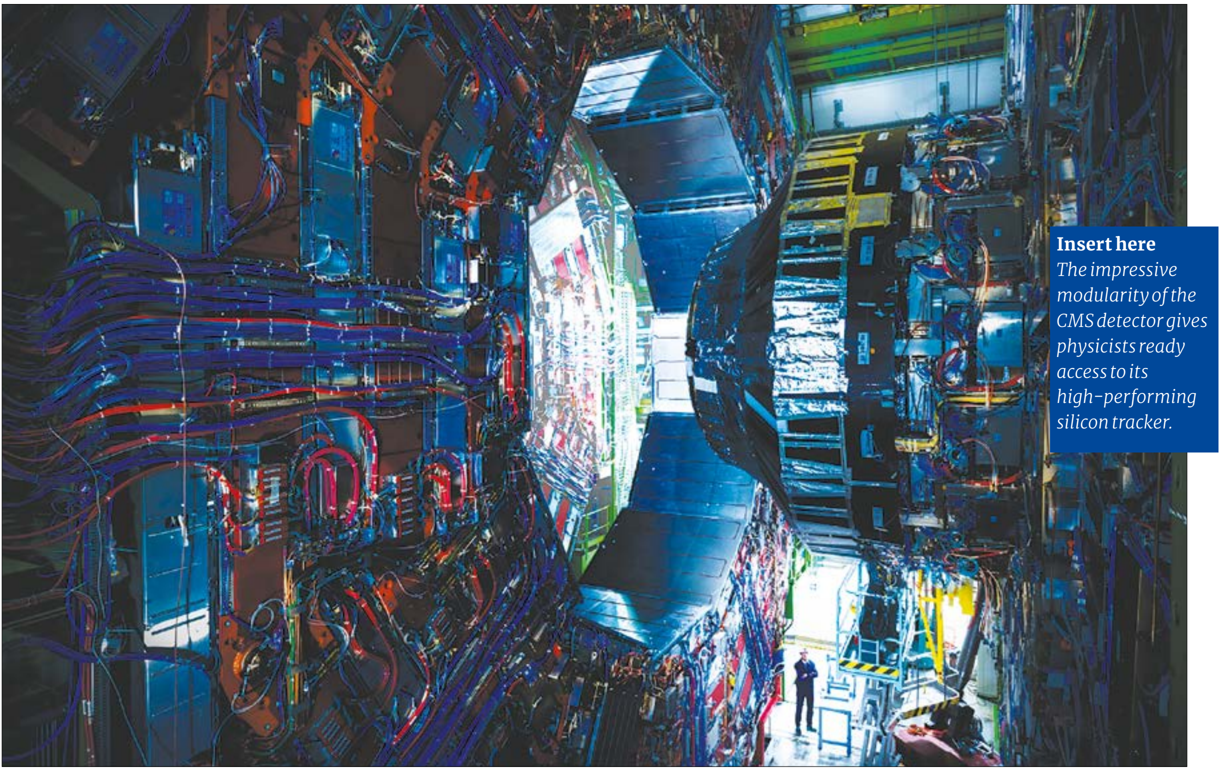

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Insert here *The impressive modularity of the CMS detector gives physicists ready access to its high-performing silicon tracker.*

A LABOUR OF LOVE

Four technological masterpieces bestride the narrow beam pipe of the Large Hadron Collider, charting unexplored territory at the frontier of knowledge. But this is only possible thanks to the work of thousands of physicists and engineers. Ten years on from the first high-energy collisions, Mark Rayner interviews some of the foremost experts on what it took to keep these onion-like arrays of silicon and steel fighting fit.

Two detectors, both alike in dignity, sit 100 m underground and 8 km apart on opposite sides of the border between Switzerland and France. Different and complementary in their designs, they stand ready for anything nature might throw at them, and over the past 10 years physicists in the ATLAS and CMS collaborations have matched each other paper for paper, blazing a path into the unknown. And this is only half of the story. A few kilometres around the ring either way sit the LHCb and ALICE experiments, continually breaking new ground in the physics of flavour and colour.

Plans hatched when the ATLAS and CMS collaborations formed in the spring of 1992 began to come to fruition in the mid 2000s. While liquid-argon and tile calorimeters lit up in ATLAS's cavern, cosmic rays careened through partially assembled segments of each layer of the CMS detector, which was beginning to be integrated at the surface. "It was terrific, we were taking cosmics and everybody else was still in pieces!" says Austin Ball, who has been technical coordinator of CMS for the entire 10-year running period of the LHC so far. "The early cosmic run with magnetic field was a byproduct of our design, which stakes everything on a single extraordinary solenoid," he explains, describing how the uniquely compact and modular detector was

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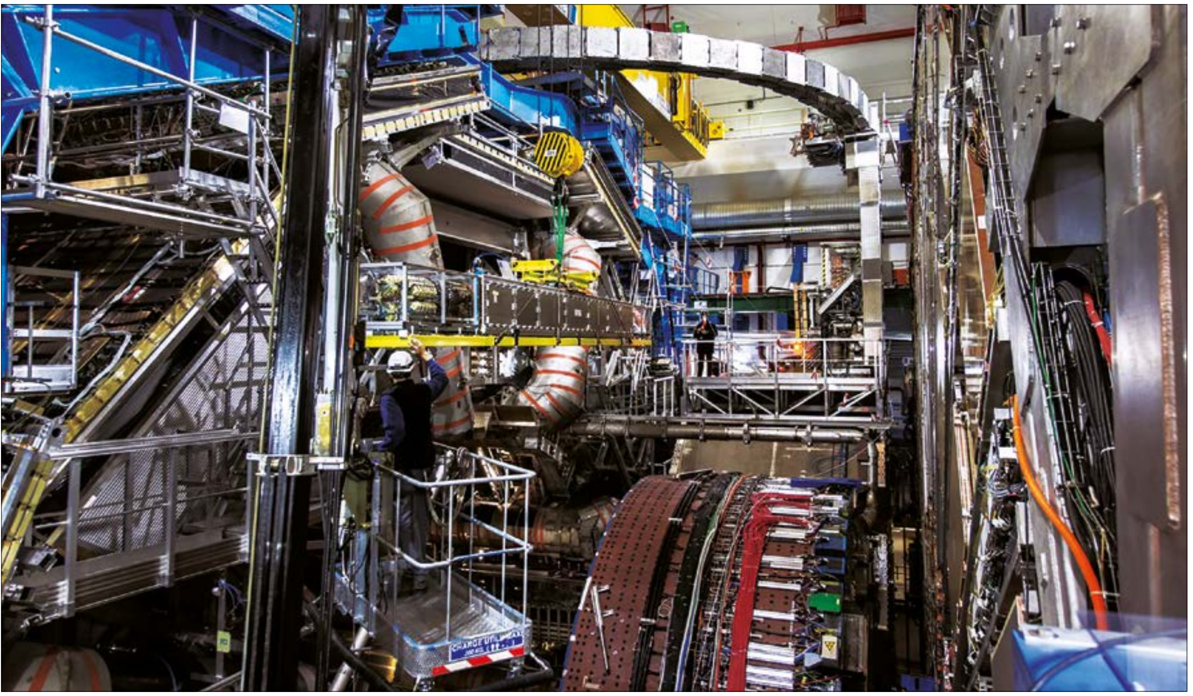


M Brice/CERN-EX-1312293-01

Heart surgery *An upgraded pixel detector is lowered into the ATLAS cavern during the first long shutdown.*

later lowered into its cavern in enormous chunks. At the same time, the colossal ATLAS experiment was growing deep underground, soon to be enveloped by the magnetic field generated by its ambitious system of eight air-core superconducting barrel loops, two end-caps and an inner solenoid. A thrilling moment for both experiments came on 10 September 2008, when protons first splashed off beam stoppers and across the detectors in a flurry of tracks. Ludovico Pontecorvo, ATLAS's technical coordinator since 2015, remembers "first beam day" as a new beginning. "It was absolutely stunning," he says. "There were hundreds of people in the control room. It was the birth of the detector." But the mood was fleeting. On 19 September a faulty electrical connection in the LHC caused a hundred or so magnets to quench, and six tonnes of liquid helium to escape into the tunnel, knocking the LHC out for more than a year.

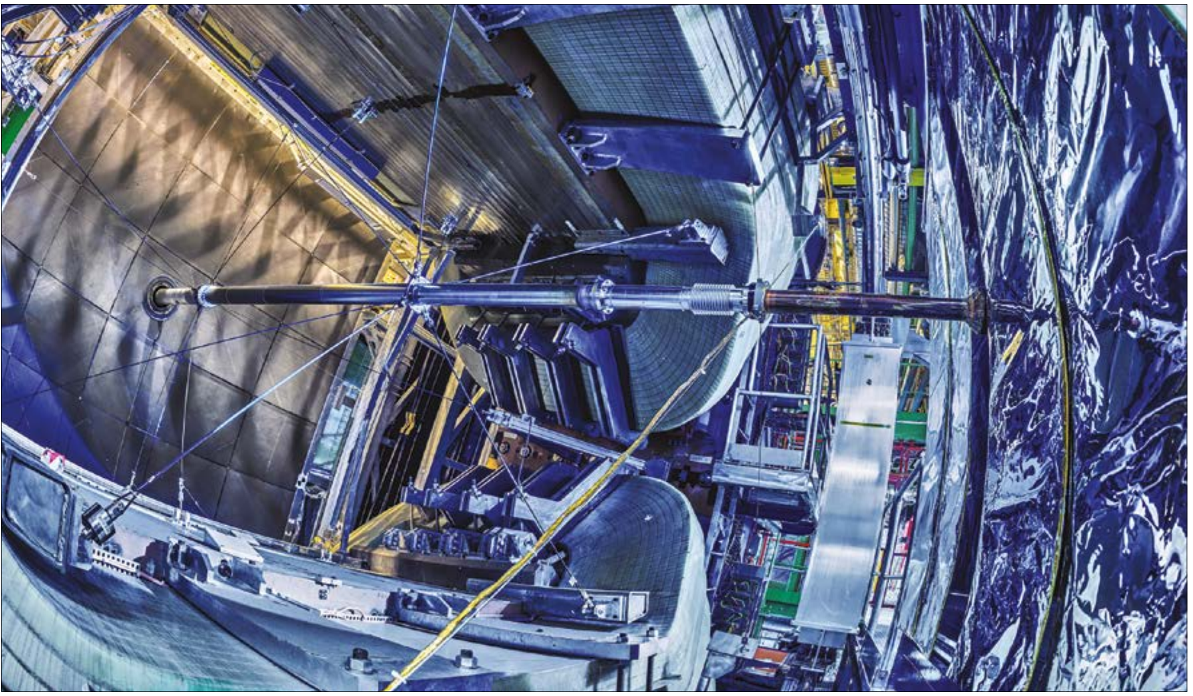
The experimentalists didn't waste a moment. "We would have had a whole series of problems if we hadn't had that extra time," says Ball. The collaborations fixed niggling issues, installed missing detector parts and automated operations to ease pressure on the experts. "Those were great days," agrees Richard Jacobsson, commissioning and run coordinator of the LHCb experiment from 2008 to 2015. "We ate pizza, stayed up nights and slept in the car. In the end I installed a control monitor at home, visible from the kitchen, the living room and the dining room, with four screens – a convenient way to avoid going to the pit every time there was a problem!" The hard work paid off as the detectors came to life once again. For ALICE, the iconic moment was the first low-energy collisions in December 2009. "We were installing the detector for 10 years, and then suddenly you see these tracks on the event display…" reminisces Werner Riegler, longtime technical coordinator for the collaboration. "I bet then-spokesperson Jürgen Schukraft three bottles of Talisker whisky that they couldn't possibly be real. You have this monster and suddenly it turns into this? Everybody was cheering. I lost the bet."

The first high-energy collisions took place on 30 March 2010, at a centre-of-mass energy of 7 TeV, three-and-a-half times higher than the Tevatron, and a leap into *terra incognita*, in the words of ATLAS's Pontecorvo. The next signal moment came on 8 November with the first heavy-ion collisions, and almost immediate insights into the quark–gluon plasma.

ALICE in wonderland

For a few weeks each year, the LHC ditches its signature proton collisions at the energy frontier to collide heavy ions such as lead nuclei, creating globules of quark–gluon plasma in the heart of the detectors. For the past 10 years, ALICE has been the best-equipped detector in the world to record the myriad tracks that spring from these hot and dense collisions of up to 416 nucleons at a time.

Like LHCb, ALICE is installed in a cavern that previously housed a LEP detector – in ALICE's case the L3 experiment. Its tracking and particle-identification subdetectors are mostly housed within that detector's magnet, fixed in place and still going strong since 1989, the only worry a milli-Amp leak current, present since L3 days, which shifters monitor watchfully. Its relatively low field is not a limitation as ALICE's specialist subject is low-momentum tracks – a specialty made possible by displacing the beams at the interaction point to suppress the luminosity. "The fact that we have a much lower radiation load than ATLAS, CMS and LHCb allows us to use technologies that are very good for low-momentum measurements, which the other experiments cannot use because their radiation-hardness requirements are much higher," says Riegler, noting that the design of ALICE requires less power, less cooling and a lower material budget. "This also presents an additional challenge in data processing and analysis in terms of reconstructing all these low-momentum particles, whereas for the other experiments, this is background that you can cut away." The star performer in ALICE has been the time-projection chamber (TPC), he counsels me, describing a detector capable of reconstructing the 8000 tracks per rapidity unit that were forecast when the detector was designed.



M Brice & J Ordan/CERN-PHOTO-201812-329-18

Rhapsody in blue *LHCb's dipole magnet sorts particles that are boosted in the forward direction (from right to left), near the beam pipe.*

But nature had a surprise in store when the LHC began running with heavy ions. The number of tracks produced was a factor three lower than expected, allowing ALICE to push the TPC to higher rates and collect more data. By the end of Run 2, a detector designed to collect "minimum-bias" events at 50 Hz was able to operate at 1 kHz – a factor 20 larger than the initial design.

The lower-than-expected track multiplicities also had a wider effect among the LHC experiments, making ATLAS, CMS and LHCb highly competitive for certain heavy-ion measurements, and creating a dynamic atmosphere in which insights into the quark–gluon plasma came thick and fast. Even independently of the less-taxing-than-expected tracking requirements, top-notch calorimetry allowed immediate insights. "The discovery of jet quenching came simply by looking at event displays in the control room," confirms Pontecorvo of ATLAS. "You would see a big jet that wasn't counterbalanced on the other side of the detector. This excitement was transmitted across the world."

Keeping cool

Despite the exceptional and expectation-busting performance of the experiments, the first few years were testing times for the physicists and engineers tasked with keeping the detectors in rude health. "Every year we had some crisis in cooling the calorimeters," recalls Pontecorvo. Fortunately, he says, ATLAS opted for "under-pressure" cooling, which prevents water spilling in the event of a leak, but still requires a big chunk of the calorimeter to be switched off. The collaboration had to carry out spectacular interventions, and put people in places that no one would have guessed would be possible, he says. "I remember crawling five metres on top of the end-cap calorimeter to arrive at the barrel calorimeter to search for a leak, and using 24 clamps to find which one of 12 cooling loops had the problem – a very awkward situation!" Ball recalls experiencing similar difficulties with CMS. There are 11,000 joints in the copper circuits of the CMS cooling system, and a leak in any one is enough to cause a serious problem. "The first we encountered leaked into the high-voltage system of the muon chambers, down into the vacuum tank containing the solenoid, right through the detector, which like the LHC itself is on a slope, and out the end as a small waterfall," says Ball.

The arresting modularity of CMS, and the relative ease of opening the detector – admittedly an odd way to describe sliding a 1500-tonne object along the axis of a 0.8 mm thick beam pipe – proved to be the solution to many problems. "We have exploited it relentlessly from day one," says Ball. "The ability to access the pixel tracker, which is really the heart of CMS, with the highest density of sensitive channels, was absolutely vital – crucial for repairing faults

J Ordan/CERN-PHOTO-201901-004-2

Welcome to the machine *ALICE's magnet is opened up for sweeping upgrades during the second long shutdown.*

as well as radiation damage. Over the course of five or six years we became very efficient at accessing it. The performance of the whole silicon tracking system has been outstanding."

The early days were also challenging for LHCb, which is set up to reconstruct the decays of beauty hadrons in detail. The dawning realisation that the LHC would run optimally with fewer but brighter proton bunches than originally envisaged set stern tests from the start. From LHCb's conception to first running, all of the collaboration's discussions were based on the assumption that the detector would veto any crossing of protons where there would be more than one interaction. In the end, faced with a typical "pile-up" of three, the collaboration had to reschedule its physics priorities and make pragmatic decisions about the division of bandwidth in the high-level trigger. "We were faced with enormous problems: synchronisation crashes, event processing that was taking seconds and getting stuck...," recalls Jacobsson. "Some run numbers, such as 1179, still send shivers down the back of my spine." By September, however, they had demonstrated that LHCb was capable of running with much higher pile-up than anybody had thought possible.

Necessity was the mother of invention. In 2011 and 2012 LHCb introduced a feedback system that maintains a manageable luminosity during each fill by increasing the overlap between the colliding beams as protons "burn out" in collisions, and the brightness of the bunches decreases. When Jacobsson and his colleagues mentioned it to the CERN management in September 2010, the then director of accelerators, Steve Myers, read the riot act, warning of risks to beam stability, recalls Jacobsson. "But since I had a few good friends at the controls of the LHC, we could carefully and quietly test this, and show that it produced stable beams. This changed life on LHCb completely. The effect was that we would have one stable condition throughout every fill for the whole year – perfect for precision physics."

Initially, LHCb had planned to write events at 200 Hz, recalls Rolf Lindner, the experiment's longtime technical coordinator, but by the end of Run 1, LHCb was collecting data at up to 10 kHz, turning offline storage, processing and "physics stripping" into an endless fire fight. Squeezing every ounce of performance out of the LHC generated greater data volumes than anticipated by any of the experiments, and even stories (probably apocryphal) of shifters running down to local electronics stores to buy data discs because they were running out of storage. "The LHC would run for several months with stable beams for 60% of every 24 hours in a day," says Lindner. "No machine has ever been so stable in its operational mode."

Engineering all-stars

The eyes of the world turned to ATLAS and CMS on 4 July 2012 as the collaborations announced the discovery of a new boson – an iconic moment to validate countless hours of painstaking work by innumerable physicists, engineers and computer scientists, which is nevertheless representative of just one of a multitude of physics insights made possible by the LHC experiments (see p40). The period running up to the euphoric Higgs discovery had been smooth for all except LHCb, who had to scramble to disprove unfounded suggestions that their dipole magnet, occasionally reversed in field to reduce systematic uncertainties, was causing beam instabilities. But new challenges would shortly follow. Chief among several hair-raising moments in CMS was the pollution of the magnet cryogenic system in 2015 and 2016, which caused instability in the detector's cold box and threatened the reliable operation of the superconducting solenoid surrounding the tracker and calorimeters. The culprit turned out to be superfluous lubricant – a mere half a litre of oil, now in a bottle in Ball's office – which clogged filters and tiny orifices crucial to the cyclical expansion cycle used to cool the helium. "By the time we caught on to it, we hadn't just polluted the cold box, we had polluted the whole of the distribution from upstairs to downstairs," he recalls, launching into a vivid account of seat-of-the-pants interventions, and also noting that the team turned their predicament into an opportunity. "With characteristic physics ingenuity, and faced with spoof versions of the CMS logo with straightened tracks, we exploited data with the magnet off to calibrate the calorimeters and understand a puzzling 750 GeV excess in the diphoton invariant mass distribution," he says.

With resolute support from CERN, bold steps were taken to fix the problem. It transpired that slightly-undersized replaceable filter cartridges were failing to remove the oil after it was mixed with the helium to lubricate screw-turbine compressors in the surface installation. "Now I look back on the cryogenic crisis as the best project I ever worked on at CERN, because we were allowed to assemble this cross-departmental superstar engineering team," says Ball. "You could ask for anyone and get them. Cryogenics experts, chemists and mechanical engineers... even Rolf Heuer, then the Director-General, showed up frequently. The best welders basically lived in our underground area – you could normally only see their feet sticking out from massive pipework. If you looked carefully you might spot a boot. It's a complete labyrinth. That one will stick with me for a long time. A crisis can be memorable and satisfying if you solve it."

Heroic efforts

During the long shutdown that followed, the main task for LHCb was to exchange a section of beryllium beam pipe in which holes had been discovered and meticulously varnished over in haste before being used in Run 1. At the same time, right at the end of an ambitious and successful consolidation and improvement programme, CMS suffered the perils of extraordinarily dense circuit design when humid air condensed onto cold silicon sensor modules that had temporarily been moved to a surface clean room. 10% of the pixels short-circuited when it was powered up again, and heroic efforts were needed to re-manufacture replacements and install them in time for the returning LHC beams. Meanwhile, wary of deteriorating optical readout, ATLAS refurbished their pixel-detector cabling, taking electronics out of the detector to make it serviceable and inserting a further inner pixel layer just 33 mm from the beam pipe to up their b-tagging game. The bigger problem was mechanical shearing of the bellows that connect the cryostat of one of the end-cap toroids to the vacuum system – the only problem experienced so far with ATLAS's ambitious magnet system. "At the beginning people speculated that with eight superconducting coils, each independent from the others, we would experience one quench after another, but they have been perfect really," confirms Pontecorvo. Combined with the 50-micron alignment of the 45 m-long muon detector, ATLAS has exceeded the design specifications for resolving the momentum of high-momentum muons – just one example of a pattern repeated across all the LHC detectors.

As the decade wore on, the experiments streamlined operations to reach unparalleled performance levels, and took full advantage of technical and end-of-year stops to keep their detectors healthy. Despite their very high-luminosity environments, ATLAS and CMS pushed already world-beating initial data-taking efficiencies of around 90% beyond the 95% mark. "ATLAS and CMS were designed to run with an average pile-up of 20, but are now running with a pile-up of 60. This is remarkable," states Pontecorvo.

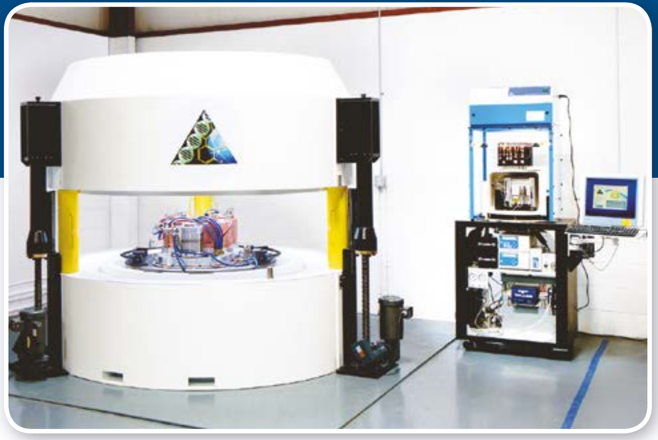
Accelerator rising

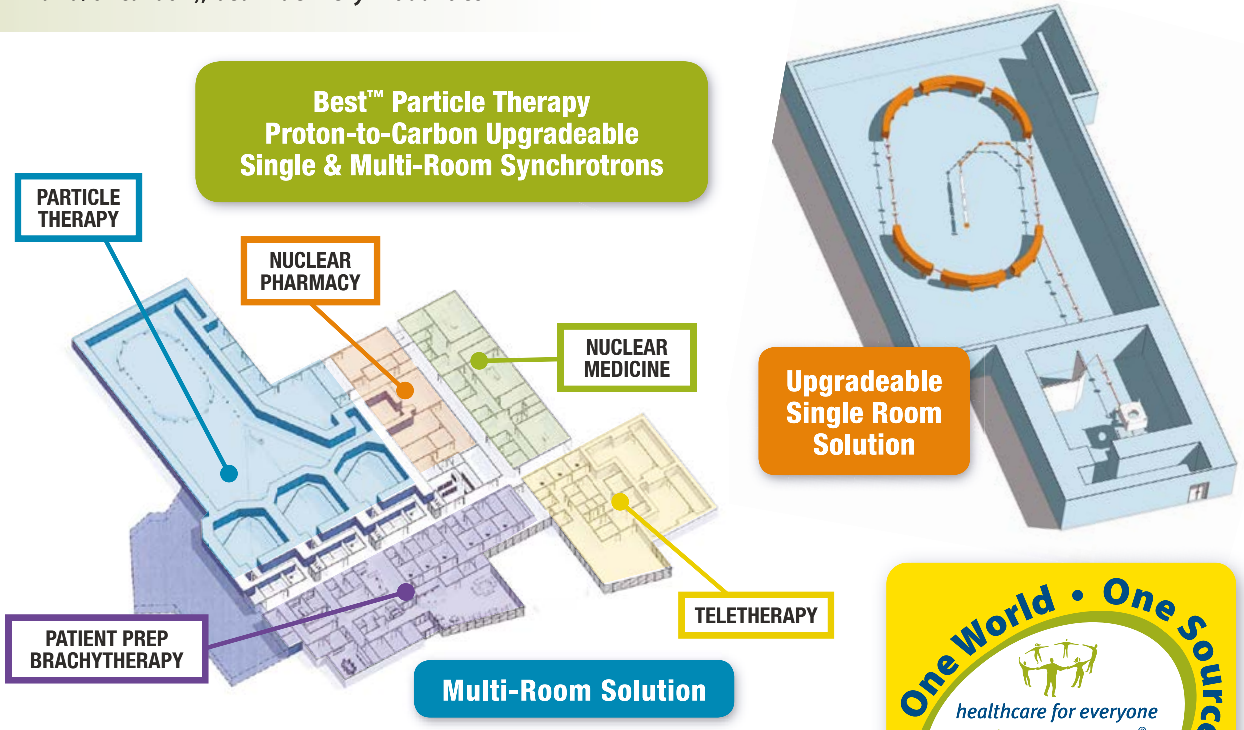
At 10, with thousands of physics papers behind them and many more stories to tell, the LHC experiments are as busy as ever, using the second long shutdown, which is currently underway, to install upgrades, many of which are geared to the high-luminosity LHC (HL-LHC) due to operate later this decade. Many parts are being recycled, for example with ALICE's top-performing TPC chambers donated to Fermilab for the near detector of the DUNE long-baseline neutrino-oscillation experiment. And major engineering challenges remain. A vivid example is that the LHC tunnel, carved out of water-laden rock 30 years ago, is rising up, while the experiments – particularly the very compact CMS, which has a density almost the same as rock – remain fixed in place, counterbalancing upthrust due to the removed rock with their weight. CMS faces the greatest challenge due to the geology of the region, explains Ball. "The LHC can use a corrector magnet to adjust the level of the beam, but there is a risk of running out of magnetic power if the shifts are big. Just a few weeks ago they connected a parallel underground structure for HL-LHC equipment, and the whole tunnel went up 3 mm almost overnight. We haven't solved that one yet."

Most of all, it is important to acknowledge the dedication of the people who run the experiments

Everyone I interviewed agrees wholeheartedly on one crucial point. "Most of all, it is important to acknowledge the dedication of the people who run the experiments," explains Pontecorvo of ATLAS, expressing a sentiment emphasised by his peers on all the experiments. "These people are absolutely stunning. They devote their life to this work. This is something that we have to keep and which it is not easy to keep. Unfortunately, many feel that this work is undervalued by selection committees for academic positions. This is something that must change, or our work will finish – as simple as that."

Pontecorvo hurries out of the door at the end of our early-morning interview, hastily squeezed into a punishing schedule. None of the physicists I interviewed show even a smidgen of complacency. Ten years in, the engineering and technological marvels that are the four biggest LHC experiments are just getting started. ●





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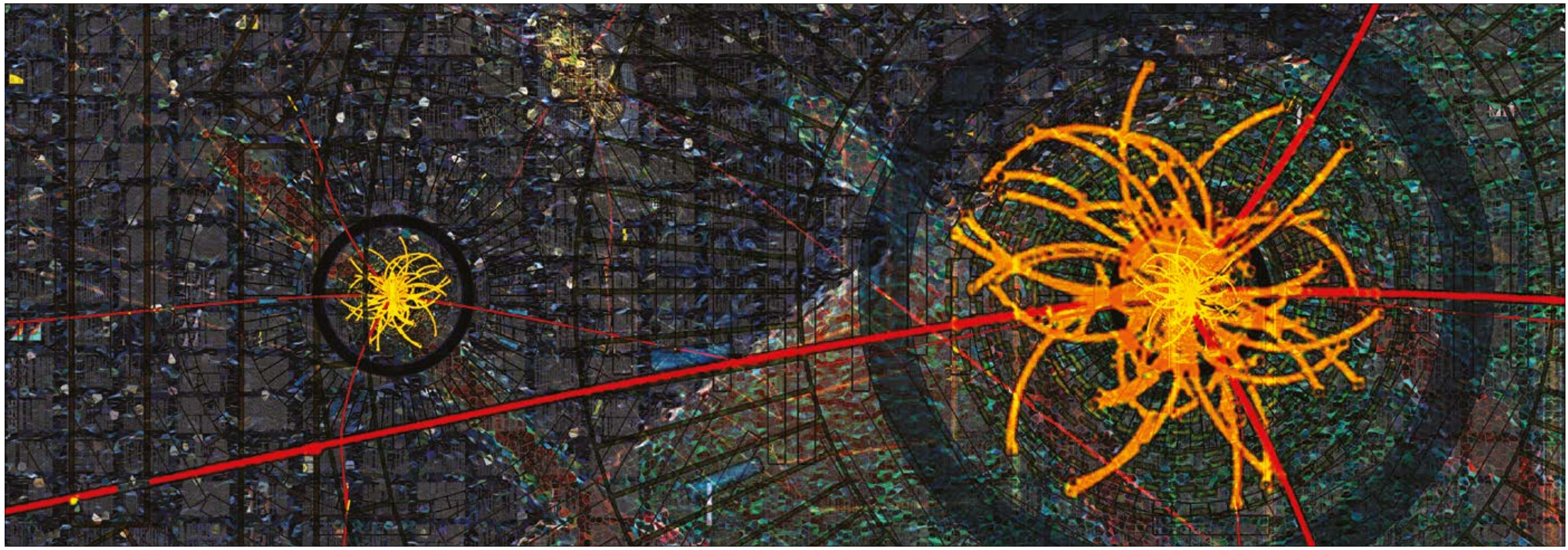
LHC AT 10: THE PHYSICS LEGACY

With just 5% of its ultimate dataset collected so far, the LHC's vast and unique physics programme has already transformed and enriched our understanding of elementary particles, writes Michelangelo Mangano.



X Cortada

Artful science *Detail from* In Search of the Higgs Boson, *a series of works produced by artist Xavier Cortada in collaboration with CMS.*

Ten years have passed since the first high-energy proton–proton collisions took place at the Large Hadron Collider (LHC). Almost 20 more are foreseen for the completion of the full LHC programme. The data collected so far, from approximately 150 fb^{-1} of integrated luminosity over two runs (Run 1 at a centre-of-mass energy of 7 and 8 TeV, and Run 2 at 13 TeV), represent a mere 5% of the anticipated 3000 fb^{-1} that will eventually be recorded. But already their impact has been monumental.

Three major conclusions can be drawn from these first 10 years. First and foremost, Run 1 has shown that the Higgs boson – the previously missing, last ingredient of the Standard Model (SM) – exists. Secondly, the exploration of energy scales as high as several TeV has further consolidated the robustness of the SM, providing no compelling evidence for phenomena beyond the SM (BSM). Nevertheless, several discoveries of new phenomena *within* the SM have emerged, underscoring the power of the LHC to extend and deepen our understanding of the SM dynamics, and showing the unparalleled diversity of phenomena that the LHC can probe with unprecedented precision.

Exceeding expectations

Last but not least, we note that 10 years of LHC operations, data taking and data interpretation, have overwhelmingly surpassed all of our most optimistic expectations. The accelerator has delivered a larger than expected luminosity, and the experiments have been able to operate at the top of their ideal performance and efficiency. Computing, in particular via the Worldwide LHC Computing Grid, has been another crucial driver of the LHC's success. Key ingredients of precision measurements, such as the determination of the LHC luminosity, or of detection efficiencies and of backgrounds using data-driven techniques beyond anyone's expectations, have been obtained thanks to novel and powerful techniques. The LHC has also successfully provided a variety of beam and optics configurations, matching the needs of different experiments and supporting a broad research programme. In addition to the core high-energy goals of the ATLAS and CMS experiments, this has enabled new studies of flavour physics and of hadron spectroscopy, of forward-particle production and total hadronic cross sections. The operations with beams of heavy nuclei have reached a degree of virtuosity that made it possible to collide not only the anticipated lead beams, but also beams of xenon, as well as combined proton–lead, photon–lead and photon–photon collisions, opening the way to a new generation of studies of matter at high density.

THE AUTHOR

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Theoretical calculations have evolved in parallel to the experimental progress. Calculations that were deemed of impossible complexity before the start of the LHC have matured and become reality. Next-to-leading-order (NLO) theoretical predictions are routinely used by the experiments, thanks to a new generation of automatic tools. The next frontier, next-to-next-to-leading order (NNLO), has been attained for many important processes, reaching, in a few cases, the next-to-next-to-next-to-leading order (N^{3}LO), and more is coming (*CERN Courier* April 2017 p18).

Aside from having made these first 10 years an unconditional success, all these ingredients are the premise for confident extrapolations of the physics reach of the LHC programme to come (*CERN Courier* March/April 2019 p9).

To date, more than 2700 peer-reviewed physics papers have been published by the seven running LHC experiments (ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL and TOTEM). Approximately 10% of these are related to the Higgs boson, and 30% to searches for BSM phenomena. The remaining 1600 or so report measurements of SM particles and interactions, enriching our knowledge of the proton structure and of the dynamics of strong interactions, of electroweak (EW) interactions, of flavour properties, and more. In most cases, the variety, depth and precision of these measurements surpass those obtained by previous experiments using dedicated facilities. The multi-purpose nature of the LHC complex is unique, and encompasses scores of independent research directions. Here it is only possible to highlight a fraction of the milestone results from the LHC's expedition so far.

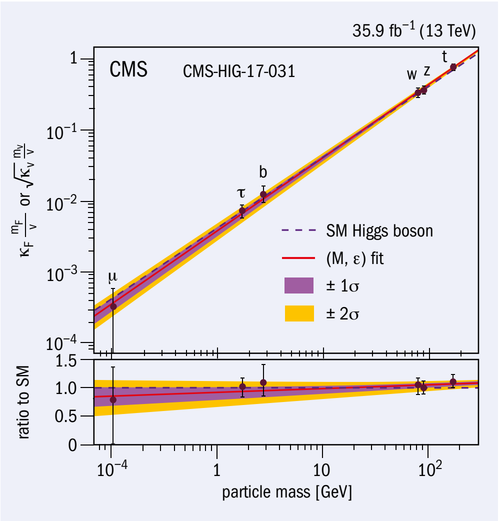
Entering the Higgs world

The discovery by ATLAS and CMS of a new scalar boson in July 2012, just two years into LHC physics operations, was a crowning early success. Not only did it mark the end of a decades-long search, but it opened a new vista of exploration. At the time of the discovery, very little was known about the properties and interactions of the new boson. Eight years on, the picture has come into much sharper focus.

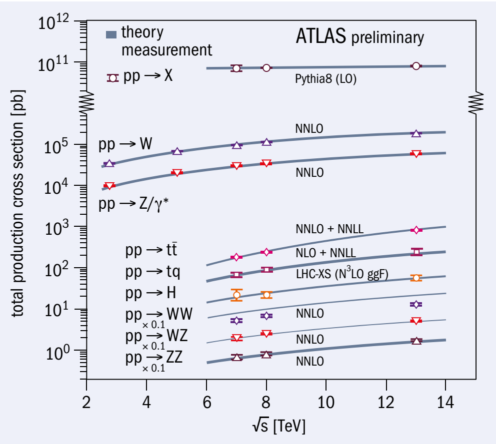
The structure of the Higgs-boson interactions revealed by the LHC experiments is still incomplete. Its couplings to the gauge bosons (W, Z, photon and gluons) and to the heavy third-generation fermions (bottom and top quarks, and tau leptons) have been detected, and the precision of these measurements is at best in the range of 5–10%. But the LHC findings so far have been key to establish that this new particle correctly embodies the main observational properties of the Higgs boson, as specified by the Brout–Englert–Guralnik–Hagen–Higgs–Kibble EW-symmetry breaking mechanism, referred hereafter as "BEH", a cornerstone of the SM. To start with, the measured couplings to the W and Z bosons reflect the Higgs' EW charges and are proportional to the W and Z masses, consistently with the properties of a scalar field breaking the SM EW symmetry. The mass dependence of the Higgs interactions with the SM fermions is confirmed by the recent ATLAS and CMS observations of the $H \to bb$ and $H \to \tau\tau$ decays, and of the associated production of a Higgs boson together with a $t\bar{t}$ quark pair (see figure 1).

These measurements, which during Run 2 of the LHC have surpassed the five-sigma confidence level, provide the second critical confirmation that the Higgs fulfills the role envisaged by the BEH mechanism. The Higgs couplings to the photon and the gluon (g), which the LHC experiments have probed via the $H \to \gamma\gamma$ decay and the $gg \to H$ production, provide a third, subtler test. These couplings arise from a combination of loop-level interactions with several SM particles, whose interplay could be modified by the presence of BSM particles, or interactions. The current agreement with data provides a strong validation of the SM scenario, while leaving open the possibility that small deviations

Fig. 1. *Mass dependence of the Higgs-boson interactions with the Standard Model fermions and massive gauge bosons, as confirmed by CMS and ATLAS (not shown) observations, revealing remarkable agreement with the predicted Yukawa interaction strength.*



Source: CMS-HIG-17-031



Source: ATL-PHYS-PUB-2019-024

Fig. 2. *Cross sections for key SM processes measured at different centre-of-mass energies, showing excellent agreement with state-of-the-art calculations.*

could emerge from future higher statistics.

The process of firmly establishing the identification of the particle discovered in 2012 with the Higgs boson goes hand-in-hand with two research directions pioneered by the LHC: seeking the deep origin of the Higgs field and using the Higgs boson as a probe of BSM phenomena.

The breaking of the EW symmetry is a fact of nature, requiring the existence of a mechanism like BEH. But, if we aim beyond a merely anthropic justification for this mechanism (i.e. that, without it, physicists wouldn't be here to ask why), there is no reason to assume that nature chose its minimal implementation, namely the SM Higgs field. In other words: where does the Higgs boson detected at the LHC come from? This summarises many questions raised by the possibility that the Higgs boson is not just "put in by hand" in the SM, but emerges from a larger sector of new particles, whose dynamics induces the breaking of the EW symmetry. Is the Higgs elementary, or a composite state resulting from new confining forces? What generates its mass and self-interaction? More generally, is the existence of the Higgs boson related to other mysteries, such as the origin of dark matter (DM), of neutrino masses or of flavour phenomena?

Ever since the Higgs-boson discovery, the LHC experiments have been searching for clues to address these questions, exploring a large number of observables (*CERN Courier* July/August 2017 p34). All of the dominant production channels (gg fusion, associated production with vector bosons and with top quarks, and vector-boson fusion) have been discovered, and decay rates to WW, ZZ, γγ, bb and ττ were measured. A theoretical framework (effective field theory, EFT) has been developed to interpret in a global fashion all these measurements, setting strong constraints on possible deviations from the SM. With the larger data set accumulated during Run 2, the production properties of the Higgs have been studied with greater detail, simultaneously testing the accuracy of theoretical calculations, and the resilience of SM predictions.

The Higgs boson is becoming an increasingly powerful exploratory tool to probe the origin of the Higgs itself

To explore the nature of the Higgs boson, what has not been seen as yet can be as important as what was seen. For example, lack of evidence for Higgs decays to the fermions of the first and second generation is consistent with the SM prediction that these should be very rare. The H → μμ decay rate is expected to be about 3×10^{-3} times smaller than that of H → ττ; the current sensitivity is two times below, and ATLAS and CMS hope to first observe this decay during the forthcoming Run 3, testing for the first time the couplings of the Higgs boson to second-generation fermions. The SM Higgs boson is expected to conserve flavour, making decays such as H → μτ, H → eτ or t → Hc too small to be seen. Their observation would be a major revolution in physics, but no evidence has shown up in the data so far. Decays of the Higgs to invisible particles could be a signal of DM candidates, and constraints set by the LHC experiments are complementary to those from standard DM searches. Several BSM theories predict the existence of heavy particles decaying to a Higgs boson. For example, heavy top partners, T, could decay as T → Ht, and heavy bosons X decay as X → HV (V = W, Z). Heavy scalar partners of the Higgs, such as charged Higgs states, are expected in theories such as supersymmetry. Extensive and thorough searches of all these phenomena have been carried out, setting strong constraints on SM extensions.

As the programme of characterising the Higgs properties continues, with new challenging goals such as the measurement of the Higgs self-coupling through the observation of Higgs pair production, the Higgs boson is becoming an increasingly powerful exploratory tool to probe the origin of the Higgs itself, as well as a variety of solutions to other mysteries of particle physics.

Interactions weak and strong

The vast majority of LHC processes are controlled by strong interactions, described by the quantum-chromodynamics (QCD) sector of the SM. The predictions of production rates for particles like the Higgs or gauge bosons, top quarks or BSM states, rely on our understanding of the proton

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Source: arXiv:1701.07240

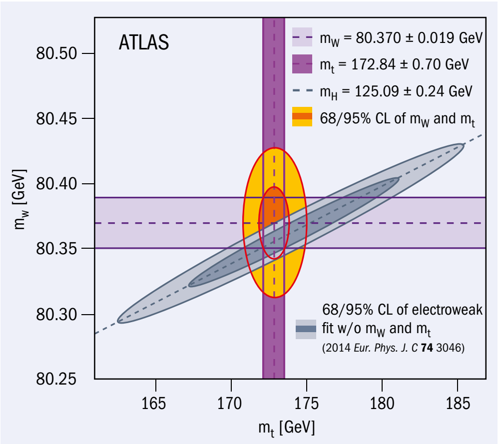

Fig. 3. *ATLAS measurements of the W-boson and top-quark masses (horizontal and vertical bands, combined as orange contours) compared to their indirect determination from a global EW fit using the observed Higgs mass as input (grey contours).*

Source: Nat. Phys. 13 535

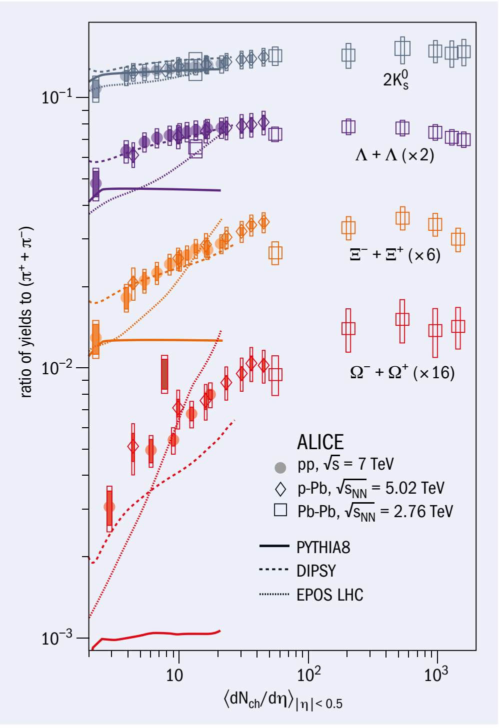

Fig. 4. *Production yields for hadrons containing one (K, Λ), two (Ξ) and three (Ω) strange quarks, relative to the pion yield, as a function of the multiplicity of charged particles measured by ALICE in pp, pPb and PbPb collisions. The unexpected continuity across colliding systems is suggestive of the onset of a new class of collective phenomena for pp and pPb, progressively leading towards the PbPb behaviour, which is attributed to the formation of the quark–gluon plasma.*

structure, in particular of the energy distribution of its quark and gluon components (the parton distribution functions, PDFs). The evolution of the final states, the internal structure of the jets emerging from quark and gluons, the kinematical correlations between different objects, are all governed by QCD. LHC measurements have been critical, not only to consolidate our understanding of QCD in all its dynamical domains, but also to improve the precision of the theoretical interpretation of data, and to increase the sensitivity to new phenomena and to the production of BSM particles.

Collisions galore

Approximately 10^9 proton–proton (pp) collisions take place each second inside the LHC detectors. Most of them bear no obvious direct interest for the search of BSM phenomena, but even simple elastic collisions, pp → pp, which account for about 30% of this rate, have so far failed to be fully understood with first-principle QCD calculations. The ATLAS ALFA spectrometer and the TOTEM detector have studied these high-rate processes, measuring the total and elastic pp cross sections, at the various beam energies provided by the LHC. The energy dependence of the relation between the real and imaginary part of the pp forward scattering amplitude has revealed new features, possibly described by the exchange of the so-called odderon, a coherent state of three gluons predicted in the 1970s (*CERN Courier* April 2018 p9).

The structure of the final states in generic pp collisions, aside from defining the large background of particles that are superimposed on the rarer LHC processes, is of potential interest to understand cosmic-ray (CR) interactions in the atmosphere. The LHCf detector measured the forward production of the most energetic particles from the collision, those driving the development of the CR air showers. These data are a unique benchmark to tune the CR event generators, reducing the systematics in the determination of the nature of the highest-energy CR constituents (protons or heavy nuclei?), a step towards solving the puzzle of their origin.

On the opposite end of the spectrum, rare events with dijet pairs of mass up to 9 TeV have been observed by ATLAS and CMS. The study of their angular distribution, a Rutherford-like scattering experiment, has confirmed the point-like nature of quarks, down to 10^{-18} cm. The overall set of production studies, including gauge bosons, jets and top quarks, underpins countless analyses. Huge samples of top quark pairs, produced at 15 Hz, enable the surgical scrutiny of this mysteriously heavy quark, through its production and decays. New reactions, unobservable before the LHC, were first detected. Gauge-boson scattering (e.g. $W^+W^+ \to W^+W^+$), a key probe of electroweak symmetry breaking proposed in the 1970s, is just one example. By and large, all data show an extraordinary agreement with theoretical predictions resulting from decades of innovative work (figure 2). Global fits to these data refine the proton PDFs, improving the predictions for the production of Higgs bosons or BSM particles.

The cross sections σ of W and Z bosons provide the most precise QCD measurements, reaching a 2% systematic uncertainty, dominated by the luminosity uncertainty. Ratios such as $\sigma(W^+)/\sigma(W^-)$ or $\sigma(W)/\sigma(Z)$, and the shapes of differential distributions, are known to a few parts in 1000. These data challenge the theoretical calculations' accuracy, and require caution to assess whether small discrepancies are due to PDF effects, new physics or yet imprecise QCD calculations.

As already mentioned, the success of the LHC owes a lot to its variety of beam and experimental conditions. In this context, the data at the different centre-of-mass energies

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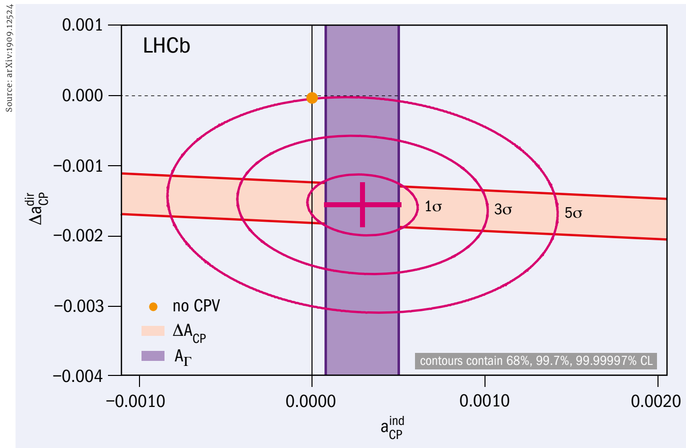


Source: arXiv:1909.12524

Fig. 5. *A combination of LHCb measurements of two types of CP violation in charm decays used to extract two underlying theory parameters. The vertical axis shows the difference in CP violation in two charm decays, and here the combination (cross) is more than five standard deviations from the point of zero CP violation, constituting the first observation of CP violation in charm decays.*

provided in the two runs are a huge bonus, since the theoretical prediction for the energy-dependence of rates can be used to improve the PDF extraction, or to assess possible BSM interpretations. The LHCb data, furthermore, cover a forward kinematical region complementary to that of ATLAS and CMS, adding precious information.

The precise determination of the W and Z production and decay kinematics has also allowed new measurements of fundamental parameters of the weak interaction: the W mass (m_W) and the weak mixing angle ($\sin\theta_W$). The measurement of $\sin\theta_W$ is now approaching the precision inherited from the LEP experiments and SLD, and will soon improve to shed light on the outstanding discrepancy between those two measurements. The m_W precision obtained by the ATLAS experiment, $\Delta m_W = 19$ MeV, is the best worldwide, and further improvements are certain. The combination with the ATLAS and CMS measurements of the Higgs boson mass ($\Delta m_H \cong 200$ MeV) and of the top quark mass ($\Delta m_{top} \lesssim 500$ MeV), provides a strong validation of the SM predictions (see figure 3). For both m_W and $\sin\theta_W$ the limiting source of systematic uncertainty is the knowledge of the PDFs, which future data will improve, underscoring the profound interplay among the different components of the LHC programme.

QCD matters

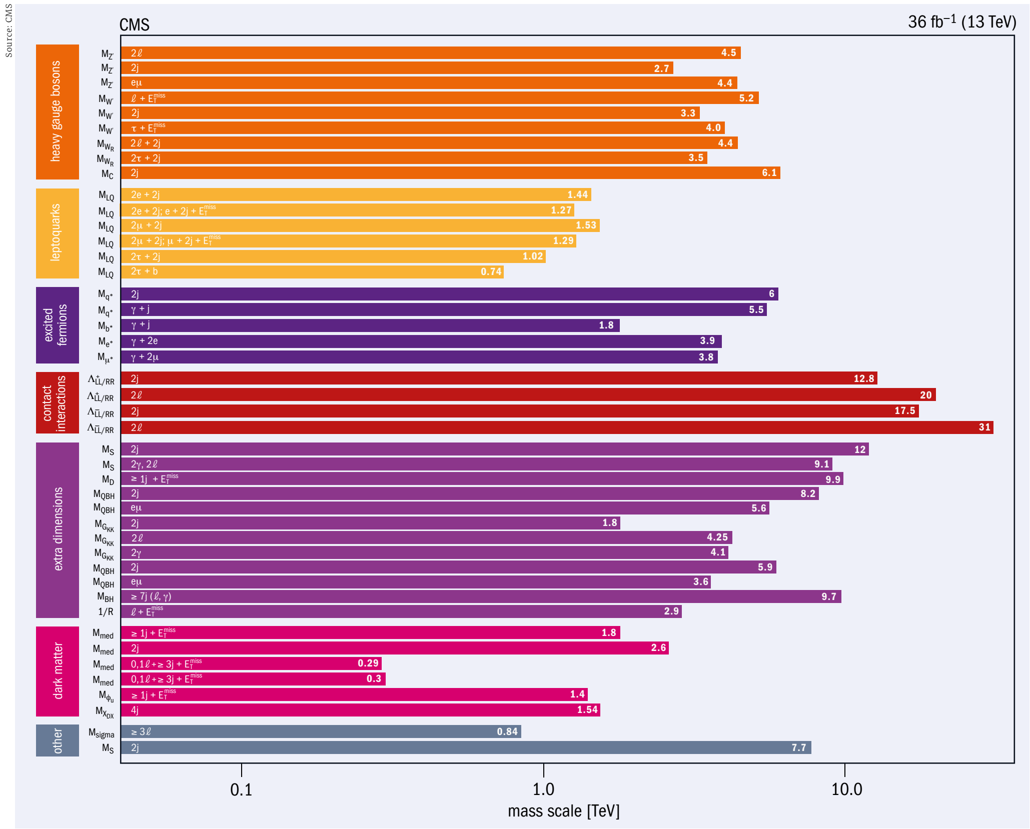
The understanding of the forms and phases that QCD matter can acquire is a fascinating, broad and theoretically challenging research topic, which has witnessed great progress in recent years. Exotic multi-quark bound states, beyond the usual mesons ($q\bar{q}$) and baryons (qqq), were initially discovered at e^+e^- colliders. The LHCb experiment, with its large rates of identified charm and bottom final states, is at the forefront of these studies, notably with the first discovery of heavy pentaquarks ($qqqc\bar{c}$) and with discoveries of tetraquark candidates in the charm sector ($qc\bar{c}\bar{q}$), accompanied by determinations of their quantum numbers and properties. These findings have opened a new playground for theoretical research, stimulating work in lattice QCD, and forcing a rethinking of established lore (*CERN Courier* April 2017 p31).

The study of QCD matter at high density is the core task of the heavy-ion programme. While initially tailored to the ALICE experiment, all active LHC experiments have since joined the effort. The creation of a quark–gluon plasma (QGP) led to astonishing visual evidence for jet quenching, with 1 TeV jets shattered into fragments as they struggle their way out of the dense QGP volume. The thermodynamics and fluctuations of the QGP have been probed in multiple ways, indicating that the QGP behaves as an almost perfect fluid, the least viscous fluid known in nature. The ability to explore the plasma interactions of charm and bottom quarks is a unique asset of the LHC, thanks to the large production rates, which unveiled new phenomena such as the recombination of charm quarks, and the sequential melting of $b\bar{b}$ bound states.

While several of the qualitative features of high-density QCD were anticipated, the quantitative accuracy, multitude and range of the LHC measurements have no match (*CERN Courier* April 2017 p26). Examples include ALICE's precise determination of dynamical parameters such as the QGP shear-viscosity-to-entropy-density ratio, or the higher harmonics of particles' azimuthal correlations. A revolution ensued in the sophistication of the required theoretical modelling. Unexpected surprises were also discovered, particularly in the comparison of high-density states in PbPb collisions with those occasionally generated by smaller systems such as pp and pPb. The presence in the latter of long-range correlations, various collective phenomena and an increased strange baryon abundance (figure 4), resemble behaviour typical of the QGP. Their deep origin is a mysterious property of QCD, still lacking an explanation. The number of new challenging questions raised by the LHC data is almost as large as the number of new answers obtained!

Flavour physics

Understanding the structure and the origin of flavour phenomena in the quark sector is one of the big open challenges of particle physics (*CERN Courier* January/February 2020 p23). The search for new sources of CP violation, beyond those present in the CKM mixing matrix, underlies the efforts to explain the baryon asymmetry of the universe. In addition to flavour studies with Higgs bosons and top quarks, more than 10^{14} charm and bottom quarks have been produced so far by the LHC, and the recorded subset has led to landmark discoveries and measurements. The rare $B_s \to \mu\mu$ decay, with a minuscule rate of approximately 3×10^{-9}, has been discovered by the LHCb, CMS and ATLAS experiments. The rarer $B_d \to \mu\mu$ decay is still unobserved, but its expected $\sim10^{-10}$ rate is within reach. These two results alone had a big impact on constraining the parameter space of several BSM theories, notably supersymmetry, and their precision and BSM sensitivity will continue improving. LHCb has discovered $D\bar{D}$ mixing and the long-elusive CP violation in D-meson decays, a first for up-type quarks (figure 5). Large hadronic non-perturbative uncertainties make the interpretation of these results particularly challenging, leaving under debate whether the measured properties are consistent with the SM, or signal new physics. But the experimental findings are a textbook milestone in the worldwide flavour physics programme.



Source: CMS

Fig. 6. *Exclusion limits from CMS on the masses of certain exotic phenomena beyond the Standard Model, using data collected in 2016, which extend to several TeV.*

LHCb produced hundreds more measurements of heavy-hadron properties and flavour-mixing parameters. Examples include the most precise measurement of the CKM angle $\gamma = (74.0\,^{+5.0}_{-5.8})^\circ$ and, with ATLAS and CMS, the first measurement of ϕ_s, the tiny CP-violation phase of $B_s \to J/\psi\varphi$, whose precisely predicted SM value is very sensitive to new physics. With a few notable exceptions, all results confirm the CKM picture of flavour phenomena. Those exceptions, however, underscore the power of LHC data to expose new unexpected phenomena: $B \to D^{(*)}\ell\nu$ ($\ell = \mu,\tau$) and $B \to K^{(*)}\ell^+\ell^-$ ($\ell = e,\mu$) decays hint at possible deviations from the expected lepton flavour universality (*CERN Courier* April 2019 p23). The community is eagerly waiting for further developments.

Beyond the Standard Model

Years of model building, stimulated before and after the LHC start-up by the conceptual and experimental shortcomings of the SM (e.g. the hierarchy problem and the existence of DM), have generated scores of BSM scenarios to be tested by the LHC. Evidence has so far escaped hundreds of dedicated searches, setting limits on new particles up to several TeV (figure 6). Nevertheless, much was learned. While none of the proposed BSM scenarios can be conclusively ruled out, for many of them survival is only guaranteed at the cost of greater fine-tuning of the parameters, reducing their appeal. In turn, this led to rethinking the principles that implicitly guided model building. Simplicity, or the ability to explain at once several open problems, have lost some drive. The simplest realisations of BSM models relying on supersymmetry, for example, were candidates to at once solve the hierarchy problem, provide DM candidates and set the stage for the grand unification of all forces. If true, the LHC should have piled up evidence by now. Supersymmetry remains a preferred candidate to achieve that, but at the price of more Byzantine constructions. Solving the hierarchy problem remains the outstanding theoretical challenge. New ideas have come to the forefront, ranging from the Higgs potential being determined by the early-universe evolution of an axion field, to dark sectors connected to the SM via a Higgs portal. These latter scenarios could also provide DM candidates alternative to the weakly-interacting massive particles, which so far have eluded searches at the LHC and elsewhere.

With such rapid evolution of theoretical ideas taking place as the LHC data runs progressed, the experimental analyses underwent a major shift, relying on "simplified models": a novel model-independent way to represent the results of searches, allowing published results to be later reinterpreted in view of new BSM models. This amplified the impact of experimental searches, with a surge of phenomenological activity and the proliferation of new ideas.

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The cooperation and synergy between experiments and theorists have never been so intense.

Having explored the more obvious search channels, the LHC experiments refocused on more elusive signatures. Great efforts are now invested in searching corners of parameter space, extracting possible subtle signals from large backgrounds, thanks to data-driven techniques, and to the more reliable theoretical modelling that has emerged from new calculations and many SM measurements. The possible existence of new long-lived particles opened a new frontier of search techniques and of BSM models, triggering proposals for new dedicated detectors (Mathusla, CODEX-b and FASER, the last of which was recently approved for construction and operation in Run 3). Exotic BSM states, like the milli-charged particles present in some theories of dark sectors, could be revealed by MilliQan, a recently proposed detector. Highly ionising particles, like the esoteric magnetic monopoles, have been searched for by the MoEDAL detector, which places plastic tracking films cleverly in the LHCb detector hall.

While new physics is still eluding the LHC, the immense progress of the past 10 years has changed forever our perspective on searches and on BSM model building.

Precision is the keystone to consolidate our description of nature

Final considerations

Most of the results only parenthetically cited, like the precision on the mass of the top quark, and others not even quoted, are the outcome of hundreds of years of person-power work, and would have certainly deserved more attention here. Their intrinsic value goes well beyond what was outlined, and they will remain long-lasting textbook material, until future work at the LHC and beyond improves them.

Theoretical progress has played a key role in the LHC's progress, enhancing the scope and reliability of the data interpretation. Further to the developments already mentioned, a deeper understanding of jet structure has spawned techniques to tag high-p_T gauge and Higgs bosons, or top quarks, now indispensable in many BSM searches. Innovative machine-learning ideas have become powerful and ubiquitous. This article has concentrated only on what has already been achieved, but the LHC and its experiments have a long journey of exploration ahead.

The terms *precision* and *discovery*, applied to concrete results rather than projections, well characterise the LHC 10-year legacy. Precision is the keystone to consolidate our description of nature, increase the sensitivity to SM deviations, give credibility to discovery claims, and to constrain models when evaluating different microscopic origins of possible anomalies. The LHC has already fully succeeded in these goals. The LHC has also proven to be a discovery machine, and in a context broader than just Higgs and BSM phenomena. Altogether, it delivered results that could not have been obtained otherwise, immensely enriching our understanding of nature. ●

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A new dawn *The CERN Control Centre on 30 March 2010, moments before first colliding beams at 3.5 TeV were achieved.*

BANG, BEAM, BUMP, BOSON

Bringing the LHC to life and steering it beyond its design performance has been a rollercoaster journey for those at the helm, describes Mike Lamont.

The start-up of the LHC was an exciting time and the culmination of years of work, made manifest in the process of establishing circulating beams, ramping, squeezing and producing the first collisions. The two major events of the commissioning era were first circulating beams on 10 September 2008 and first high-energy collisions on 30 March 2010. For both of these events the CERN press office saw fit to invite the world's media, set up satellite links, arrange numerous interviews and such. Combined with the background attention engendered by the LHC's potential to produce miniature black holes and the LHC's supporting role in the 2009 film *Angels and Demons*, the LHC enjoyed a huge amount of coverage, and in some sense became a global brand in the process (*CERN Courier* September 2018 p44).

The LHC is one of biggest, most complex and powerful instruments ever built. The large-scale deployment of the main two-in-one dipoles and quadrupoles cooled to 1.9 K by superfluid helium is unprecedented even in particle physics. Many unforeseen issues had to be dealt with in the period before start-up. A well-known example was that of the "collapsing fingers". In the summer of 2007, experts realised that the metallic modules responsible for the electrical continuity between different vacuum pipe sections in the magnet interconnects could occasionally become distorted as the machine was warmed up. This distortion led to a physical obstruction of the beam pipe. The solution was surprisingly low-tech: to blow a ping-pong-sized ball fitted with a 40 MHz transmitter through the pipes and find out where it got stuck.

The commissioning effort was clearly punctuated by the electrical incident that occurred during high-current tests on 19 September 2008, just nine days after the success of "first beam day". Although the incident was a severe blow to CERN and the LHC community, it did provide a hiatus of which full use was made (see p33). The LHC and experiments returned at "an unprecedented state of readiness" and beam was circulated again on 20 November 2009. Rapid progress followed. Collisions with stable beam conditions were quickly established at 450 GeV, and a ramp to the maximum beam energy at the time (1.18 TeV, compared to the Tevatron's 0.98 TeV) was successfully achieved on 30 November. All beam-based systems were at least partially commissioned and LHC operators managed to start to master the control of a hugely complex machine.

After the 2009 Christmas technical stop, which saw continued deployment of the upgraded quench-protection

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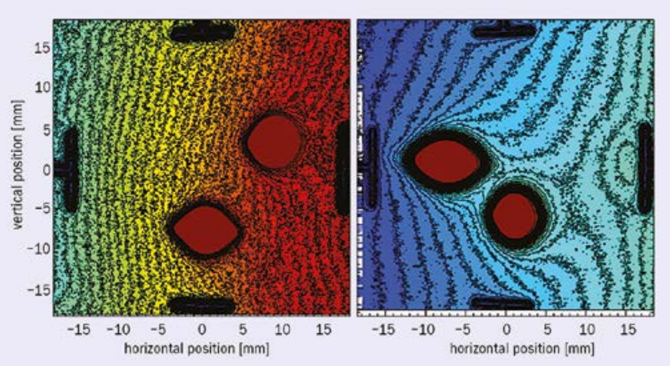
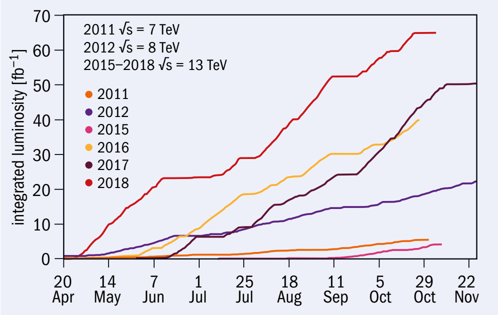


Beam day *First turns on 10 September 2008 as seen on the screens in the injection regions.*



On the rise *Delivered integrated luminosity (average of ATLAS and CMS) during the LHC's operational lifetime.*

system that had been put in place following the 2008 incident, commissioning started again in the new year. Progress was rapid, with first colliding beams at 3.5 TeV being established on 30 March 2010. It was a tense day in the control room with the scheduled collisions delayed by two unsuccessful ramps and all under the watchful eye of the media. In the following days, squeeze-commissioning successfully reduced the β^* parameter (which is related to the transverse size of the beam at the interaction points) to 2.0 m in ATLAS and CMS. Stable beams were declared, and the high-energy exploitation of the four main LHC experiments could begin in earnest.

Tales from Run 1

Essentially 2010 was devoted to commissioning and then establishing confidence in operational procedures and the machine protection system before starting the process of ramping up the number of bunches in the beam.

In June the decision was taken to go for bunches with nominal population (1.15×10^{11} protons), which involved another extended commissioning period. Up to this point, only around one fifth of the nominal bunch population was used. To further increase the number of bunches, the move to bunch trains separated by 150 ns was made and the crossing angles spanning the experiments' insertion regions brought in. This necessitated changes to the tertiary collimators and a number of ramps and squeezes. We then performed a carefully phased increase in total intensity. The proton run finished with beams of 368 bunches of around 1.2×10^{11} protons per bunch, and a peak luminosity of 2.1×10^{32} cm^{-2}s^{-1}, followed by a successful four-week long lead–lead ion run.

In 2011 it was decided to keep the LHC beam energy at 3.5 TeV, and to operate with 50 ns bunch spacing – opening the way to significantly more bunches per beam. Following several weeks of commissioning, a staged ramp-up in the number of bunches took us to a maximum of 1380 bunches. Reducing the transverse size of the beams delivered by the injectors and gently increasing the bunch population resulted in a peak luminosity of 2.4×10^{33} cm^{-2}s^{-1} and some healthy luminosity-delivery rates. Following a reduction in β^* in ATLAS and CMS from 1.5 m to 1.0 m, and further gradual increases in bunch population, the LHC achieved a peak luminosity of 3.8×10^{33} cm^{-2}s^{-1} – well beyond expectations at the start of the year – and delivered a total of around 5.6 fb^{-1} to both ATLAS and CMS.

The initial 50 and 25 ns intensity ramp-up phase was tough going

2012 was a production year at an increased beam energy of 4 TeV, with 50 ns bunch spacing and 1380 bunches. A decision to operate with tighter collimator settings allowed a more aggressive squeeze to a β^* of 0.6 m, and the peak luminosity was quickly close to its maximum for the year, followed by determined and long-running attempts to improve peak performance. Beam instabilities, although never debilitating, were a reoccurring problem and there were phases when they cut into operational efficiency. By the middle of the year another 6 fb^{-1} had been delivered to both ATLAS and CMS. Combined with the 2011 dataset, this paved the way for the announcement of the Higgs discovery on 4 July 2012. It was a very long operational year and included the extension of the proton–proton run until December, resulting in the shift of a four-week-long proton–lead run to 2013. Integrated-luminosity rates were healthy at around the 1 fb^{-1} per-week level and this allowed a total for the year of about 23 fb^{-1} to be delivered to both ATLAS and CMS.

To Run 2 and beyond

In early 2015 the LHC emerged from "long-shutdown one". The aims were to re-commission the machine without beam following major consolidation and upgrades, and from a beam perspective to safely establish operations at 6.5 TeV with 25 ns bunch spacing and around 2800 bunches. This was anticipated to be more of a challenge than previous operations at 4 TeV with 50 ns beams. Increased energy implies lower quench margins and thus lower tolerance to beam loss, with hardware pushed closer to maximum with potential knock-on effects to availability. A 25 ns beam was anticipated to have significantly higher electron-cloud effects (see "Five phrases LHC operators learned to love" box) than that experienced with 50 ns; in addition, there was a higher total beam current and higher intensity per injection. All of these factors came into play to make 2015 a challenging year.

The initial 50 and 25 ns intensity ramp-up phase was tough going and had to contend with a number of issues, including earth faults, unidentified falling objects, an unidentified aperture restriction in a main dipole, and radiation affecting specific electronic components in the tunnel. Nonetheless, the LHC was able to operate with up to 460 bunches and deliver some luminosity to the experiments, albeit with poor efficiency. The second phase of the ramp-up, following a technical stop at the start of September, was dominated by the electron-cloud-generated heat load and the subsequent challenge for the cryogenics, which had to wrestle with transients and operation close to their cooling power limits. The ramp-up in number of bunches was consequently slow but steady, culminating in the final figure for the year of 2244 bunches per beam. Importantly, the electron cloud generated during physics operations at 6.5 TeV served to slowly condition the surface of the beam screens in the cold sectors and so reduce the heat load at a given intensity. As time passed, this effect opened a margin for the use of more bunches.

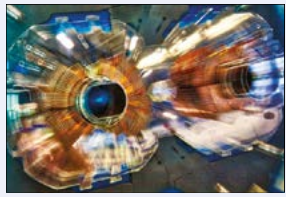
Five phrases LHC operators learned to love

Single-event effects

Caused by beam-induced radiation to tunnel electronics, these were a serious cause of inefficiency in the LHC's early days. However, the problem had been foreseen and its impact was considerably reduced following a sustained programme of mitigation measures – including shielding campaigns prior to the 2011 run.

Unidentified falling objects

Microscopic particles of the order of 10 microns across, which fall from the top of the vacuum chamber or beam screen, become ionised by collisions with circulating protons and are then repelled by the positively charged beam. While interacting with the circulating protons they generate localised beam loss, which may be sufficient to dump the beam or, in the limit, cause a quench. During the first half of 2015 they were a serious issue, but happily they have subsequently conditioned down in frequency.


E V Hove/CERN

Focused effort *A treated image of the LHC beam pipes.*

Beam-induced heating

This is where regions of the LHC near the beam become too warm, and has been a long-running issue. Essentially, all cases have been local and, in some way, due to non-conformities either in design or installation. Design problems have affected the injection protection devices and the mirror assemblies of the synchrotron radiation telescopes, while installation problems have occurred in a low number of vacuum assemblies. These issues have all been addressed and are not expected to be a problem in the long term.

Beam instabilities

This was an interesting problem that occasionally dogged operations. Operations with 25 ns bunch spacing and lower bunch population have meant that intrinsically instabilities should have been less of an issue. However, high electron cloud (see "Electron cloud effects") also proved to be a driver and defence mechanisms were deployed in the form of high-chromaticity, high-octupole field strength, and the all-important transverse damper system.

Electron cloud effects

These result from an avalanche-like process in which electrons from gas ionisation or photo-emission are accelerated in the electromagnetic field of the beam and hit the beam-chamber walls with energies of a few hundreds of eV, producing more electrons. This can lead to beam oscillations and blow-up of the proton bunches. "Scrubbing", the deliberate invocation of high electron cloud with beam, provides a way to reduce or suppress subsequent electron cloud build-up. Extensive scrubbing was needed for 25 ns running. Conditioning thereafter has been slow and the heat load from electron cloud to cryogenics system remained a limitation in 2018.

The overall machine availability remained respectable with around 32% of the scheduled time spent in "stable beams" mode during the final period of proton–proton physics from September to November. By the end of the 2015 proton run, 2244 bunches per beam were giving peak luminosities of 5.5×10^{33} cm^{-2}s^{-1} in the high-luminosity experiments, with a total integrated luminosity of around 4 fb^{-1} delivered to both ATLAS and CMS. Levelled luminosities of 3×10^{32} cm^{-2}s^{-1} in LHCb and 5×10^{30} cm^{-2}s^{-1} in ALICE were provided throughout the run.

A luminous future

Following an interesting year, 2016 was the first full year of exploitation at 6.5 TeV. The beam size at the interaction point was further reduced (β^* = 0.4 m) and the LHC design luminosity of 10^{34} cm^{-2}s^{-1} was achieved. Reasonable machine availability allowed a total of 40 fb^{-1} to be delivered to both ATLAS and CMS. 2017 saw a further reduction in beam size at the interaction point (β^* = 0.3 m), which, together with small beams from the injectors, gave a peak luminosity of 2.2×10^{34} cm^{-2}s^{-1}. Despite the effects of an accidental ingress of air into the beam vacuum during the winter technical stop, around 50 fb^{-1} was delivered to ATLAS and CMS.

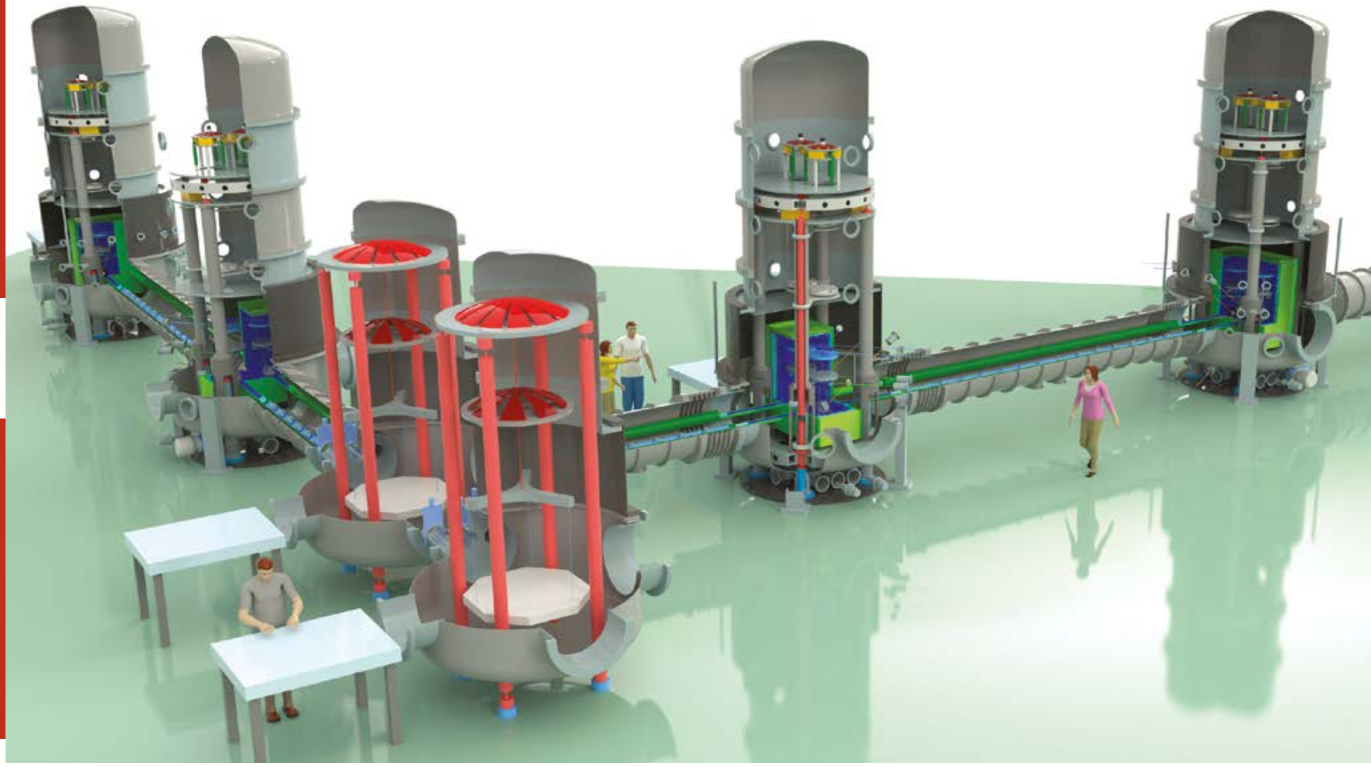
2018 essentially followed the set-up of 2017 with a squeeze to β^* = 0.3 m in ATLAS and CMS. The effects of the air ingress lingered on, limiting the maximum bunch intensity to approximately 1.2×10^{11}. Despite this, the peak luminosity was systematically close to 2×10^{34} cm^{-2}s^{-1} and around 63 fb^{-1} was delivered to ATLAS and CMS. Somewhat more integrated luminosity was possible thanks to the novel luminosity levelling strategy pursued. This involved continuous adjustment of the crossing angle in stable beams, and for the first time the LHC dynamically changed the optics in stable-beams mode, with β^* reduced from 0.30 to 0.27 to 0.25 m while colliding. The year finished with a very successful lead–ion run, helped by the impressive ion delivery from the injectors. In December 2018 the machine entered long-shutdown two, recovery from which is scheduled in 2021.

It is nearly 12 years since first beam, and 10 since first high-energy operations at the LHC. The experience has shown that, remarkably, not only can a 27 km superconducting collider work, it can work well! This on the back of some excellent hardware system performance, impressive availability, high beam quality from the injectors and some fundamental operational characteristics of the LHC. Thanks to the work of many, many people over the years, the LHC is now well understood and continues to push our understanding of how to operate high-energy hadron colliders and to surpass expectations. Today, as plans for Run 3 take shape and work advances on the challenging magnets needed for the high-luminosity LHC upgrade, things promise to remain interesting. ●

Not only can a 27 km superconducting collider work, it can work well!

SCOPING OUT THE EINSTEIN TELESCOPE

Activities are gathering pace at two sites in Europe where the Einstein Telescope, a proposed next-generation gravitational-wave observatory, may be built.



Triangulating for the future *The layout of the ETpathfinder facility in the southern tip of the Netherlands, one of two sites being considered for a future third-generation gravitational-wave laboratory called the Einstein Telescope. (Credit: M Kraan/Nikhef)*

In a former newspaper printing plant in the southern Dutch town of Maastricht, the future of gravitational-wave detection is taking shape. In a huge hall, known to locals as the "big black box", construction of a facility called ETpathfinder has just got under way, with the first experiments due to start as soon as next year. ETpathfinder will be a testing ground for the new technologies needed to detect gravitational waves in frequency ranges that the present generation of detectors cannot cover. At the same time, plans are being developed for a full-scale gravitational-wave detector, the Einstein Telescope (ET), in the Dutch–Belgian–German border region. Related activities are taking place 1500 km south in the heart of Sardinia, Italy. In 2023, one of these two sites (which have been selected from a total of six possible European locations) will be selected as the location of the proposed ET.

In 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO), which is based at two sites in the US, made the first direct detection of a gravitational wave. The Virgo observatory near Pisa in Italy came online soon afterwards, and the KAGRA observatory in Japan is about to become the third major gravitational-wave observatory in operation. All are L-shaped laser interferometers that detect relative differences in light paths between mirrors

THE AUTHORS

Martijn van Calmthout *Nikhef (for ETpathfinder)* *and* **Paola Catapano** *CERN (for Sar-Grav).*


M Struik

View from the south *The surface above the Sar-Grav laboratory in Sardinia, showing the three hilltops that roughly mark the vertices of a future Einstein Telescope were the Sardinian site to be selected.*

spaced far apart (4 km in LIGO; 3 km in Virgo and KAGRA) at the ends of two perpendicular vacuum tubes. A passing gravitational wave changes the relative path lengths by as little as one part in 10^{21}, which is detectable via the interference between the two light paths. Since 2015, dozens of gravitational waves have been detected from various sources, providing a new window onto the universe. One event has already been linked to astronomical observations in other channels, marking a major step forward in multi-messenger astronomy (*CERN Courier* December 2017 p17).

Back in time

The ET would be at least 10 times more sensitive than Advanced LIGO and Advanced Virgo, extending its scope for detections and enabling physicists to look back much further in cosmological time. For this reason, the interferometer has to be built at least 200 m underground in a geologically stable area, its mirrors have to operate in cryogenic conditions to reduce thermal disturbance, and they have to be larger and heavier to allow for a larger and more powerful laser beam. The ET would be a triangular laser interferometer with sides of 10 km and four ultra-high vacuum tubes per tunnel. The triangle configuration is equivalent to three overlapping interferometers with two arms each, allowing sources in the sky to be pinpointed via triangulation from just one location instead of several as needed by existing observatories. First proposed more than a decade ago and estimated to cost close to €2 billion, the ET, if approved, is expected to start looking at the sky sometime in the 2030s.

"In the next decade we will implement new technologies in Advanced Virgo and Advanced LIGO, which will enable about a factor-two increase in sensitivity, gaining in detection volume too, but we are reaching the limits of the infrastructure hosting the detectors, and it is clear that at a certain point these will strongly limit the progress you can make by installing new technologies," explains Michele Punturo of INFN Perugia, who is co-chair of the international committee preparing the ET proposal. "The ET idea and its starting point is to have a new infrastructure capable of hosting further and further evolutions of the detectors for decades."

Economic studies also show a net benefit, both regional and national, from the high-tech infrastructure the ET would need

Belgian, Dutch and German universities are investing heavily in the ETpathfinder project, which is also funded by European Union budgets for interregional development, and are considering a bid for the ET in the flowing green hills of the border region around Vaals between Maastricht (Netherlands) and Luik (Belgium). A geological study in September 2019 concluded that the area has a soft-soil top layer that provides very good environmental noise isolation for a detector built in granite-like layers 200 m below. Economic studies also show a net benefit, both regional and national, from the high-tech infrastructure the ET would need. But even if ET is not built there, ETpathfinder will still be essential to future gravitational-wave detection, stresses project leader Stefan Hild of Maastricht University. "This will become *the* testing ground for the disruptive technologies we will need in this field anyway," he says.

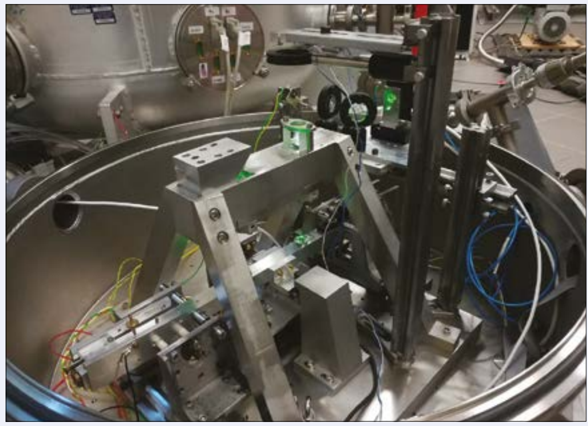
ET in search of home

ETpathfinder is a research infrastructure, not a scale model for the future ET. Its short length means that it is not aimed at detecting gravitational waves at any point in time. The L-shaped apparatus (image on previous page) has two arms about 20 m long, with two large steel suspension towers each containing large mirrors. The arms meet in a central fifth steel optical tower and one of the tubes extends behind the central tower, ending in a sixth tower. The whole facility will be housed in a new climate-controlled clean room inside the hall, and placed on a new low-vibration concrete floor. ETpathfinder is not a single interferometer but consists of two separate research facilities joined at one point for shared instrumentation and support systems. The two arms could be used to test different mirrors, suspensions, temperatures or laser frequencies independently. Those are the parameters Hild and his team are focusing on to further reduce noise in the interferometers and enhance their sensitivity.

Deep-cooling the mirrors is one way to beat noise, says Hild. But it also brings huge new challenges. One is that thermal conductivity of silica glass is not perfect at deep cryogenic temperatures, leading to deformations due to local laser heating. For that reason, pure silicon has to be used, but silicon is not transparent to the conventional 1064 nm laser light used for detecting gravitational waves and to align the optical systems in the detector. Instead, a whole new laser technology at 1550 nm will have to be developed and tested, including fibre-laser sources, beam control and manipulation, and specialised low-noise sensors. "All these key technologies and more need testing before they can be scaled up to the 10 km scales of the future ET," says Hild. Massive mirrors in pure silicon of metre-sizes have never been built, he points out, nor have silicon wire suspensions for the extreme cold payloads of more than half a tonne. Opto-electronics and sensors at 1550 nm at the noise level required for gravitational-wave detectors are also non-standard.

Archimedes weighs in on the quantum vacuum

The Archimedes experiment, which will be situated under 200 m of rock at the Sar-Grav laboratory in the Sos Enattos mine in Sardinia, was conceived in 2002 to investigate the interaction between the gravitational field and vacuum fluctuations. Supported by a group of about 25 physicists from Italian institutes and the European Gravitational Observatory, it is also intended as a "bridge" between present- and next-generation interferometers. A separate project in the Netherlands, ETpathfinder, is performing a similar function (see main text).


INFN

Poise and precision *Archimedes' beam-balance apparatus takes shape.*

Quantum mechanics predicts that the vacuum is a sea of virtual particles which contribute an energy density – although one that is tens of orders of magnitude larger than what is observed. Archimedes will attempt to shed light on the puzzle by clarifying whether virtual photons gravitate or not, essentially testing the equivalent of Archimedes' principle in vacuum. "If the virtual photons do gravitate then they must follow the gravitational field around the Earth," explains principal investigator Enrico Calloni of the University of Naples Federico II. "If we imagine removing part of them from a certain volume, creating a bubble, there will be a lack of weight (and pressure differences) in that volume, and the bubble will sense a force directed upwards, similar to the Archimedes force in a fluid. Otherwise, if they do not gravitate, the bubble will not experience any variation in the force even being immersed in the gravitational field."

The experiment (pictured) will use a Casimir cavity comprising two metallic plates placed a short distance apart so that virtual photons that have too large a wavelength cannot survive and are expelled, enabling Archimedes to measure a variation of the "weight" of the quantum vacuum. Since the force is so tiny, the measurement must be modulated and performed at a frequency where noise is low, says Calloni. This will be achieved by modulating the vacuum energy contained in the cavity using plates made from a high-temperature superconductor, which exhibits transitions from a semiconducting to superconducting state and in doing so alters the reflectivity of the plates. The first prototype is ready and in March the experiment is scheduled to begin six years of data-taking. "Archimedes is a sort of spin-off of Virgo, in the sense that it uses many of the technologies learned with Virgo: low frequency, sensors. And it has a lot of requirements in common with third-generation interferometers like ET: cryogenics and low seismic noise, first and foremost," explains Calloni. "Being able to rely on an existing lab with the right infrastructure is a very strong asset for the choice of a site for ET."

On paper, the new super-low noise detection technologies to be investigated by ETpathfinder will provide stunning new ways of looking at the universe with the ET. The sensitivity at low frequencies will enable researchers to actually hear the rumblings of space–time hours before spiralling black holes or neutron stars coalesce and merge. Instead of astronomers struggling to point their telescopes at the point in the sky indicated by millisecond chirps in LIGO and Virgo, they will be poised to catch the light from cosmic collisions many billions of light years away.

Sardinian adventure

The Sos Enattos mine is situated in the wild and mountainous heart of Sardinia, an hour's drive from the Mediterranean coast. More than 2000 years ago, the Romans (who, having had a hard time conquering the land, christened the region "Barbaria") excavated around 50 km of underground tunnels to extract lead for their aqueduct pipes. Until it closed activity in 1996, the mine has been the only alternative to livestock-rearing in this area for decades. Today, the locals are hoping that Sos Enattos will be chosen as the site to host the ET. Since 2010, several underground measurement campaigns have been carried out to characterise the site in terms of environmental noise. The regional government of Sardinia is supporting the development of the "Sar-Grav" underground laboratory and its infrastructures with approximately €3.5 million, while the Italian government is supporting the upgrade of Advanced Virgo and the characterisation of the Sos Enattos site with about €17 million, as part of a strategy to make Sardinia a possible site for the ET.

Sar-Grav's control room was completed late last year, and its first experiment – Archimedes – will soon begin (panel above), with others expected to follow. Archimedes will measure the effect of quantum interactions with

Sardinia is the oldest land in Italy and the only part of the country without significant seismic risk

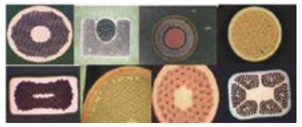
gravity via the Casimir effect and, at the same time, provide a testbed to verify the technologies needed by a third-generation gravitational-wave interferometer such as the ET. “Archimedes has the same requirements as an underground interferometer: extreme silence, extreme cooling with liquid nitrogen, and the ensuing safety requirements,” explains Domenico D’Urso, a physicist from the University of Sassari and INFN.

Follow the noise

Sardinia is the oldest land in Italy and the only part of the country without significant seismic risk. The island also has a very low population density and thus low human activity. The Sos Enattos mine has very low seismic noise and the most resistant granitic rock, which was used until the 1980s to build the skyscrapers of Manhattan. Walking along the mine’s underground tunnels – past the Archimedes cavern, amidst veins of schist, quartz, gypsum and granite, ancient mining machines and giant portraits of miners bearing witness to a glorious past – an array of instruments can be seen measuring seismic noise; some of which are so sensitive that they are capable of recording the sound of waves washing against the shores of the Thyrrenian sea. “We are talking about really small sensitivities,” continues Domenico. “An interferometer needs to be able to perform measurements of 10^{-21}, otherwise you cannot detect a gravitational wave. You have to know exactly what your system is doing, follow the noise and learn how to remove it.”

The open European ET collaboration will spend the next two years characterising both the Sardinian and Netherlands sites, and then choosing which best matches the required parameters. In the current schedule, a technical design report for the ET would be completed in 2025 and, if approved, construction would take place from 2026 with first data-taking during the 2030s. “As of then, wherever it is built, ET will be our facility for decades, because its noise will be so low that any new technology that at present we cannot even imagine could be implemented and not be limited,” says Punturo, emphasising the scientific step-change. Current detectors can see black-hole mergers occurring at a redshift of around one when the universe was six billion years old, Punturo explains, while current detectors at their final sensitivity will achieve a redshift of around two, corresponding to three billion years after the Big Bang. “But we want to observe the universe in its dark age, before stars existed. To do so, we need to increase sensitivity to a redshift tenfold and more,” he says. “With ET, we have 50 years of history ahead. It will study events from the entire universe. Gravitational waves will become a common tool just like conventional astronomy has been for the past four centuries.” ●

With the Einstein Telescope, we have 50 years of history ahead



OPINION VIEWPOINT

A recipe for sustainable particle physics

In addition to designing bold experiments, particle physicists must adopt new environmental practices to sustain the field into the next century, says Véronique Boisvert.


N Caraban

Self-sufficient *The SESAME light source is the first accelerator infrastructure to be powered by renewable energy, but not all facilities have that option.*

Véronique Boisvert *is group leader of the centre for particle physics at Royal Holloway, University of London and a member of the ATLAS collaboration.*

There has been a marked increase in awareness about climate change in society. Whether due to the recent school strikes initiated by Greta Thunberg or the destructive bushfires gripping Australia, the climate emergency has now moved up in the public's list of concerns. Governments around the world have put in place various targets to reduce greenhouse-gas emissions as part of the Intergovernmental Panel on Climate Change (IPCC) 2015 Paris agreement. The scientific community, like others, will increasingly be expected to put in place measures to reduce its greenhouse-gas emissions. It is then timely to create structures that will minimise the carbon footprint of current and future experiments, and their researchers.

The LHC uses 1.25 TWh of electricity annually, the equivalent of powering around 300,000 homes, or roughly 2% of the annual consumption of Switzerland. Fortunately, the electricity supply of the LHC comes from France, where only about 10% of electricity is produced by fossil fuels. CERN is adopting several green initiatives. For example, it recently released plans to use hot water from a cooling plant at Point 8 of the LHC (where the LHCb detector is situated) to heat 8000 homes in the nearby town of Ferney-Voltaire. In 2015, CERN introduced an energy-management panel and the laboratory is about to publish a wide-ranging environmental report. CERN is also involved in the biennial workshop series Energy for Sustainable Science at Research Infrastructures, which started in 2011 and is where useful ideas are shared among research infrastructures. Whether it be related to high-performance computing or the LHC's cryogenic systems, increased energy efficiency both reduces CERN's carbon footprint and provides financial savings.

It is a moral imperative for the community to look at ways to reduce its carbon footprint

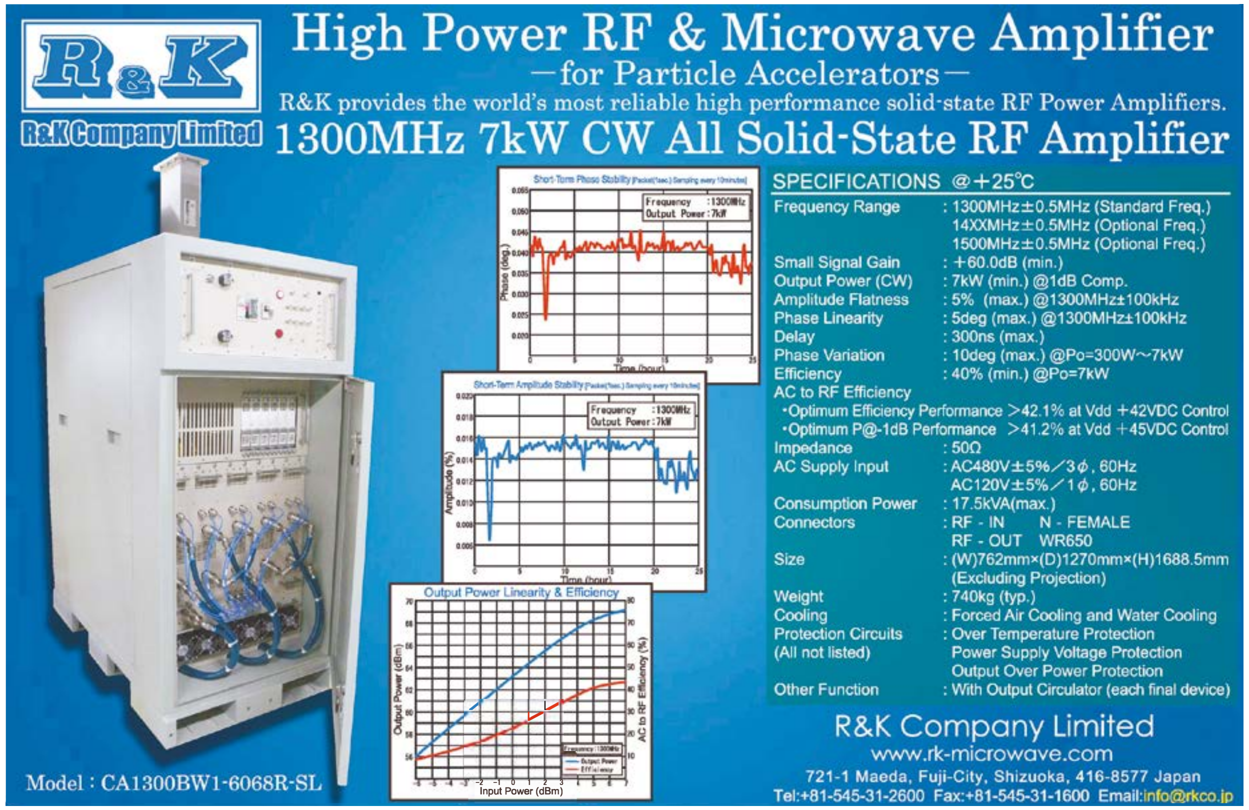
In addition to colliders, particle physics also involves detectors, some of which need particular gases for their operation or cooling. Unfortunately, some of these gases have very high global-warming potential. For example, sulphur hexafluoride, which is commonly used in high-voltage supplies and also in certain detectors such as the resistive plate chambers in the ATLAS muon spectrometer, causes 16,000 times more warming than CO_2 over a 20-year period. Though mostly used in closed circuits, some of these gases are occasionally vented to the atmosphere or leak from detectors, and, although the quantities involved are small, it is likely that some of the gases used by current detectors are about to be banned by many countries, making them very hard to procure and their price volatile. A lot is already being done to combat this issue. At CERN, for instance, huge efforts have gone into replacing detector cooling fluids and investigating new gas mixtures.

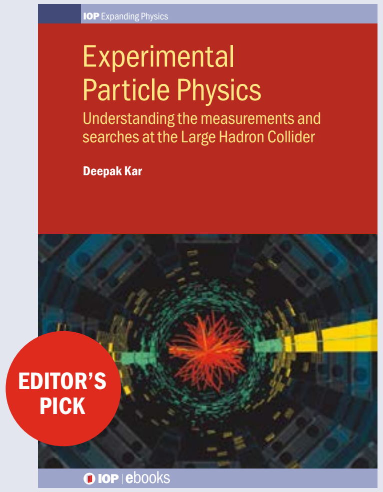
Strategic approach

The European particle-physics community is currently completing the update of its strategy for the next five years or so, which will guide not only CERN activities but also those in all European countries. It is of the utmost importance that sustainability goals be included in this strategy. To this end, myself and my colleagues Cham Ghag and David Waters (University College London) and Francesco Spano (Royal Holloway) arrived at three main recommendations on sustainability as input into the strategy process.

First, as part of their grant-giving process, European laboratories and funding agencies should include criteria evaluating the energy efficiency and carbon footprint of particle-physics proposals, and should expect to see evidence that energy consumption has been properly estimated and minimised. Second, any design of a major experiment should consider plans for reduction of energy consumption, increased energy efficiency, energy recovery and carbon-offset mechanisms. (Similarly, any design for new buildings should consider the highest energy-efficiency standards.) Third, European laboratories should invest in next-generation digital meeting spaces including virtual-reality tools to minimise the need for frequent travel. Many environmental groups are calling for a frequent-flyer levy, since roughly 15% of the population take about 70% of all flights. This could potentially have a massive effect on the travel budgets of particle physicists, but it is a moral imperative for the community to look at ways to reduce this carbon footprint. Another area that the IPCC has identified will need to undergo a massive change is food. Particle physicists could send a very powerful message by choosing to have all of its work-related catering be mostly vegetarian.

Particle physics is flush with ideas for future accelerators and technologies to probe deeper into the structure of matter. CERN and particle physicists are important role models for all the world's scientific community. Channelling some of our scientific creativity into addressing the sustainability of our own field, or even finding solutions for climate change, will produce ripples across all of society.



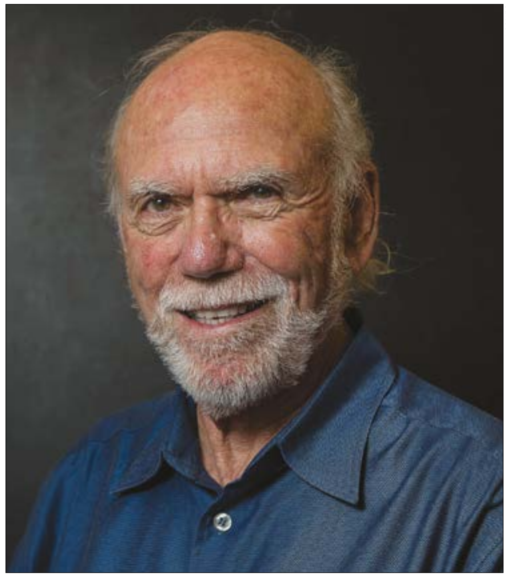


Success in scientific management

While visiting CERN in December, experimental physicist Barry Barish spoke to the *Courier* about his role in turning LIGO from a physics project into a Nobel Prize-winning machine.

Your co-Nobelists in the discovery of gravitational waves, Kip Thorne and Rainer Weiss, have both recognised your special skills in the management of the LIGO collaboration. When you landed in LIGO in 1994, what was the first thing you changed?
When I arrived in LIGO, there was a lot of dysfunction and people were going after each other. So, the first difficult problem was to make LIGO smaller, not bigger, by moving people out who weren't going to be able to contribute constructively in the longer term. Then, I started to address what I felt were the technical and management weaknesses. Along with my colleague, Gary Sanders, who had worked with me on one of the would-be detectors for the Superconducting Super Collider (SSC) before the project was cancelled, we started looking for the kind of people that were missing in technical areas.

For example, LIGO relies on very advanced lasers but I was convinced that the laser that was being planned for, a gas laser, was not the best choice because lasers were, and still are, a very fast-moving technology and solid-state lasers were more forward-looking. Coming from particle physics, I'm used to not seeing a beam with my own eyes. So I wasn't disturbed that the most promising lasers at that time emitted light in the infrared, instead of green, and that technology had advanced to where they could be built in industry. People who worked with interferometers were used to "little optics" on lab benches where the lasers were all green and the alignment of mirrors etc was straightforward. I asked three of the most advanced groups in the world who worked on lasers of the type we needed (Hannover in Germany, Adelaide in Australia and Stanford in California) if they'd like to work together with us, and we brought these experts into LIGO to form the core of what we still have today as our laser group.



Caltech

Leadership role *Barry Barish of Caltech and the University of California, Riverside held leadership roles in experimental particle physics before joining LIGO in 1994.*

This story is mirrored in many of the different technical areas in LIGO. Physics expertise and expertise in the use of interferometer techniques were in good supply in LIGO, so the main challenge was to find expertise to develop the difficult forefront technologies that we were going to depend on to reach our ambitious sensitivity goals. We also needed to strengthen the engineering and project-management areas, but that just required recruiting very good people. Later, the collaboration grew a lot, but mostly on the data-analysis side, which today makes up much of our collaboration.

> **Project management for forefront science experiments is very different, and it is hard for people to do it well**

According to Gary Sanders of SLAC, "efficient management of large science facilities requires experience and skills not usually found in the repertoire of research scientists". Are you a rare exception?
Gary Sanders was a student of Sam Ting, then he went to Los Alamos where he got a lot of good experience doing project work. For myself, I learned what was needed kind of organically as my own research grew into larger and larger projects. Maybe my personality matched the problem, but I also studied the subject. I know how engineers go about building a bridge, for example, and I could pass an exam in project management. But, project management for forefront science experiments is very different, and it is hard for people to do it well. If you build a bridge, you have a boss, and he or she has three or four people who do tasks under his/her supervision, so generally the way a large project is structured is a big hierarchical organisation. Doing a physics research project is almost the opposite. For large engineering projects, once you've built the bridge, it's a bridge, and you don't change it. When you build a physics experiment, it usually doesn't do what you want it to do. You begin with one plan and then you decide to change to another, or even while you're building it you develop better approaches and technologies that will improve the instruments. To do research in physics, experience tells us that we need a flat, rather than vertical, organisational style. So, you can't build a complicated, expensive ever-evolving research project using just what's taught in the project-management books, and you can't do what's needed to succeed in cost, schedule, performance, etc, in the style found in a typical physics-department research group. You have to employ

some sort of hybrid. Whether it's LIGO or an LHC experiment, you need to have enough discipline to make sure things are done on time, yet you also need the flexibility and encouragement to change things for the better. In LIGO, we judiciously adapted various project-management formalities, and used them by not interfering any more than necessary with what we do in a research environment. Then, the only problem – but admittedly a big one – is to get the researchers, who don't like any structure, to buy into this approach.

How did your SSC experience help?
It helped with the political part, not the technical part, because I came to realise how difficult the politics and things outside of a project are. I think almost anything I worked on before has been very hard, because of what it was or because of some politics in doing it, but I didn't have enormous problems that were totally outside my control, as we had in the SSC.

How did you convince the US government to keep funding LIGO, which has been described as the most costly project in the history of the NSF?
It's a miracle, because not only was LIGO costly, but we didn't have much to show in terms of science for more than 20 years. We were funded in 1994, and we made the first detection more than 20 years later. I think the miracle wasn't me, rather we were in a unique situation in the US. Our funding agency, the NSF, has a different mission than any other agency I know about. In the US, physical sciences are funded by three big agencies. One is the DOE, which has a division that does research in various areas with national labs that have their own structures and missions. The other big agency that does physical science is NASA, and they have the challenge of safety in space. The NSF gets less money than the other two agencies, but it has a mission that I would characterise by one word: science. LIGO has so far seen five different NSF directors, but all of them were prominent scientists. Having the director of the funding agency be someone who understood the potential importance of gravitational waves, maybe not in detail, helped make NSF decide both to take such a big risk on LIGO and then continue supporting it until it succeeded. The NSF leadership understands that risk-taking is integral to making big advancements in science.

M Struik/CERN

Global view *Barry Barish delivers a colloquium at CERN on 12 December.*

The NSF leadership understands that risk-taking is integral to making big advancements

What was your role in LIGO apart from management?
I concentrated more on the technical side in LIGO than on data analysis. In LIGO, the analysis challenges are more theoretical than they are in particle physics. What we have to do is compare general relativity with what happens in a real physical phenomenon that produces gravitational waves. That involves more of a mixed problem of developing numerical relativity, as well as sophisticated data-analysis pipelines. Another challenge is the huge amount of data because, unlike at CERN, there are no triggers. We just take data all the time, so sorting through it is the analysis problem. Nevertheless, I've always felt and still feel that the real challenge for LIGO is that we are limited by how sensitive we can make the detector, not by how well we can do the data analysis.

What are you doing now in LIGO?
Now that I can do anything I want, I am focusing on something I am interested in and that we don't employ very much, which is artificial intelligence and machine learning (ML). In LIGO there are several problems that could adapt themselves very well to ML with recent advances. So we built a small group of people, mostly much younger than me, to do ML in LIGO. I recently started teaching at the University of California Riverside, and have started working with young faculty in the university's computer-science department on adapting some techniques in ML to problems in physics. In LIGO, we have a problem in the data that we call "glitches", which appear when something that happens in the apparatus or outside world appears in the data. We need to get rid of glitches, and we use a lot of human manpower to make the data clean. This is a problem that should adapt itself very well to a ML analysis.

Now that gravitational waves have joined the era of multi-messenger astronomy, what's the most exciting thing that can happen next?
For gravitational waves, knowing what discovery you are going to make is almost impossible because it is really a totally new probe of the universe. Nevertheless, there are some known sources that we should be able to see soon, and maybe even will in the present run. So far we've seen two sources of gravitational waves: a collision of two black holes and a collision of two neutron stars, but we haven't yet seen a black hole with a neutron star going around it. They're particularly interesting scientifically because they contain information about nuclear physics of very compact objects, and because the two objects are very different in mass and that's very difficult to calculate using numerical relativity. So it's not just checking off another source that we found, but new areas of gravitational-wave science. Another attractive possibility is to detect a spinning neutron star, a pulsar. This is a continuous signal that is another interesting source which we hope to detect in a short time. Actually, I'm more interested in seeing unanticipated sources where we have no idea what we're going to see, perhaps phenomena that uniquely happen in gravity alone.

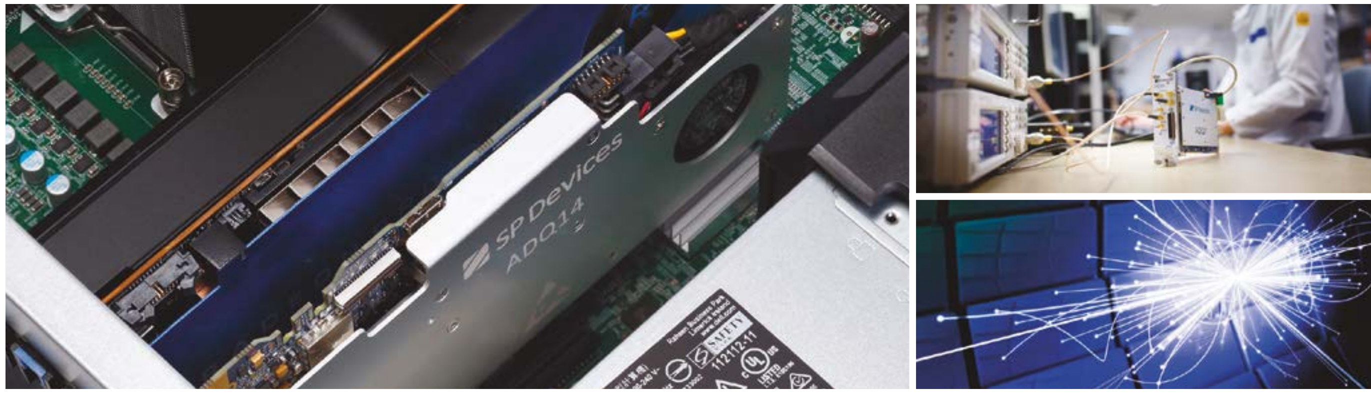
Will we ever see gravitons?
That's a really good question because gravitons don't exist in Einstein's equations. But that's not necessarily nature, that's Einstein's equations! The biggest problem we have in physics is that we have two fantastic theories. One describes almost anything you can imagine on a large scale, and that's Einstein's equations, and the other, which describes almost too well everything you find here at CERN, is the Standard Model, which is based on quantum field theory. Maybe black holes have the feature that they satisfy Einstein's equations and at the same time conserve quantum numbers and all the things that happen in quantum physics. What we are missing is the experimental clue, whether it's gravitons or something else that needs to be explained by both these theories. Because theory alone has not been able to bring them together, I think we need experimental information.

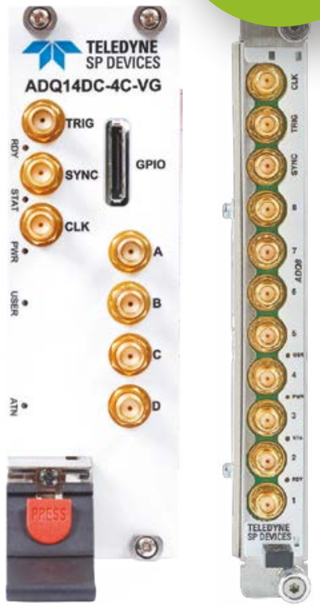
Do particle accelerators still have a role in this?
We never know because we don't know the future, but our best way of understanding what limits our present understanding has been traditional particle accelerators because we have the most control over the particles we're studying. The unique feature of particle accelerators is that of being able to measure all the parameters of particles that we want. We've found the Higgs boson and that's wonderful, but now we know that the neutrinos also have mass and the Higgs boson possibly doesn't describe that. We have three families of particles, and a whole set of other very fundamental questions that we have no handle on at all, despite the fact that we have this nice "standard" model. So is it a good reason to go to higher energy or a different kind of accelerator? Absolutely, though it's a practical question whether it's doable and affordable.

The biggest problem we have in physics is that we have two fantastic theories

What's the current status of gravitational-wave observatories?
We will continue to improve the sensitivity of LIGO and Virgo in incremental steps over the next few years, and LIGO will add a detector in India to give better global coverage. KAGRA in Japan is also expected to come online. But we can already see that next-generation interferometers will be needed to pursue the science in the future. A good design study, called the Einstein Telescope, has been developed in Europe. In the US we are also looking at next-generation detectors and have different ideas, which is healthy at this point. We are not limited by nature, but by our ability to develop the technologies to make more sensitive interferometers. The next generation of detectors will enable us to reach large red shifts and study gravitational-wave cosmology. We all look forward to exploiting this new area of physics, and I am sure important discoveries will emerge.

Interview by **Paola Catapano** *CERN.*





OPINION
REVIEWS

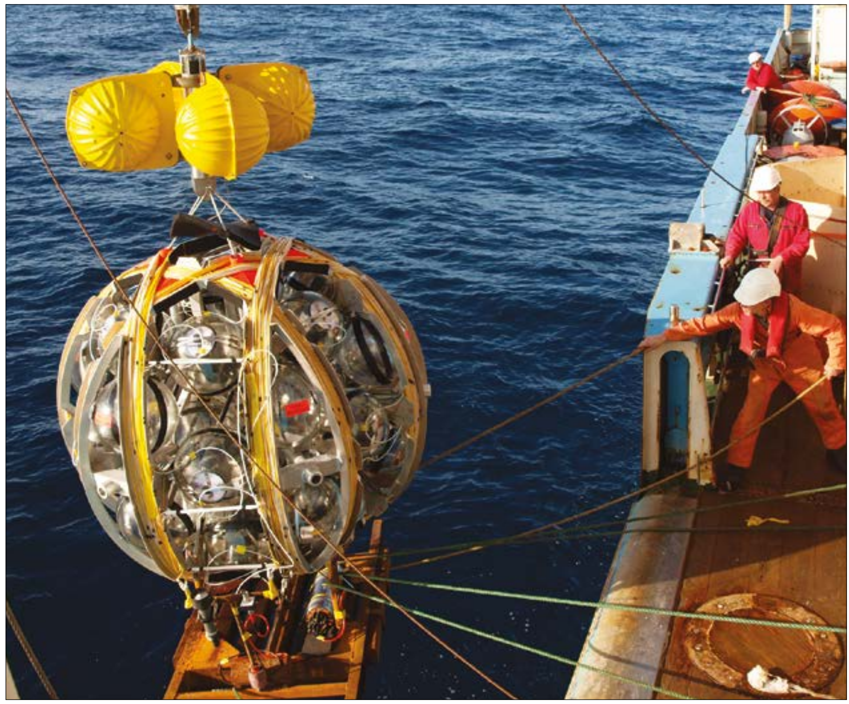
A first taste of neutrino physics

The State of the Art of Neutrino Physics: A Tutorial for Graduate Students and Young Researchers

Edited by Antonio Ereditato

World Scientific

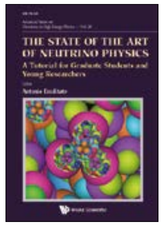
Almost 90 years since Pauli postulated its existence, much remains to be learnt about the neutrino. The observation in 1998 of neutrino oscillations revealed that the particle's flavour and mass eigenstates mix and oscillate. At least two must be massive, like the other known fermions, though with far smaller masses. The need for a mechanism to generate such small masses strongly hints at the existence of new physics beyond the Standard Model. Faced with such compelling questions, neutrino experiments are springing up at an unprecedented rate, from a plethora of searches for neutrinoless double-beta decay to gigantic astrophysical-neutrino detectors at the South Pole (IceCube) and soon in the Mediterranean Sea (KM3NeT), and two projects of enormous scope on the horizon in DUNE and Hyper-Kamiokande. Now, then, is a timely moment for the publication of a tutorial for graduate students and young researchers who are entering this fast-moving field.


KM3NeT

Casting a wide KM3NeT *A string of optical detectors is lowered into the Mediterranean Sea for the KM3NeT neutrino telescope. When the launcher vehicle reaches the seabed, it unravels and deploys the sensors as it floats to the surface.*

Access all areas

Edited by former spokesperson of the OPERA experiment Antonio Ereditato, *The State of the Art of Neutrino Physics* provides an historical account and introduction to basic concepts, reviews of the various subfields where neutrinos play a significant role, and gives a detailed account of the data produced by present experiments in operation. An extremely valuable compilation of topical articles, the book covers essentially all areas of research in experimental neutrino physics, from astrophysical, solar and atmospheric neutrinos to accelerator and reactor neutrinos. The large majority of the articles are written in a didactic style by leading experts in the field, allowing young researchers to acquaint themselves with the diverse research in the field. In particular the chapter describing the formalism of neutrino oscillations should be required reading for all aspiring neutrino physicists. In all cases special attention is given to experimental challenges.



From the theory side, chapters cover measurements at neutrino experiments of the low-energy interactions of neutrinos with nuclei (a key way to reduce systematic uncertainties), the phenomenology and consequences of the yet-to-be-determined neutrino-mass hierarchy, and the possibility of CP violation in the lepton sector. A very detailed account of solar neutrinos and matter effects in the Sun is written by Alexei Smirnov, one of the inventors of the celebrated Mikheyev-Smirnov-Wolfenstein effect, which describes how weak interactions with electrons modify oscillation probabilities for the various neutrino flavours. More speculative scenarios, for example on the possibility of the existence of sterile neutrinos, are discussed as well.

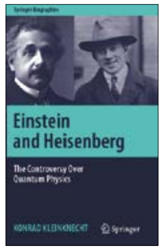
For a book like this, which has the ambition to address a broad palette of neutrino questions, it is always difficult to be totally complete, but it comes close. Some topics have evolved in the details since 2016, when the material upon which the book is based was written, but that doesn't take away from the book's value as a tutorial. I recommend it very highly to young and not-so-young aspiring neutrino aficionados alike.

Albert De Roeck *CERN.*

Einstein and Heisenberg: The Controversy over Quantum Physics

By Konrad Kleinknecht

Springer



This attractive and exciting book gives easy access to the history of the two main pillars of modern physics of the first half of the 20th century: the theory of relativity and quantum mechanics. The history unfolds along the parallel biographies of the two giants in these fields, Albert Einstein and Werner Heisenberg. It is a fascinating read for everybody interested in the science and culture of their time.

At first sight, one could think that the author presents a twin biography of Einstein and Heisenberg, and that's all. However, one quickly realises that there is much more to this concise and richly illustrated text. Einstein and Heisenberg's lives are embedded in the context of their time, with emphasis given to explaining the importance and nature of their interactions with the physicists of rank and name around them. The author cites many examples from letters and documents for both within their respective environments, which are most interesting to read, and illustrate well the spirit of the time. Direct interactions between both heroes of the book were quite sparse though.

At several stages throughout the book, the reader will become familiar with the personal life stories of both protagonists, who were, in spite of some commonalities, very different from each other. Common to both, for instance, was their devotion to music and their early interest and outstanding talent in physics as boys at schools in Munich, but on the contrary they were very different in their relations with family and partners, as the author discusses in a lively way. Many of these aspects are well known, but there are also new facets presented. I liked the way this is done, and, in particular, the author does not shy away from also documenting the perhaps less commendable human aspects, but without judgement, leaving the reader to come to their own conclusion.

Topics covering a broad spectrum are commented on in a special chapter called "Social Affinities". These include religion, music, the importance of family, and, in the case of Einstein, his relation to his wives and women in general, the way he dealt with his immense public reputation as a super scientist, and also his later years when he could be seen as "scientifically an outsider". In Heisenberg's case, one is reminded of his very major contributions to the restoration of scientific research in West Germany and Europe after World War II, not least of course in his crucial founding role in the establishment of CERN.

Do not expect a systematic, comprehensive introduction to relativity and quantum physics; this is not a textbook. Its great value is the captivating way the author illustrates how these great minds formed their respective theories in relation to the physics and academic world of their time. The reader learns not only about Einstein and Heisenberg, but also about many of their contemporary colleagues. A central part in this is the controversy about the interpretation of quantum mechanics among Heisenberg's colleagues and mentors, such as Schrödinger, Bohr, Pauli, Born and Dirac, to name just a few.

Another aspect of overriding importance for the history of that time was of course the political environment spanning the time from before World War I to after World War II. Both life trajectories were influenced in a major way by these external political and societal factors. The author gives an impressive account of all these aspects, and sheds light on how the pair dealt with these terrible constraints, including their attitudes and roles in the development of nuclear weapons.

A special feature of the book, which will make it interesting to everybody, is the inclusion of various hints as to where relativity and quantum mechanics play a direct role in our daily lives today, as well as in topical contemporary research, such as the recently opened field of gravitational-wave astronomy.

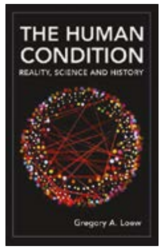
This is an ambitious book, which tells the story of the birth of modern physics in a well-documented and well-illustrated way. The author has managed brilliantly to do this in a serious, but nevertheless entertaining, way, which will make the book a pleasant read for all.

Peter Jenni *Albert Ludwig University of Freiburg and CERN.*

The Human Condition: Reality, Science and History

By Gregory Loew

Mascot Books



"Homo has much work left to become Sapiens," is Gregory Loew's catchphrase in *The Human Condition: Reality, Science and History*. An accelerator physicist with an illustrious 50-year-long career at the SLAC National Accelerator Laboratory in California, Loew also taught a seminar at Stanford University that ran the gamut from psychology and anthropology to international relations and arms control. His new book combines these passions.

This reviewer must admit to being inspired by the breadth of Loew's polymathic ambition, which he has condensed into 200 colourful pages. The author compares his work to noted Israeli historian Yuval Harari's hefty tomes *Sapiens* and *Homo Deus*, but *The Human Condition* is more idiosyncratic, and peppered with fascinating titbits. He points out the difficulties in connecting free will with quantum indeterminacy. He asks what came first: the electron or the electric field? Neglecting to mention the disagreement with the long-accepted age of the universe inferred from fits to the cosmic microwave background, he breathlessly slips in a revised-down value of 12.8 billion years, tacitly accepting the 2019 measurement of the Hubble constant based on observations by the Hubble Space Telescope. He even digresses momently to note the almost unique rhythmic awareness of cockatoo parrots.

But this is not a scenic drive through the nature of existence. Loew wants to be complete. He reverses from epistemology to evolution and the nature of perception, before pulling out onto the open road of mathematics and the sciences, both fundamental and social, via epigenetics, Thucydides and the Cuban missile crisis. The final chapter, which looks to the future, is really a thoughtful critique of Harari's books, which he discovered while writing. It's heartening to join Loew on an expansive road trip from metaphysics and physics to economic theory and realpolitik.

No scientific knowledge or mathematical training is necessary to enjoy *The Human Condition*, which will entertain and intrigue physicists and lay audiences alike. While some subjects, such as homosexuality, are treated with inappropriate swiftness, in that case with a rapid and highly questionable hop from Freud to Kinsey to Schopenhauer to Pope Francis, in general Loew writes with a refreshing élan. His final thought is that "if all Homo Sapientes became wiser, they would certainly be happier." Here, he flirts with contradicting Kant, a philosopher he frequently esteems, who wrote that the cultivation of reason sooner leads to misery than happiness. But perhaps the key word is "*all* Homo Sapientes". If every one of us became wiser, perhaps through the utopic initiatives advocated by Loew, we would indeed be happier.

Mark Rayner *associate editor.*

PEOPLE CAREERS

Learning language by machine

Former CMS user Mait Müntel left physics to found Lingvist, an education company harnessing big data and artificial intelligence to accelerate language learning.

Mait Müntel came to CERN as a summer student in 2004 and quickly became hooked on particle physics, completing a PhD in the CMS collaboration in 2008 with a thesis devoted to signatures of double-charged Higgs bosons. Continuing in the field, he was one of the first to do shifts in the CMS control room when the LHC ramped up. It was then that he realised that the real LHC data looked nothing like the Monte Carlo simulations of his student days. Many things had to be rectified, but Mait admits he was none too fond of coding and didn't have any formal training. "I thought I would simply 'learn by doing'," he says. "However, with hindsight, I should probably have been more systematic in my approach." Little did he know that, within a few years, he would be running a company with around 40 staff developing advanced language-learning algorithms.

J Fichet/CERN

Talking shop *Lingvist CEO Mait Müntel (left) talks to Rachel Bray of the CERN Office of Alumni Relations at a LinkedIn Live event last year.*

Memory models

Despite spending long periods in the Geneva region, Mait had not found the time to pick up French. Frustrated, he began to take an interest in the use of computers to help humans learn languages at an accelerated speed. "I wanted to analyse from a statistical point of view the language people were actually speaking, which, having spent several years learning both Russian and English, I was convinced was very different to what is found in academic books and courses," he says. Over the course of one weekend, he wrote a software crawler that enabled him to download a collection of French subtitles from a film database. His next step was to study memory models to understand how one acquires new knowledge, calculating that, if a computer program could intelligently decide what would be optimal to learn in the next moment, it would be possible to learn a language in only 200 hours. He started building some software using ROOT (the object-oriented program and library developed by CERN for data analysis) and, within two weeks, was able to read a proper book in French. "I had included a huge book library in the software and as the computer knew my level of vocabulary, it could recommend books for me. This was immensely gratifying and pushed me to progress even further." Two months later, he passed the national French language exam in Estonia.

Mait became convinced that he had to do something with his idea. So he went on holiday, and hired two software developers to develop his code so it would work on the web. Whilst on holiday, he happened to meet a friend of a friend, who helped him set up Lingvist as a company. Estonia, he says, has a fantastic start-up and software-development culture thanks to Skype, which was invented there. Later, Mait met the technical co-founder of Skype at a conference, who coincidentally had been working on software to accelerate human learning. He dropped his attempts and became Lingvist's first investor.

The pair secured a generous grant from the European Union Horizon 2020 programme and things were falling into place, though it wasn't all easy says Mait: "You can use the analogy of sitting in a nice warm office at CERN, surrounded by beautiful mountains. In the office, you are safe and protected, but if you go outside and climb the mountains, you encounter rain and hail, it is an uphill struggle and very uncomfortable, but immensely satisfying when you reach the summit. Even if you work more than 100 hours per week."

Lingvist currently has three million users, and Mait is convinced that the technology can be applied to all types of education. "What our data have demonstrated is that levels of learning in people are very different. Short-term memory capabilities can differ between five minutes and two seconds! Currently, based on our data, the older generation has much better memory characteristics. The benefit of our software is that it measures memory, and no matter one's retention capabilities, the software will help improve retention rates."

New talents

Faced with a future where artificial intelligence will make many jobs extinct, and many people will need to retrain, competitiveness will be derived from the speed at which people can learn, says Mait. He is now building Lingvist's data-science research team to grow the company to its full potential, and is always on the lookout for new CERN talent. "Traditionally, physicists have excellent modelling, machine-learning and data-analysis skills, even though they might not be aware of it," he says.

Rachel Bray *CERN.*

RECRUITMENT

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Please contact us for information about rates, colour options, publication dates and deadlines.

Universidad de los Andes
Colombia

UNIVERSIDAD DE LOS ANDES - BOGOTA, COLOMBIA
PHYSICS DEPARTMENT

Faculty Positions in Theoretical Physics

The Physics Department at Universidad de los Andes, Colombia (http://fisica.uniandes.edu.co), is seeking to fill a full-time faculty position in **Theoretical Physics**.

We are seeking applicants with research experience in one or several of the following areas: Statistical Physics, Mathematical Physics, Gravitational Physics and Quantum Information Theory. Priority will be given to candidates with a proven research record encompassing a diverse spectrum of theoretical interests, and capacity and willingness to teach upper division and graduate theoretical courses.

A Ph.D. degree and commitment to excellence in independent research and teaching are required. Postdoctoral experience is preferred. To be considered, applicants should submit 1) Full CV; 2) research statement; 3) teaching statement; and 4) the contact information for three referees, through the following link: https://fisicaconvocatoriasp.uniandes.edu.co/index.php. The referees will receive instructions to submit their recommendation letters through the application platform.
Deadline: March 30th, 2020.

The Physics Department at Universidad de Los Andes, Bogotá, Colombia is seeking to fill a full-time faculty position in
Theoretical High Energy Physics.

Preference will be given to candidates working on theoretical aspects of Particle Physics, Nuclear Physics, Astroparticle Physics and Cosmology. The successful candidate will have a proven research record in at least one of the areas mentioned above, and capacity and willingness to teach undergraduate and graduate theoretical courses.

A Ph.D. degree and commitment to excellence in independent research and teaching are required. Postdoctoral experience is preferred. Applicants should submit the following information: 1) Full CV; 2) research statement; 3) teaching statement; and 4) the contact information for three referees, through the following link: https://fisicaconvocatoriasp.uniandes.edu.co/index.php. The referees will receive instructions to submit their recommendation letters through the application platform.

UNIANDES is a private university, which strives for excellence in both teaching and research. According with the QS academic ranking, UNIANDES is ranked in the top ten universities in Latin America. More information about our physics department can be found in the following link: https://fisica.uniandes.edu.co/en/.

Deadline: March 30th, 2020.

For further information, please contact: Dr. Chad Leidy, Chairman, Physics Department, Universidad de Los Andes, Bogotá, Colombia.

e-mail: director-fisica@uniandes.edu.co

Phone (57-1)-332-4500, Fax (57-1)-332-4516

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

For our location in Hamburg we are seeking:

DESY-Fellowships - experimental particle physics

DESY

DESY is one of the world's leading research centres for photon science, particle and astroparticle physics as well as accelerator physics. More than 2400 employees work at our two locations Hamburg and Zeuthen in science, technology and administration.

Particle physics and the investigation of the fundamental building blocks of nature and their interactions are at the core of the DESY mission. The lab is among the globally leading research institutions in this field. We take significant responsibility in internationally leading projects, e.g. at CERN and at KEK, and on our campus. We develop detectors and technologies relevant for our experimental activities, and we engage in scientific computing and in the development of future accelerators for particle physics.

The position

You are invited to take an active role in one or more of the following areas at Hamburg.

- Our involvements at CERN (ATLAS, CMS) and at KEK (Belle II)
- Experimental activities on-site (ALPS II and future on-site experiments)
- Preparations for future particle physics experiments, in particular detector and technology development
- Scientific computing
- Accelerator development

Requirements

- Ph.D. in physics completed within the last four years
- Interest in particle physics
- Expertise relevant for at least one of the areas listed above

For further information please contact Ingo Bloch +49 33762 7-7392
DESY-Fellowships are awarded for a duration of 2 years with the possibility of prolongation by one additional year.

Futher informations and a link to the submission system for your application and the references can be found here:
www.desy.de/FellowFH

Please note that it is the applicants responsibility that all material, including letter of references, reach DESY before the deadline for the application to be considered.

Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. Handicapped persons will be given preference to other equally qualified applicants. DESY operates flexible work schemes. DESY is an equal opportunity, affirmative action employer and encourages applications from women. Vacant positions at DESY are in general open to part-timework. During each application procedure DESY will assess whether the post can be filled with part-time employees.

We are looking forward to your application via our application system:
www.desy.de/onlineapplication

Deutsches Elektronen-Synchrotron DESY
Human Resources Department | Code: FHFE001/2020
Notkestraße 85 | 22607 Hamburg Germany
Phone: +49 40 8998-3392
http://www.desy.de/career

Deadline for applications: 2020/03/31

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

For our location in Zeuthen we are seeking:

Postdoc Detector Development & Construction for the ATLAS Phase-II Upgrade

Remuneration Group 13

DESY

DESY is one of the world's leading research centres for photon science, particle and astroparticle physics as well as accelerator physics. More than 2400 employees work at our two locations Hamburg and Zeuthen in science, technology and administration.

The DESY ATLAS Detector Development Group in Zeuthen is responsible for the development and construction of a significant fraction of the silicon strip detector modules for the ATLAS Phase-II tracking detector upgrade. The production phase is close at hand and the current major focus is on module quality and performance tests. There are opportunities to perform generic detector R&D within the ATLAS group or collaborating with the astroparticle detector development group. For the project we are looking for an experienced scientist in the field of detector physics and development.

The position

- Development of testing procedures and setups in coordination with the international ITk strip tracker project
- Assembly and quality control of ITk strip tracker modules
- Supervision of students
- Documentation of procedures and results and presentation in international meetings
- Own research in either detector physics or HEP data analysis

Requirements

- Ph.D. in physics or similar discipline
- Experience in work with silicon tracking detectors or similar instrumentation
- Ability and wish to work in a team environment and to supervise students
- Very good language and communication skills
- Preferably experience in working with cleanrooms, electronics and with python/C++/ROOT

For further information please contact Ingo Bloch +49 33762 7-7392

The position is limited to 3 years.

Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. Handicapped persons will be given preference to other equally qualified applicants. DESY operates flexible work schemes. DESY is an equal opportunity, affirmative action employer and encourages applications from women. Vacant positions at DESY are in general open to part-time-work. During each application procedure DESY will assess whether the post can be filled with part-time employees.

We are looking forward to your application via our application system:
www.desy.de/onlineapplication

Deutsches Elektronen-Synchrotron DESY
Human Resources Department | Code: APP0003/2020
Notkestraße 85 | 22607 Hamburg Germany
Phone: +49 40 8998-3392
http://www.desy.de/career

Deadline for applications: Until the position is filled.

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

KEK, High Energy Accelerator Research Organization

Call for Nomination for Next Director General of KEK

KEK, High Energy Accelerator Research Organization, invites nominations for the next Director General whose term will begin April 1, 2021.

In view of his/her role that presides over the business of KEK as a representative of the Inter-University Research Institute Corporation, nominees shall be:

1) persons of noble character, with relevant knowledge and experience and having abilities to manage its educational and research activities properly and effectively.

2) persons expected to promote with long-term vision and strong scientific leadership, the highly advanced, internationalized, and inter-disciplinary research activities of KEK by getting support from the public.

3) persons expected to establish and carry out the medium-term goals and plans.

The term of appointment is three years until March 31, 2024 and shall be eligible for reappointment only twice. Thus, he/she may not remain in office continuously over a period 9 years.

We widely accept the nomination of the candidates regardless of their nationalities.

We would like to ask you to recommend the best person who satisfies requirements for the position written above.

Nomination should be accompanied by:
1) letter of recommendation, 2) brief personal history of the candidate, and 3) list of major achievements (publications, academic papers, commendations and membership of councils, etc.). The nomination should be submitted to the following address no later than May 29, 2020:

- Documents should be written either in English or in Japanese.
- Forms are available at: https://www.kek.jp/en/newsroom/2020/03/02/1000/

Inquiries concerning the nomination should be addressed to:

General Affairs Division
High Energy Accelerator Research Organization (KEK)
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Tel: +81-29-864-5114
Email: kek.dgsc@ml.post.kek.jp
Fax: +81-29-864-5560

SISSA

The International School for Advanced Studies (Scuola Internazionale Superiore di Studi Avanzati, SISSA (http://www.sissa.it/) seeks candidates for the position of **Director of the School**. SISSA is a public University founded in 1978 in Trieste, Italy and organized in the three Areas of Physics, Mathematics, and Neuroscience, plus an Interdisciplinary Laboratory. The faculty and student body are international; the English language is used in teaching, research and all academic affairs.

The successful candidate is expected to assume the Directorship by November 1, 2021, for a non-renewable term of 6 years. The Director must be of an academic stature for appointment as a tenured full-time SISSA professor and will be based in Trieste without substantial commitments to other institutions. The Director will be responsible for (1) the academic and financial functions of the School and (2) the relations of the School with national and local levels of government.

The profile of candidates should include a record of outstanding scientific contributions in Physics, Mathematics, Neuroscience or related fields of science. Experience in managing institutional operations, knowledge of the Italian language and familiarity with the Italian university system are advantageous. Applicants resident abroad might be eligible for a significant reduction in the tax rate applied to the gross salary, according to current Italian regulations.

Inquiries or statements of interest are welcome both from candidates and from those wishing to nominate third parties.
Please send statements of interest, or documented nominations to the Search Committee by May 15, 2020 at the latest using the address search@sissa.it.

UNIVERSITY OF BIRMINGHAM

Lecturer/ Senior Lecturer in Particle Physics Instrumentation

Opportunity to join the semiconductor instrumentation programme in the particle physics group at the University of Birmingham as a member of the academic faculty.

The successful candidate will work and develop new activities in the Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA) suite of cleanroom laboratories, as well as taking a full role in teaching and administration.

The largest current BILPA activity is preparation for the inner detector upgrade of the ATLAS experiment, specifically for silicon micro-strip module assembly, testing, quality control and quality assurance, including irradiations at the Birmingham cyclotron. We also have a strong programme in medical applications of particle physics detector technologies and fast-growing generic R&D towards sensor concepts for experiments at future facilities.

Closing date: March 22nd 2020

For further information and details of how to apply, see https://www.jobs.ac.uk/job/BYK976/

PEOPLE OBITUARIES

David Mark Ritson 1924–2019

A pathfinder to discovery

David Mark Ritson, professor emeritus of physics at Stanford University, died peacefully at home on 4 November 2019, just shy of his 95th birthday. He was the last of the leaders of the original seven physics groups formed at SLAC: four of the other leaders were awarded Nobel prizes in physics.

Dave Ritson was born in London and grew up in Hampstead. His ancestors emigrated from Australia, Germany and Lithuania, and his father, a Cambridge alumnus, wrote *Helpful Information and Guidance for Every Refugee*, distributed in the 1930s and 1940s. Dave won scholarships to Merchant Taylors' School and to Christ Church, Oxford. His 1948 PhD work included deploying the first high-sensitivity emulsion at the Jungfraujoch research station, and then developing it. Within the data were two particle-physics icons: the whole $\pi \rightarrow \mu \rightarrow e$ sequence, and τ-meson decay.

Dave moved to the Dublin IAS, to Rochester and to MIT, doing experiments which helped prove that the s-quark exists. His results were among many that underpinned the "τ–θ puzzle", solved by the discovery of parity violation in beta and muon decay. Dave also assisted accelerator physicist Ken Robinson with the proof that stable storage of an electron beam in a synchrotron was possible. In 1961 he and Ferdinando Amman published the equation for disruption caused by colliding e^+e^- beams. "Low beta" collider interaction regions are based on the Amman–Ritson equation.


H Lynch

David Ritson (left) with Bjørn Wiik, director of DESY 1993–1999, at the 1989 Lepton–Photon Symposium at Stanford.

Dave edited the book *Techniques of High Energy Physics*, published in 1961, and then took a faculty position in the Stanford physics department – bringing British acuity and economy to the ambitious SLAC team. Between 1964 and 1969, he and Burt Richter submitted four proposals to the US Atomic Energy Commission (AEC) for an e^+e^- collider, all of which were rejected. Dave designed the 1.6 GeV spectrometer in End Station A to detect proton recoils, which were used to reconstruct "missing mass" and to measure the photoproduction of hard-to-detect bosons.

After 1969 Dave founded Fermilab E-96, the Single Arm Spectrometer Facility, and obtained contributions from many institutions, including Argonne, CERN, Cornell, INFN Bari, MIT and SLAC. It was unusual for accelerator labs to support the fabrication of experiments at other lab's facilities. Meanwhile, SLAC found internal funding for the SPEAR e^+e^- collider, a stripped-down version of the last proposal rejected by the AEC and led by Richter, driving the epic 1974 c-quark discovery.

Dave returned to SLAC and in 1976 led the formation of the MAC collaboration for SLAC's new PEP e^+e^- collider. The MAC design of near-hermetic calorimetry with central and toroidal outer spectrometers is now classic. Bill Ford from Colorado used MAC to first observe the long b-quark lifetime. In 1983 Dave led the close-in tracker (vertex detector) project with the first layer only 4.6 cm from the e^+e^- beams, and verified the long b-quark life with reduced errors.

He formally retired in 1987 but was active until 2003 in accelerator design at SLAC, CERN, Fermilab and for the SSC. He helped guide the SLC beams through their non-planar path into collision, and wrote several articles for *Nature*. He also contributed to the United Nations' Intergovernmental Panel on Climate Change.

Dave was intensely devoted to his wife Edda, from Marsala, Sicily, who died in 2004, and is survived by their five children.

Harry Nelson *University of California at Santa Barbara.*

Vladislav Šimák 1934–2019

Life with antiprotons and quarks

Experimental particle physicist and founder of antiproton physics in Czechoslovakia (later the Czech Republic), Vladislav Šimák, passed away on 26 June 2019. Since the early 1960s his vision and organisational skills helped shape experimental particle physics, not only in Prague, but the whole of the country.

Vlada played a pivotal role in the decision of the Czech and Slovak particle-physics community to focus on accession to CERN membership

After graduating from Charles University in Prague, he joined the group at the Institute of Physics of the Czechoslovak Academy of Sciences studying cosmic rays using emulsion techniques, earning a PhD in 1963. Though it was difficult to travel abroad at that time, Vlada got a scholarship and went to CERN, where he joined the group led by Bernard French investigating collisions of antiprotons using bubble chambers. It was there and then that his lifelong love affair with antiprotons began. He brought back to Prague film material showing the results of collisions of 5.7 GeV antiprotons and protons from a hydrogen bubble chamber, and formed a group of physicists and technicians, involving many diploma and PhD students who processed them. Vlada also fell in love with the idea of quarks as proposed by Gell-Mann and Zweig, and ▷

was the first Czech or Slovak physicist to apply a quark model to pion production in proton–antiproton collisions.

In the early 1970s, when contacts with the West were severely limited, Vlada exploited the experiences he accumulated at CERN and put together a group of Czech and Slovak physicists involved in the processing and analysis of data from proton–antiproton collisions, using the then-highest-energy beam of antiprotons (22.4 GeV) and a hydrogen bubble chamber at the Serpukhov accelerator in Russia. This experiment, which in the later stage provided collisions of antideuterons with protons and deuterons, gave many young physicists the chance to work on unique data for their PhDs and earned Vlada respect in the international community.

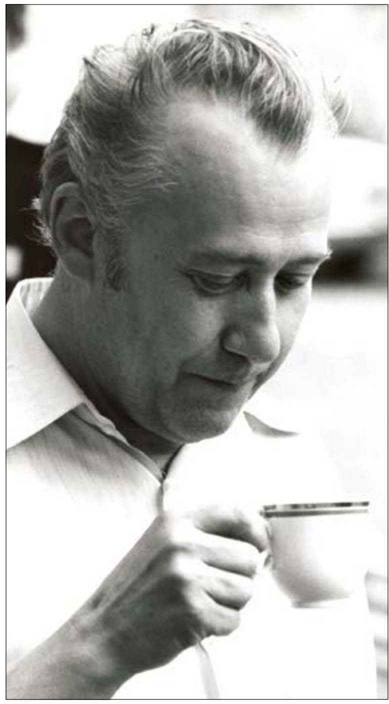
In the late 1980s, when the political atmosphere in Czechoslovakia eased, Vlada together with his PhD student joined the UA2 experiment at CERN's proton–antiproton collider, where he devoted his attention to jet production. After the Velvet Revolution in November 1989 he played a pivotal role in the decision of the Czech and Slovak particle-physics community to focus on accession to CERN membership.

In 1992 Vlada took Czechoslovak particle physicists into the newly formed ATLAS collaboration, and in 1997 he joined the D0 experiment at Fermilab. He was active in ATLAS until very recently, and in 2014, in acknowledgment of his services to physics, the Czech Academy of Sciences awarded Vlada the Ernst Mach Medal for his contributions to the development of physics.

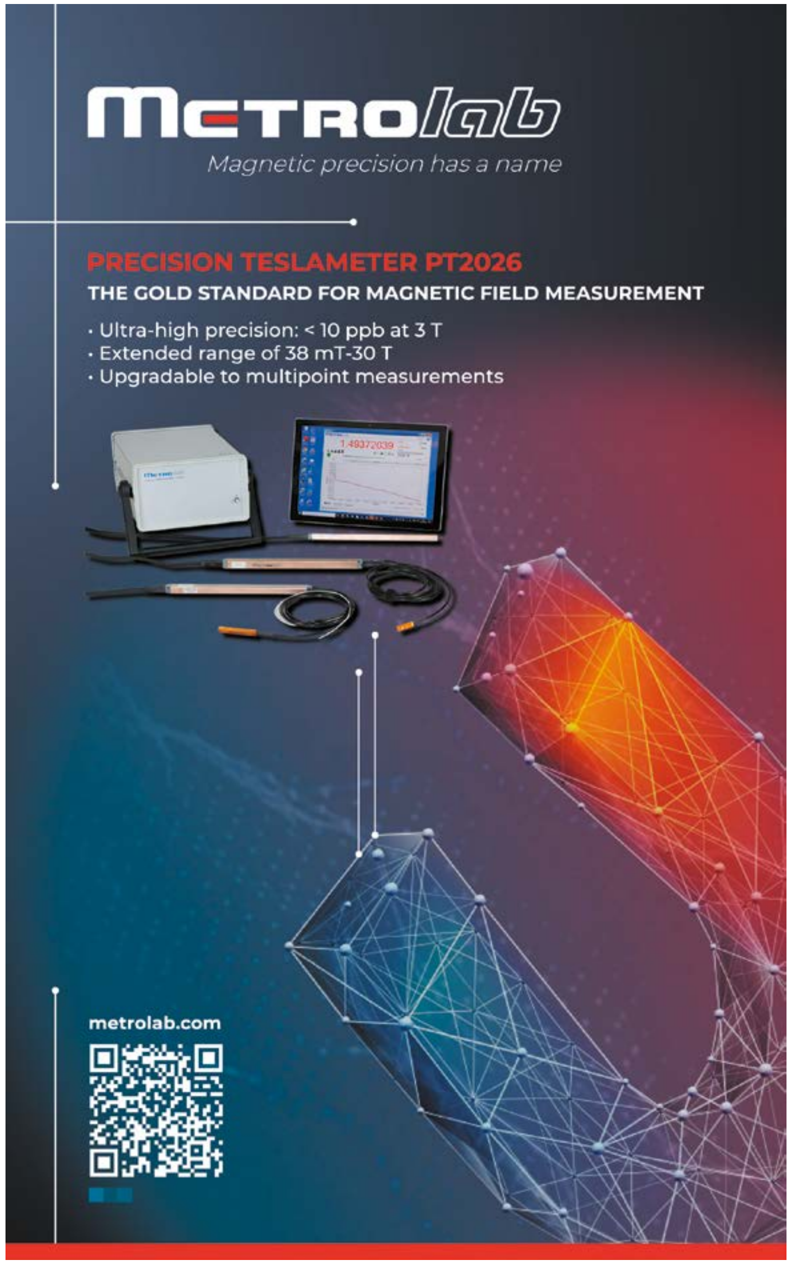
Throughout his life he combined his passion for physics with a love for music, for many years playing the violin in the Academy Chamber Orchestra. For many of us Vlada was a mentor, colleague and friend. We all admired his vitality and enthusiasm for physics, which was contagious. Vlada clearly enjoyed life and we very much enjoyed his company.

He will be sorely missed.

His friends and colleagues *in the Czech particle-physics community.*


Czech Academy of Sciences

Vladislav Šimák had a contagious enthusiasm for physics.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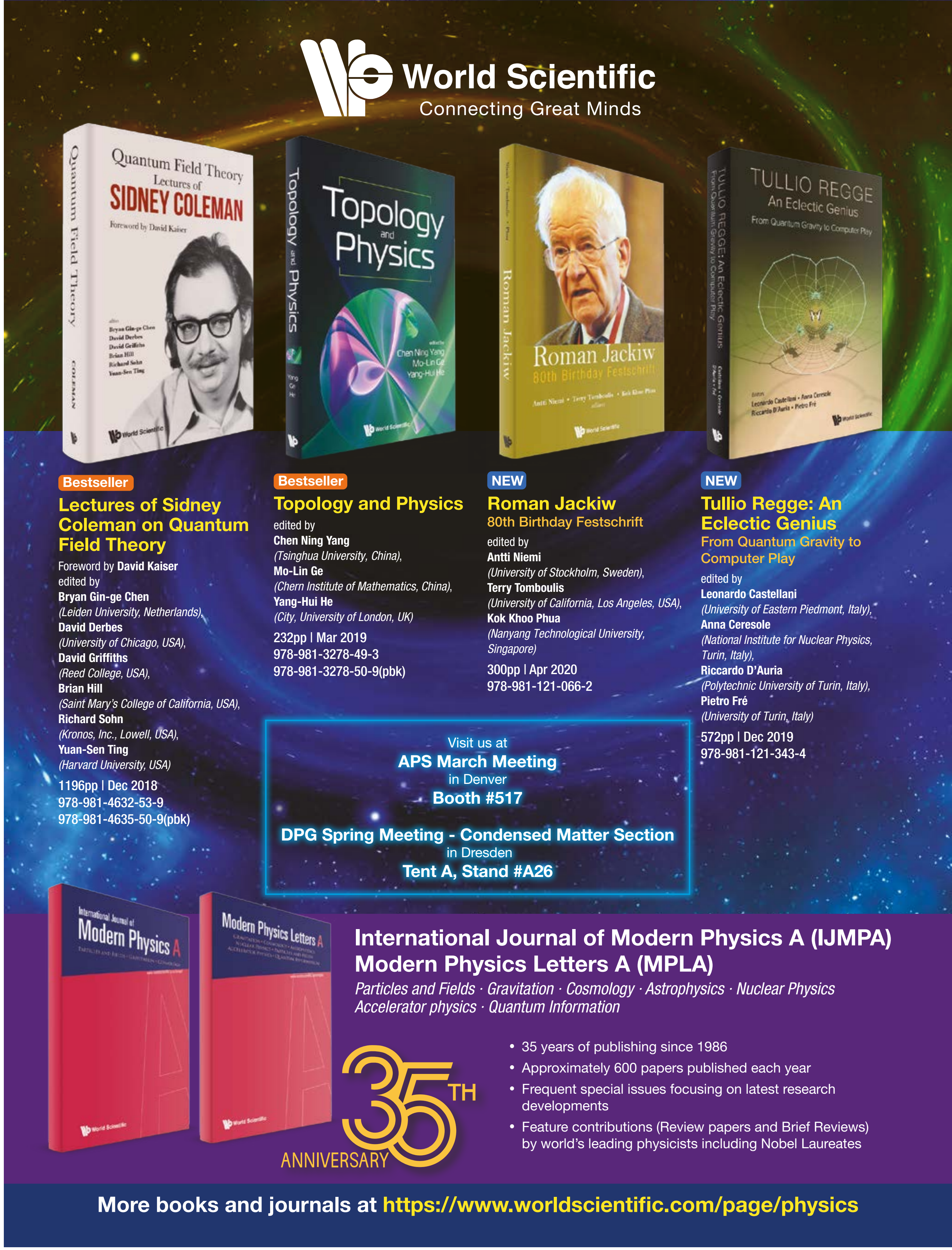
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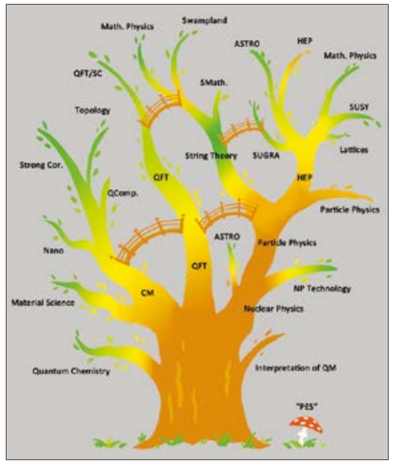
BACKGROUND

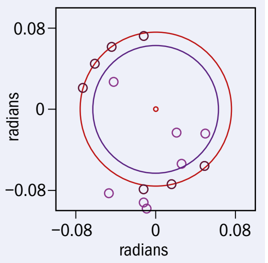
Notes and observations from the high-energy physics community

Tree-level musings



Theorist Mikhail Shifman of the University of Minnesota has abstracted a century of science stemming from the discovery of quantum mechanics to a tree. Condensed matter (CM) and quantum field theory (QFT) were two early branches, leading to quantum chemistry, materials science and new growth such as nanophysics and quantum computing. A third branch, nuclear physics, grew into particle physics which, following the branching out of high-energy physics (HEP) and astrophysics (ASTRO), has been pruned to a withered limb. No green shoots are seen in HEP, though supersymmetry, astroparticle physics and the swampland conjecture of string theory are budding. A possibly hallucinogenic fungus lurking among the roots represents post-empirical science (PES). "My humble musings do not pretend to be more than they are: just a personal opinion of a theoretical physicist," writes Shifman. "I would say that the most important message we have received is the absence of dramatic or surprising new results." (arXiv:2001.00101).

Ringing in the future



Just when claims of superluminal behaviour seemed the stuff of the past, physicists have uncovered anomalous Cherenkov rings in old LEP data, which they interpret as an indication of the existence of tachyons. Vassili Perepelitsa (ITEP Moscow) and co-workers scoured data from the Ring-Imaging Cherenkov (RICH) detector in the former DELPHI experiment and found events (example shown) in which the radii of the rings (red) are greater than those produced by particles with $\beta = 1$ (blue), corresponding to two peaks in the tachyon mass-parameter distribution at 0.29 ± 0.01 and 4.6 ± 0.2 GeV. Estimating the probability that the events can be explained by known physical processes to be below 10^{-3}, the authors conclude that further searches for faster-than-light particles should be made in dedicated experiments, citing the RICHes of ALICE and LHCb as additional possible hiding places (arXiv:2001.08576).

From the archive: April 1980

Speeches on science


Felici

Outside the standard CERN COURIER content are two recent important speeches on the role of science, given from very distinct standpoints. One was by His Holiness Pope John Paul II (left) in the Vatican in November 1979, at the Pontifical Academy of Science celebration of the centenary of the birth of Albert Einstein. 'The search for truth is the task of basic science. Like every other truth, scientific truth is accountable in the last resort only to itself and to the supreme Truth which is God, creator of man and of all things'.

The other was by Professor Abdus Salam to the Executive Board of UNESCO in October 1979, having been awarded the UNESCO Einstein Medal and the Nobel Prize for Physics. 'The Holy Quran enjoins us to reflect on the verities of Allah's created laws of nature; however, that our generation has been privileged to glimpse a part of His design is a bounty and a grace for which I render thanks with a humble heart'.

- Compiled from text on pp65–70 of *CERN Courier* April 1980.

Compiler's note

These speeches, one by a Christian, one by a Muslim, were triggered by events related to Einstein, a giant of the third Abrahamic culture. John Paul II, reflecting on the Galileo affair, expounded the putative complementarity between science and theology. Abdus Salam, reflecting on the prevailing situation in developing countries, recounted the historical shift and impact of scientific eminence across the major civilisations. In all or in part, their words remain pertinent to the troubled times of today.

Media corner

"Our ability to collaborate with European colleagues with ease is fundamental to the success of Ireland's physics community, yet Ireland is currently one of only three European countries that are not members or associates of CERN."

Yvonne Kavanagh, chair of the Institute of Physics in Ireland, in a letter to *The Irish Times* (4 February).

"Until very recently, the mightiest telescopes on Earth have been on American mountaintops like Palomar, Kitt Peak and Mauna Kea… But no more."

New York Times journalist ***Dennis Overbye*** (23 December) asks if the US will "lose the universe" when European giants such as the ELT come online.

"I hope people are willing to look past the defensiveness that often emerges when you talk about these issues."

Shirley Malcom of the AAAS quoted in *Physics Today* (1 February) on an American Institute of Physics report highlighting the under-representation of African Americans in physics.

"We might even witness a reversion to the scientific fragmentation of the 1930s, when some eminent German physicists championed 'Deutsche Physik' as superior to that of other nations."

Michael Riordan, *Scientific American* (28 January), calling for scientists to stand up for internationalism in increasingly inward-looking times.