WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the July/August 2018 issue of *CERN Courier*.

A muon collider has long been high on the wish list for particle physicists, since it offers a compact, high-energy lepton collider for precision measurements and could act as a driver for a neutrino factory. The discovery of a 125 GeV Higgs boson at CERN six years ago has strengthened the case for a muon collider, which would be able to create Higgs bosons in copious quantities via a direct s-channel production. The main obstacle against such a machine is the short lifetime of muons, which demands that they are "cooled" before they are accelerated. Now, following more than a decade of R&D, the UK-based Muon Ionization Cooling Experiment (MICE) has demonstrated this vital step. Meanwhile, at J-PARC in Japan, researchers have demonstrated the first acceleration of muons using a radio-frequency cavity. Further highlights from this month's issue include a whirlwind tour of CERN's arts programme, reports on the rise of deep learning in particle physics, and a roundup of the latest results from the neutrino sector.

Readers will also notice the launch of a new-look CERN Courier *website, a first step towards a more dynamic online presence that is set to launch in full in 2019. To help guide the* Courier's *evolution, both in print and online, and for the chance to win some CERN merchandise, readers are invited to give feedback now by e-mail or soon via an online survey.*

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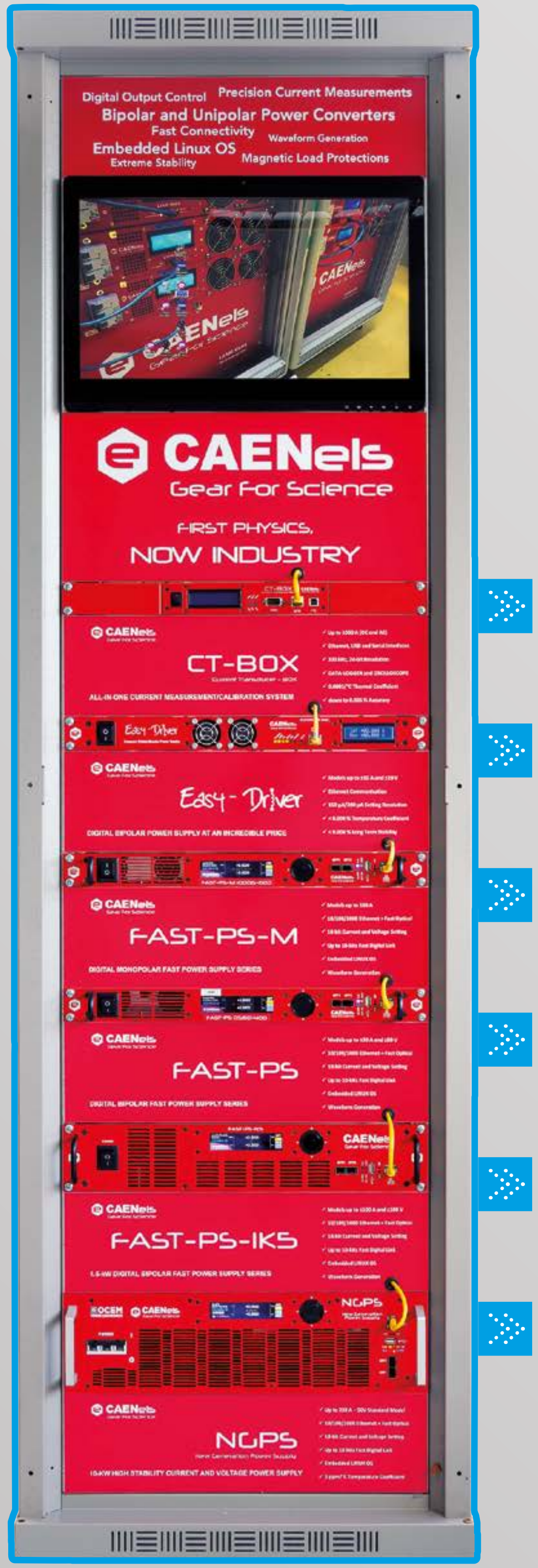
CERNCOURIER

VOLUME 58 NUMBER 6 JULY/AUGUST 2018

Targeting a muon collider

Art and science fuse at CERN
Neutrinos in their prime
Learning by machine



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Covering current developments in high-energy physics and related fields worldwide

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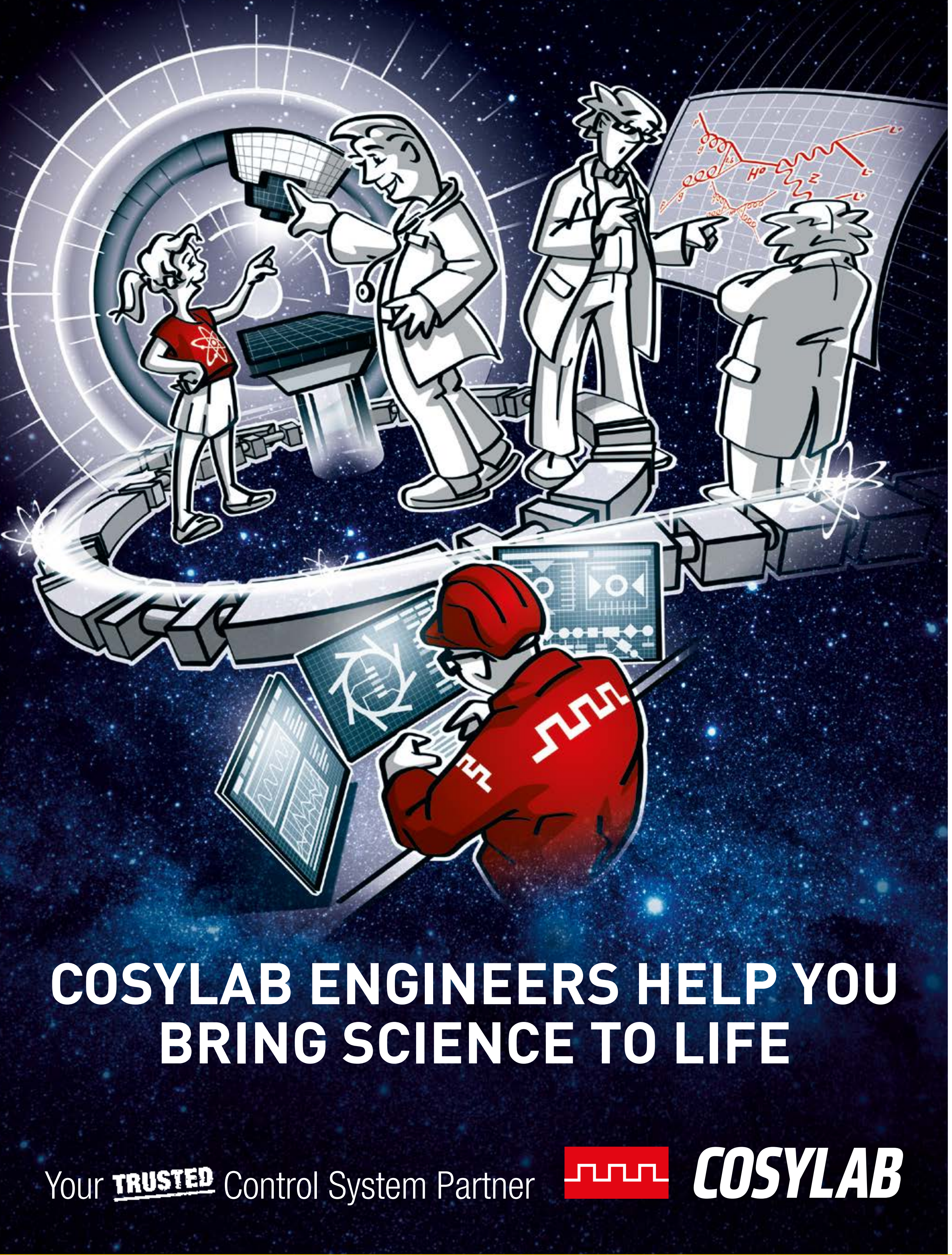
On the cover: MICE pion-production target, showing the upper half of the target shaft emerging from the Vespel bearing. (Image credit: P Hodgson.)



Viewpoint

A golden age for neutrinos

20 years since the discovery of neutrino oscillations, a complete understanding is within our grasp.


CERN-201710-248-3

Inside a prototype detector module for the international DUNE experiment, which was built at CERN and is about to be filled with liquid argon before undergoing its first tests with beam.

By Albert De Roeck

On 3 July 1998, researchers working on the Super-Kamiokande experiment in Japan announced the first evidence for atmospheric-neutrino flavour oscillations. Since neutrinos can only oscillate among different flavours if at least some of them have a non-zero mass, the result proved that neutrinos are massive, albeit with very small mass values. This is not expected in the Standard Model.

Neutrino physics was already an active field, but the 1998 observation sent it into overdrive. The rich scientific programme and record attendance of the Neutrino 2018 conference in Heidelberg last month (see p37) is testament to our continued fascination with neutrinos. Many open questions remain: what generates the tiny masses of the known neutrinos, and what is their mass ordering? Are there more than the three known neutrino flavours, such as additional sterile or right-handed versions? Is there CP violation in the neutrino sector and, if so, how large is it? In addition, there are solar neutrinos, atmospheric neutrinos, cosmic/supernova neutrinos, relic neutrinos, geo-neutrinos, reactor neutrinos and accelerator-produced neutrinos – allowing for a plethora of experimental and theoretical activity.

Many of these questions are expected to be answered in the next decade thanks to vigorous experimental efforts. Concerning neutrino-flavour oscillations, new results are anticipated in the short term from the accelerator-based T2K and NOvA experiments in Japan and the US, respectively. These experiments probe the CP-violating phase in the neutrino-flavour mixing matrix and the ordering of the neutrino mass states; evidence for large CP violation could be established, in particular thanks to the planned ND280 near-detector upgrade of T2K.

The next generation of accelerator-based experiments is already under way. The Deep Underground Neutrino Experiment (DUNE) in South Dakota, US, which will use a neutrino beam sent from Fermilab, is taking shape and two large prototypes of the DUNE far detector are soon to be tested at CERN. In Japan, plans are shaping up for Hyper-Kamiokande, a large detector with a fiducial volume around 10 times larger than that of Super-Kamiokande, and this effort is complemented with other sensitivity improvements and a possible second detector in Korea for analysing a neutrino beam sent from J-PARC in Japan. These experiments, which are planned to come online in 2026, will allow precision neutrino-oscillation measurements and provide decisive statements on the neutrino mass hierarchy and CP-violating phase.

Important insights are also expected from reactor sources. In China, the JUNO experiment should start in 2021 and could settle the mass-hierarchy question and determine complementary oscillation parameters. Meanwhile, very-short-baseline reactor experiments – such as PROSPECT, STEREO, SoLid, NEOS and DANSS – are soon to join the hunt for sterile neutrinos. Together with detectors at the short-baseline neutrino beam at Fermilab (SBND, MicroBooNE and ICARUS), the next few years should see conclusive results on the existence of sterile neutrinos. In particular, the recently reported update on the intriguing excess seen by the MiniBooNE experiment will be scrutinised.

Together with the ever-increasing sensitivities achieved by double-beta-decay experiments, which test whether neutrinos have a Majorana mass term, the SHiP experiment is proposed to search for right-handed neutrinos, while KATRIN in Germany has just started its campaign to measure the mass of the electron antineutrino with sub-eV precision. The interplay with astronomy and cosmology, using detectors such as IceCUBE and KM3NeT, which survey atmospheric neutrinos, further underlines the vibrancy and breadth of modern neutrino physics. Also, the European Spallation Source, under construction in Sweden, is investigating the possibility of a precise neutrino-measurement programme.

Neutrino experiments are spread around the globe, but Europe is a strong player. A discussion forum on neutrino physics for the update of the European strategy for particle physics will be hosted by CERN on 22–24 October. Clearly, neutrino science promises many exciting results in the near future.


Albert De Roeck is a staff physicist at CERN, a professor at the University of Antwerp, Belgium, a member of the CMS collaboration and group leader of the CERN experimental neutrino group.

HL-LHC

CERN marks beginning of a luminous future

A ceremony at CERN on 15 June celebrated the start of civil-engineering works for the high-luminosity upgrade of the Large Hadron Collider (HL-LHC). The upgrade will allow about 10 times more data to be accumulated by the LHC experiments between 2026 and 2036, corresponding to a total integrated luminosity of 3000 fb^{-1}, thereby enhancing the chances of discovery and bringing increased precision to measurements.

The HL-LHC project began in earnest in November 2011 as an international endeavour today involving 29 institutes from 13 countries. Two years later, the project was identified as one of the main priorities of the European Strategy for Particle Physics. The upgrade, targeting a luminosity of at least 5×10^{34} cm^{-2} s^{-1}, was formally approved by the CERN Council in June 2016.

Although it concerns only about 5% of the current machine, the HL-LHC is a major upgrade requiring a number of innovative technologies, many of which pave the way for future higher-energy colliders. At its heart are powerful new dipole and quadrupole magnets that operate at unprecedented fields of 11 and 11.5 T, respectively, and which employ novel niobium-tin superconducting cables. The quadrupoles, which will be installed on both sides of the collision points, will squeeze the proton beams to increase the probability of a collision (*CERN Courier* March 2017 p23).

Sixteen brand-new radio-frequency "crab cavities" will also be installed around the ATLAS and CMS experiments to maximise the overlap of the proton bunches at the collision points (*CERN Courier* May 2018 p18). Their function is to tilt the bunches so that they appear to move sideways, and the first ever tests of this technology in a proton beam were successfully carried out at the Super Proton Synchrotron in May.

CERN-PHOTO-201806-146-3

A time capsule is buried at point 5 of the LHC, symbolising the start of civil-engineering work for the HL-LHC upgrade. From left to right: Lucio Rossi (head of the HL-LHC project), Sijbrand de Jong (president of the CERN Council), Pascal Larour (adjoint au Maire de Cessy), Stéphane Bouillon (préfet de la Région Auvergne-Rhône-Alpes), Fabiola Gianotti (CERN Director-General), Pierre Maudet (president of the Conseil d'Etat de la République et Canton de Genève), Pierre-Alain Tschudi (mayor of Meyrin) and Frédérick Bordry (CERN director for accelerators and technology).

To prepare the CERN accelerator complex for the immense challenges of the HL-LHC, the LHC Injectors Upgrade project (LIU) was launched in 2010. In addition to enabling the necessary injector chains to deliver the HL-LHC beams, the LIU project is also tasked with replacing ageing equipment and improving radioprotection measures (*CERN Courier* October 2017 p32).

Overall, more than 1.2 km of the current LHC will need to be replaced with new components. This requires civil-engineering work at two main sites in Switzerland and in France, involving the construction of new buildings, shafts, caverns and underground galleries (*CERN Courier* March 2017 p28). The LHC will continue to operate until early December.

"The High-Luminosity LHC will extend the LHC's reach beyond its initial mission, bringing new opportunities for discovery, measuring the properties of particles such as the Higgs boson with greater precision, and exploring the fundamental constituents of the universe ever more profoundly," said CERN Director-General Fabiola Gianotti during the ceremony.

● On 25 June, the Canadian government announced a contribution of C$10 million to the HL-LHC, with an additional C$2 million in in-kind contributions. Working with Canadian researchers and industry, the TRIUMF laboratory will lead the production of five cryogenic modules for the HL-LHC crab cavities.

CERN Courier is evolving …

Since its first issue in August 1959, the *Courier* has undergone many transformations to keep up with the needs of the global high-energy physics community. You will soon notice changes to the *CERN Courier* website, a first step towards a more dynamic online presence. To help guide the *Courier*'s evolution both in print and online, and for the chance to win some CERN merchandise, readers are invited to give feedback via: cern.ch/go/courier-evolving.

Sommaire en français

ACCELERATORS

Muons accelerated in Japan

Muons have been accelerated by a radio-frequency accelerator for the first time, in an experiment performed at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan. The work paves the way for a compact muon linac that would enable precision measurements of the muon anomalous magnetic moment and the electric dipole moment.

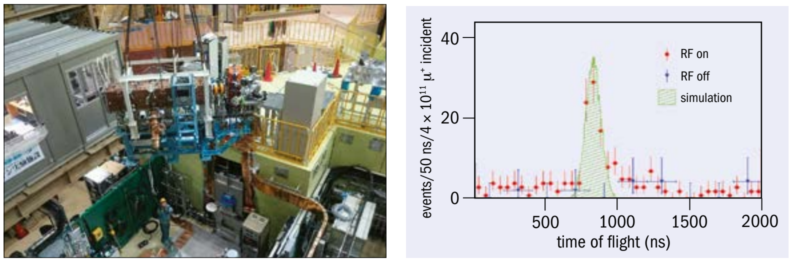
Around 15 years ago, the E821 storage-ring experiment at Brookhaven National Laboratory (BNL) reported the most precise measurement of the muon anomalous magnetic moment (g-2). Achieving an impressive precision of 0.54 parts per million (ppm), the measured value differs from the Standard Model prediction by more than three standard deviations. Following a major effort over the past few years, the BNL storage ring has been transported to and upgraded at Fermilab and recently started taking data to improve on the precision of E821. In the BNL/Fermilab setup, a beam of protons enters a fixed target to create pions, which decay into muons with aligned spins. The muons are then transferred to the 14 m-diameter storage ring, which uses electrostatic focusing to provide vertical confinement, and their magnetic moments are measured as they precess in a magnetic field.

The new J-PARC experiment, E34, proposes to measure muon g-2 with an eventual precision of 0.1 ppm by storing ultra-cold muons in a mere 0.66 m-diameter magnet, aiming to reach the BNL precision in a first phase. The muons are produced by laser-ionising muonium atoms (bound states of a positive muon and an electron), which, since they are created at rest, results in a muon beam with very little spread in the transverse direction – thus eliminating the need for electrostatic focusing. The ultracold muon beam is stored in a high-precision magnet where the spin-precession of muons is measured by detecting muon decays. This low-emittance technique, which allows a smaller magnet and lower muon energies, enables researchers to circumvent some of the dominant systematic uncertainties in the previous g-2 measurement. To avoid decay losses, the J-PARC approach requires muons to be accelerated using a conventional radio-frequency accelerator.

In October 2017, a team comprising physicists from Japan, Korea and Russia successfully demonstrated the first acceleration of negative muonium ions, reaching an energy of 90 keV. The experiment was conducted using a radio-frequency quadrupole linac (RFQ) installed at a muon beamline at J-PARC, which is driven by a high-intensity pulsed proton beam. Negative muonium atoms were first accelerated electrostatically and then injected into the RFQ, after which they were guided to a detector through a transport beamline. The accelerated negative muonium atoms were identified from their time of flight: because a particle's velocity at a given energy is uniquely determined from its mass, its type is identified by measuring the velocity (see figure).

The researchers are now planning to further accelerate the beam from the RFQ. In addition to precise measurements in particle physics, the J-PARC result offers new muon-accelerator applications including the construction of a transmission muon microscope for use in materials and life-sciences research, says team member Masashi Otani of KEK laboratory. "Part of the construction of the experiment has started with partial funding, which includes the frontend muon beamline and detector. The experiment can start properly three years after full funding is provided."

Muon acceleration is also key to a potential muon collider and neutrino factory, for which it is proposed that the large, transverse emittance of the muon beam can be reduced using ionisation cooling (see p19).


J-PARC

(Left) Installation of the RFQ in the experimental area. (Right) When turning on the RFQ (red), a peak is observed at the expected timing (green). The peak disappears when turning off the RFQ (blue), suggesting acceleration has taken place.

● **Further reading**

S Bae *et al.* 2018 *Phys. Rev. Accel. Beams* **21** 050101.

FACILITIES

Jefferson Lab inaugurates upgraded CEBAF


Jefferson Lab

Left to right: US Department of Energy undersecretary for science Paul Dabbar, Jefferson Lab director Stuart Henderson and congressman Bobby Scott in the new experimental hall D.

On 2 May, the Thomas Jefferson National Accelerator Facility in Virginia, US, celebrated the completion of the 12 GeV CEBAF upgrade project. The $338 million upgrade has tripled CEBAF's original operating energy and will allow, among other studies, more in-depth investigations of nuclear confinement.

CEBAF (Continuous Electron Beam Accelerator Facility) provides high-quality beams of polarised electrons that allow physicists to extract information on the quark and gluon structure of nucleons. The CEBAF accelerator started up in 1994 and originally delivered 4 GeV beams, which were later pushed to 6 GeV thanks to efficiencies in the machine's design and extensive experience gained during operation. Previously, CEBAF operated as a pair of superconducting radio-frequency linear accelerators in a "racetrack" configuration, capable of delivering 6 GeV electron beams simultaneously to three experimental halls. In 2008 work began on a major upgrade project to double the maximum energy and add new experimental setups.

The 12 GeV CEBAF upgrade project required 10 high-performance, superconducting radio-frequency cryomodules, doubling the capacity of the existing cryogenics plant, and the addition of eight superconducting magnets and other system upgrades. The upgrade also includes the construction of a new experimental area ("hall D") for dedicated research on exotic mesons produced by energetic photons incident on a target. CEBAF's newly energetic and precise beams will enable the first 3D views of the structure of protons and neutrons, the study of the origin of confinement in QCD, and the investigation of physics beyond the Standard Model by testing the theory's completeness at low energies.

▷

INDUSTRY

Higgs centre opens for business


STFC

The new Higgs Centre for Innovation.

A new facility called the Higgs Centre for Innovation opened at the Royal Observatory in Edinburgh on 25 May as part of the UK government's efforts to boost productivity and innovation. The centre, named after Peter Higgs of the University of Edinburgh, who shared the 2013 Nobel Prize in physics for his theoretical work on the Higgs mechanism, will offer start-up companies direct access to academics and industry experts. Space-related technology and big-data analytics are the intended focus, and up to 12 companies will be based there at any one time. According to a press release from the UK Science and Technology Facilities Council (STFC), the facility incorporates laboratories and working spaces for researchers, and includes a business incubation centre based on the successful European Space Agency model already in operation in the UK.

"Professor Higgs' theoretical work could only be proven by collaboration in different scientific fields, using technology built through joint international ventures," said principal and vice-chancellor of the University of Edinburgh Peter Mathieson. "This reflects the aims and values of the Higgs Centre for Innovation, which bring scientists, engineers and students together under one roof to work together for the purpose of bettering our understanding of space-related science and driving technological advancement forward."

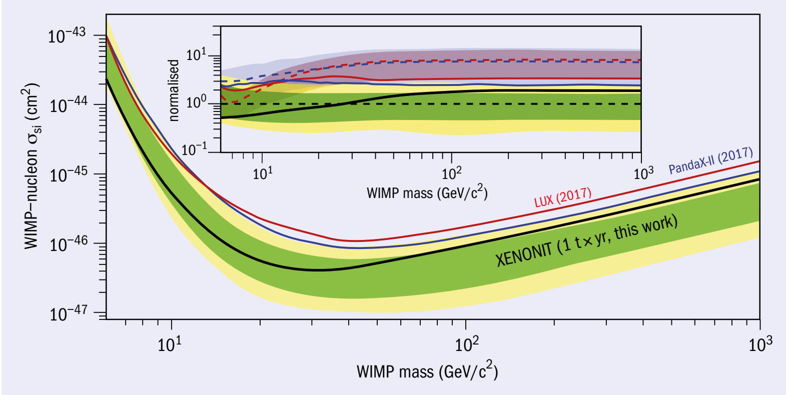
The Higgs Centre for Innovation was funded through a £10.7 million investment from the UK government via STFC, which is also investing £2 million over the next five years to operate the centre.

DARK MATTER

Largest WIMP survey sets new limits

On 28 May, the world's largest and most sensitive detector for direct searches of dark matter in the form of weakly interacting massive particles (WIMPs) released its latest results. XENON1T, a 3D-imaging liquid-xenon time projection chamber located at Gran Sasso National Laboratory in Italy, reported its first results last year (*CERN Courier* July/August 2017 p10). Now, the 165-strong international collaboration has presented the results from an unprecedentedly large exposure of approximately one tonne × year.

The results are based on 1300 kg out of the total 2000 kg active xenon target and 279 days of data-taking, improving the sensitivity by almost four orders of magnitude compared to XENON10 (the first detector of the XENON dark-matter project, which has been hosted at Gran Sasso since 2005). The data are consistent with background expectations, and place the most stringent limit yet on spin-independent interactions of WIMPs with ordinary matter for a WIMP mass higher than 6 GeV/c^2.



The latest limits on WIMP interactions, derived from one year of XENON1T data. The inset compares the new XENON1T limit and sensitivity with those of previous experiments.

XENON1T spokesperson Elena Aprile of Columbia University in the US describes the result as a milestone in dark-matter exploration. "Showing the result after a one tonne × year exposure was important in a field that moves fast," she explains. "It is also clear from the new result that we will win faster with a yet-larger mass and lower radon background, which is why we are now pushing the XENONnT upgrade."

● **Further reading**

E Aprile *et al.* 2018 arXiv:1805.12562

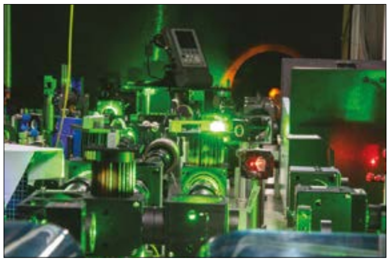
NUCLEAR PHYSICS

ISOLDE mints chromium for structure studies

CERN's radioactive ion-beam facility ISOLDE has stamped a new coin in its impressive collection. Long considered the domain of high-energy, in-flight rare-isotope facilities, chromium has now been produced at ISOLDE in prodigious quantities, thanks to a new resonant ionisation laser-ion source (RILIS) scheme. Together with the latest calculations based on chiral effective field theory, the result provides important guidance for improving theoretical approaches that bridge the gap between nuclear matter and the low-energy extension of quantum chromodynamics (QCD).

Certain configurations of protons and neutrons are more bound than others, revealing so-called magic numbers. Chromium has 24 protons, situating it squarely between magic calcium (with 20 protons) and nickel (with 28). Of particular interest to nuclear physics are isotopes with a large excess of neutrons.

The RILIS is a chemically selective ion source which relies on resonant excitation of atomic transitions using a tunable laser. In the new ISOLDE experiment, Maxime Mougeot of CSNSM/Université Paris-Saclay and collaborators used RILIS to venture 10 neutrons further on the nuclear chart to ^{63}Cr. With a total of 39 neutrons, ^{63}Cr lies exactly between the magic neutron numbers 28 and 50 and has a half-life of just 130 ms.



CERN-201602-031-7

ISOLDE's resonant ionisation laser-ion source (RILIS), which provided the first beams of neutron-rich chromium isotopes.

The masses of the newly forged chromium isotopes, as measured by ISOLDE's precision Penning-trap mass spectrometer ISOLTRAP, offer insights into its shape and structure. Magic-number nuclides have filled orbitals that favour spherical shapes, but not so the chromium nuclides weighed by ISOLTRAP, which are deformed. Whereas in some areas of the nuclear chart deformation sets in very suddenly with the addition of a further neutron, the remarkably smooth neutron binding energies of chromium show that deformation sets in very gradually – contrary to previous conclusions.

The ISOLDE measurements were compared with different theoretical results, including a very first attempt by a new *ab-initio* approach called valence-space in-medium similarity renormalization group (VS-IMSRG). While several *ab-initio* approaches exist, until now they have been restricted to the near-spherical cases that have very few valence protons and neutrons. The latest VS-IMSRG results are the first for such open-shell nuclides.

"It turns out that the *ab-initio* VS-IMSRG, an interaction derived from chiral effective field theory which reduces QCD to its relevant degrees of freedom at the nuclear scale, failed to predict these results," explains Mougeot. "So the recent chromium measurements are constructive and important for advancing this promising technique, which bridges the gap between first-principle calculations and the structure of nuclei at the extremes of the nuclear landscape."

- **Further reading**

M Mougeot *et al.* 2018 *Phys. Rev. Lett.* **120** 232501.
T Day Goodacre *et al.* 2017 *Spectroc. Acta B* **129** 58.

LHC EXPERIMENTS

CMS resolves inner structure of bottomonium

Bottomonium mesons, composed of beauty quark–antiquark pairs bound to each other through the strong force, play a special role in our understanding of hadron formation because the large quark mass allows important simplifications in the relevant theoretical calculations.

The spectroscopy of the bottomonium family has now been significantly upgraded, thanks to the first observation of the individual $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states by the CMS collaboration. Identified via the decay $\chi_b(3P) \rightarrow \Upsilon(3S)\gamma$, and adding for the first time all the LHC data collected at an energy of 13 TeV (corresponding to a staggering 80 fb^{-1} of integrated luminosity), CMS detected 16.5 million Υ mesons in the dimuon decay channel. The corresponding invariant mass distribution shows well-resolved $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances (figure 1, inset), which constitute the starting point for the reconstruction of the p-wave bottomonia through the radiative decay $\chi_b(mP) \rightarrow \Upsilon(nS)\gamma$.

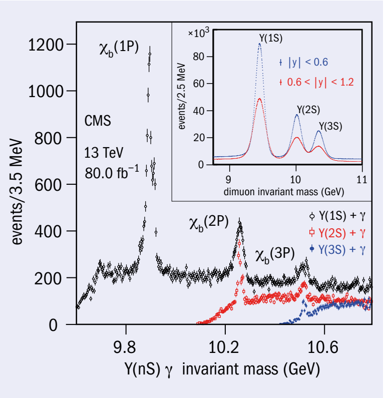


Fig.1. The $\chi_b(mP)$ states, seen in the $\Upsilon(nS)\gamma$ invariant-mass distributions. The inset shows the 10 million $\Upsilon(1S)$, 3.9 million $\Upsilon(2S)$ and 2.6 million $\Upsilon(3S)$ that were reconstructed by CMS using the full data sample at 13 TeV.

The main challenge in this study is the low energy of the photons. The CMS analysis uses photons that convert into e^+e^- pairs and are reconstructed in the silicon tracker with very high precision, leading to clear $\chi_b(mP)$ peaks in the resulting $\Upsilon(nS)\gamma$ invariant mass distributions. The resolution of the χ_b mass measurement scales with the photon energy, or the difference between the masses of the P- and S-wave mesons. The $\Upsilon(3S)\gamma$ invariant mass is measured with a remarkable resolution, enabling the first observation of a double-peak structure in the $\chi_b(3P)$ resonance, which corresponds to the states of total angular momentum $J=1$ and $J=2$ (figure 2).

The existence of two peaks is established with a significance exceeding nine standard deviations and the two masses are measured to be 10,513.42 ± 0.41 (stat) ± 0.18 (syst) MeV and 10,524.02 ± 0.57 (stat) ± 0.18 (syst) MeV. The measured mass splitting, 10.60 ± 0.64 (stat) ± 0.17 (syst) MeV, can be used to improve the theoretical calculations, which currently predict values between 8 and 18 MeV depending on the potentials describing the quark–antiquark non-perturbative interaction. The only exception predicts a value of –2 MeV, the negative sign meaning that the $\chi_{b2}(3P)$ has a mass smaller than the $\chi_{b1}(3P)$.

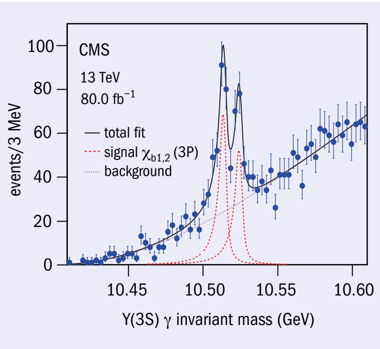


Fig. 2. The double-peak structure reflecting the $J=1$ and $J=2$ states is observed for the first time thanks to the high statistics of the data sample and the excellent mass resolution.

The new measurement is a step forward in completing the spin-dependent bottomonium spectroscopy diagram, and should significantly contribute to an improved understanding of the non-perturbative QCD processes that lead to the binding of quarks and gluons into hadrons.

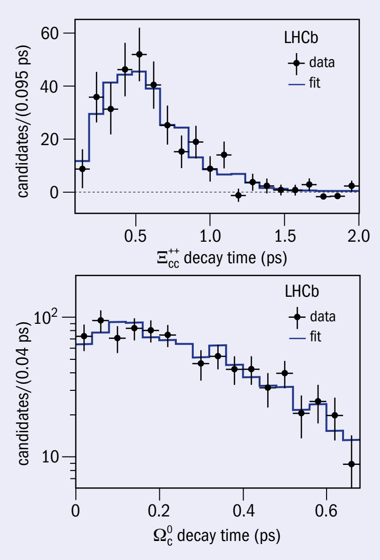
- **Further reading**

CMS Collaboration 2018 arXiv.org:1805.11192.

Charmed baryons strike back

Last year, the LHCb collaboration announced the first observation of the Ξ_{cc}^{++} baryon, a doubly charmed particle (*CERN Courier* July/August 2017 p8). It was identified via the decay $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$, with the Λ_c^+ baryon subsequently decaying to $pK^-\pi^+$. Since then, LHCb has carried out a campaign of further studies to pinpoint the properties of this special particle, namely looking for additional Ξ_{cc}^{++} decays and, more importantly, measuring its lifetime.

LHCb has now reported a first measurement of the Ξ_{cc}^{++} lifetime, exploiting the same decay mode and using a data sample and an event selection similar to those used in the first observation. The experimental technique used is to measure the decay-time distribution relative to that of another decay with a similar topology, $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$. As the lifetime of the Λ_b^0 is already known with high precision from previous measurements, once the ratio of efficiencies for reconstructing the Ξ_{cc}^{++} and Λ_b^0 decays is determined, it is possible to derive the lifetime of the Ξ_{cc}^{++} baryon from its decay-time distribution (see figure).



Decay-time distributions of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ (top) and $\Omega_c^0 \rightarrow pK^-K^-\pi^+$ decays (bottom), with the results of the fits overlaid.

The lifetime value that is obtained is 256^{+24}_{-22} (stat) ± 14 (syst) fs. Relatively large lifetimes like this are a distinctive feature of weak interactions. In addition, LHCb has also observed a new Ξ_{cc}^{++} decay: $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$, with a statistical significance of about six standard deviations, thus confirming the first observation of Ξ_{cc}^{++} in an independent analysis. The baryon's mass is measured to be 3620.6 ± 1.5 (stat) ± 0.5 (syst) MeV/c^2, which is consistent with the previous result.

Turning to a separate analysis, a puzzling result has emerged at LHCb while measuring the lifetime of another charmed baryon: the Ω_c^0. The sample of LHCb data used for this measurement comprises about 1000 $\Omega_b^- \rightarrow \Omega_c^0 \mu^- \nu_\mu X$ signal decays, where the Ω_c^0 baryon is detected via the decay $\Omega_c^0 \rightarrow pK^-K^-\pi^+$ and X represents possible additional undetected particles in the decay. The Ω_c^0 lifetime is determined from the observed decay-time distribution to be 268 ± 24 (stat) ± 10 (syst) fs (see figure).

Quite surprisingly, this value is nearly four times larger than, and inconsistent with, the current world average of 69 ± 12 fs. This average is based on three experimental results from fixed-target experiments, namely E687, FOCUS and WA89, where each experiment observed only a few dozen events with relatively large background. The new measurement from LHCb redefines the lifetime hierarchy of charmed baryons, placing the Ω_c^0 baryon as having the second largest lifetime after the Ξ_c^+ baryon, i.e. $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$. This result may lead to reconsideration of the relative importance of the roles of spectator quarks and of non-perturbative effects in the decay dynamics of hadrons containing heavy quarks.

- **Further reading**

LHCb Collaboration 2018 LHCb-PAPER-2018-019.
LHCb Collaboration 2018 LHCb-PAPER-2018-026.
LHCb Collaboration 2018 LHCb-PAPER-2018-028.

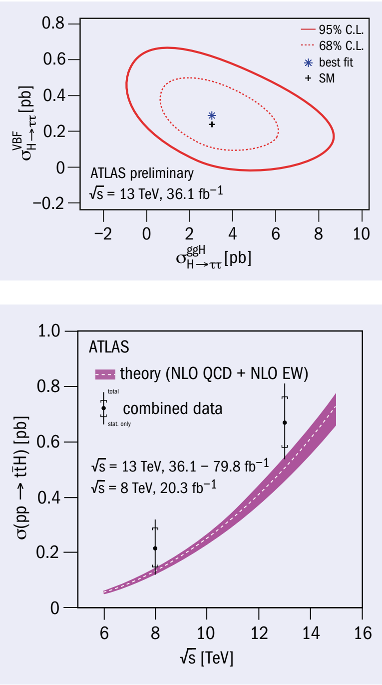
Measuring Higgs-boson interactions with third-generation fermions

According to the Standard Model (SM), fermions acquire their mass through coupling to the Higgs field. New results released by the ATLAS collaboration firmly establish and measure these so-called Yukawa couplings to third-generation fermions. The Higgs-boson coupling to top quarks has been observed in associated production with a top quark pair (ttH production), and the Higgs-boson coupling to tau leptons has been observed in Higgs-boson decays to two tau leptons ($H \rightarrow \tau\tau$). Data from LHC proton–proton collisions at a centre-of-mass energy of 13 TeV recorded during 2015, 2016 and 2017 were analysed for these results.

The measurement of $H \rightarrow \tau\tau$, which is based on 2015 and 2016 data, was ▷

challenging because the tau lepton is short-lived and can only be observed through its decay products, of which at least one is always an invisible neutrino. The unknown momentum taken away by the neutrino makes the tau reconstruction incomplete and thus susceptible to backgrounds. Events with tau leptons are difficult to select online when the visible tau decay products are hadrons. Moreover, the Z boson, which also decays to a tau-lepton pair and is relatively close in mass to the Higgs boson but much more abundant, represents a large source of background. Good reconstruction of the di-tau invariant mass is therefore essential, using information from all detector systems to account for the missing energy.

The measured $H \rightarrow \tau\tau$ signal has an observed (expected) statistical significance of 6.4 (5.4) standard deviations when combined with previous measurements using 7 and 8 TeV data. In 13 TeV data, the total cross-section times branching fraction was measured to be $3.71 \pm 0.59\,(\mathrm{stat})\,^{+0.87}_{-0.74}\,(\mathrm{syst})$ pb. In addition, separate measurements of the gluon fusion and weak-boson-fusion Higgs-boson production cross sections were performed (figure, top). SM predictions agree with these measurements.



Top: simultaneous measurement of the cross-section times branching fraction for the gluon-fusion (ggH) and vector-boson fusion (VBF) Higgs-boson production processes in Higgs-boson decays to two tau leptons. Bottom: measured ttH cross sections in pp collisions at centre-of-mass energies of 8 TeV and 13 TeV compared with the SM prediction (line with uncertainty band).

The production of ttH was measured from a combination of channels involving Higgs-boson decays to a pair of W or Z bosons (WW* or ZZ*), tau leptons, b-quarks or photons. The analyses exploiting the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ decays used the full 80 fb^{-1} proton–proton dataset collected by ATLAS between 2015 and 2017, and deployed improved reconstruction algorithms and new analysis procedures based on machine learning. The $H \rightarrow \gamma\gamma$ analysis alone observed a ttH signal with a significance of 4.1 standard deviations for 3.7 expected in the SM. The $H \rightarrow 4l$ analysis expected less than one event from ttH production in the 80 fb^{-1} dataset and observed no event.

These results, combined with those from the other ttH channels based on 2015 and 2016 data, led to an observed (expected) significance of 5.8 (4.9) standard deviations for ttH production at 13 TeV, with a ratio of measured to predicted cross section of $1.32\,^{+0.28}_{-0.26}$. Further combination with the results from Run 1 based on data taken at 7 and 8 TeV centre-of-mass energies yielded an observed significance of 6.3 standard deviations for 5.1 expected. The measured total cross-section for ttH production at 13 TeV is $670 \pm 90\,(\mathrm{stat}) \pm 110\,(\mathrm{syst})$ fb, in agreement with the SM prediction of $507\,^{+35}_{-50}$ fb. The corresponding result at 8 TeV is $220 \pm 100\,(\mathrm{stat}) \pm 70\,(\mathrm{syst})$ fb (figure, bottom).

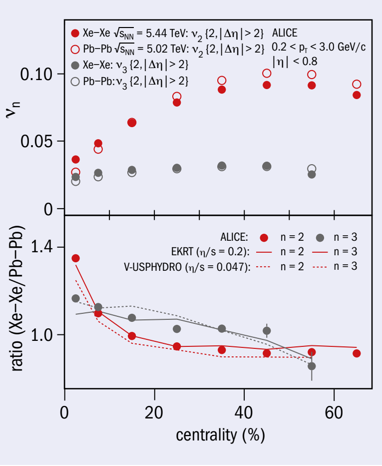
With further data being collected at the LHC, more precise measurements of cross-sections and differential distributions will allow the study of the structure of Yukawa couplings in great detail and thus provide more stringent tests of the SM and increased sensitivity to physics beyond it.

● Further reading

ATLAS Collaboration 2018 ATLAS-CONF-2018-021.
ATLAS Collaboration 2018 arXiv:1806.00425.

Anisotropic flow in Xe–Xe collisions

One of the key goals in exploring the properties of QCD matter is to determine the minimum value of the shear viscosity to entropy density ratio (η/s) for an ideal fluid. In heavy-ion collisions at the LHC, a quark-gluon plasma (QGP) is created, which is a state of hot and dense matter where quarks and gluons become deconfined. The plasma is formed at early times in the collisions and subsequently cools down to a temperature where the quarks and gluons cluster together into hadrons. The value of η/s is of particular interest, as weak coupling QCD and anti-de-Sitter/conformal field theory (AdS/CFT) theories predict different values. AdS/CFT is a technique from string theory that can be used to understand a strongly coupled system.



Anisotropic flow coefficients in Xe–Xe collisions at centre of mass energy per-nucleon of 5.44 TeV and Pb–Pb collisions at 5.02 TeV, shown with comparisons to predictions from hydrodynamic models.

The value of η/s implied by AdS/CFT is approximately 0.05–0.08, with calculations based on perturbative QCD techniques giving larger values.

The ALICE collaboration has recently released results of anisotropic-flow measurements from xenon–xenon (Xe–Xe) collisions at a per-nucleon centre of mass energy of 5.44 TeV, which offer additional constraints for the viscosity of the QGP. The anisotropic flow observed in a heavy-ion collision results from the spatial anisotropy of the initial collision zone, which is converted to momentum anisotropies ▷ via pressure gradients during the system's evolution. The magnitudes of momentum anisotropies are quantified by the harmonic coefficients ν_n of a Fourier expansion of the azimuthal distribution of particles; ν_2 is generated by initial states with an elliptic shape, ν_3 a triangular shape, and so on. The magnitude of ν_n depends not only on η/s, but also depends on the magnitude of the azimuthal asymmetries in the initial density distribution in the collisions. Comparing the new results from Xe–Xe collisions to those from lead–lead (Pb–Pb) collisions is expected to provide stronger constraints in the initial matter distribution, which will, in turn, provide a more precise determination of η/s.

The figure shows measurements of ν_n vs centrality for both Xe–Xe and Pb–Pb collisions. Centrality is a measure of the degree of overlap in heavy-ion collisions, where 0% corresponds to collisions that are head-on, and for 100% the heavy-ions do not overlap enough to interact. For mid-central collisions (20–70%), the second harmonic coefficients of the initial matter distributions are predicted to be very similar for Xe–Xe and Pb–Pb from various initial-state models. At the same centrality, however, the Xe–Xe system size is smaller than Pb–Pb and the impact of a finite η/s suppresses ν_2 by 1/R, where R corresponds to the transverse size of the system. Therefore, ratios of Xe–Xe/Pb–Pb ν_2 coefficients in the mid-centrality range could be directly sensitive to η/s, with larger values of η/s leading to a greater suppression of this ratio. When comparing our data to two different hydrodynamic models, which use parameters of η/s close to the values from AdS/CFT calculations, we find a good agreement with the data.

This shows that η/s is small, which implies a short mean-free path for the quarks and gluons in the QGP, or strong interactions. In central collisions, the ν_2 in Xe–Xe collisions is larger than in Pb–Pb collisions. This is due to the ^{129}Xe nucleus not being exactly spherical and to larger fluctuations of the initial density distributions for the smaller Xe nucleus. The latter also gives rise to larger values of ν_3 in the centrality range of 0–50%.

● Further reading

ALICE Collaboration 2018: arXiv:1805.01832.

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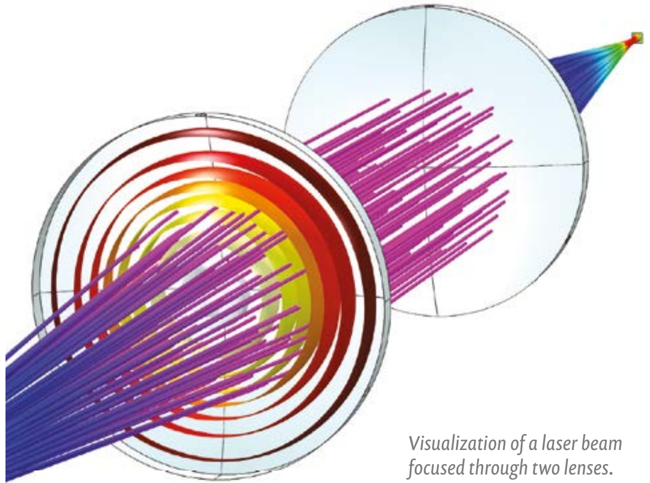
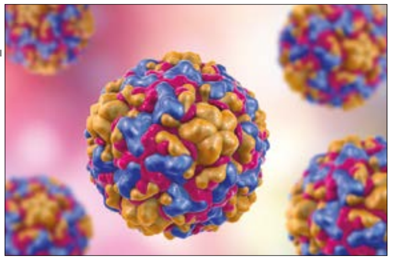


Sciencewatch

Compiled by John Swain, Northeastern University

Compound blocks rhinoviruses



iStock/Dr_Microbe

A new chemical compound can block the viruses that cause the common cold.

Rhinoviruses (RVs), far from being just a seasonal nuisance causing common colds, can also lead to serious complications in conditions such as asthma and cystic fibrosis. The huge diversity of RVs precludes the development of a broad-spectrum vaccine, so new ideas are needed to tackle them. Working on human cells *in vitro*, Aurélie Mousnier from Imperial College London and colleagues have shown that a new chemical compound dubbed IMP-1088, which inhibits human proteins called NMTs, can prevent RV replication without being toxic to cells. At the nanomolar level, it is effective against multiple RV strains, poliovirus and foot-and-mouth disease, and protects cells from virus-induced killing.

● **Further reading**
A Mousnier *et al.* 2018 *Nat. Chem.* **10** 599.

Quantum computing a nucleus

Quantum computing, which exploits quantum phenomena such as entanglement and superposition, is rapidly gaining ground. Now, Eugene Dumitrescu from Oak Ridge National Laboratory in Tennessee and colleagues have used quantum machines to calculate the binding energy of the deuteron to a few percent. The researchers used only publicly available software and two quantum processors accessed via cloud servers: IBM Q Experience and Rigetti 19Q. While the computation is relatively straightforward, involving a simple Hamiltonian, it clearly shows an interesting future for practical quantum computing with public software and cloud-based services.

● **Further reading**
E F Dumitrescu *et al.* 2018 *Phys. Rev. Lett.* **120** 210501.

The slipperiness of ice

Conventional thinking has it that ice is slippery due to a thin film of liquid water created by actual melting or the pressure of objects such as skate blades. Using molecular dynamics simulations of the ice–air interface, Bart Weber of the University of Amsterdam and colleagues have now shown that the truth below freezing is a bit subtler. It appears that over the fairly limited subzero temperatures typical for skating, weakly hydrogen-bonded surface molecules diffuse over the surface in a rolling motion, their number and mobility increasing with increasing temperature. This effect indicates that the slipperiness of ice arises from the high mobility of the surface molecules rather than genuine melting.

● **Further reading**
B Weber *et al.* 2018 *J. Phys. Chem. Lett.* **9** 2838.

Fish schooling revisited

The collective dynamics of fish schooling has traditionally been approached using simple behavioural rules, with little consideration of the flow of water induced by the fish. Audrey Filella of Aix-Marseille University in France and colleagues have now used computer simulations to show that fish in a school may use far-field fluid effects in interesting and nontrivial ways. Including such effects in the simulations leads to several outcomes, including fish swimming faster, a reduction in the energy needed to swim, and the emergence of a new "turning phase" in which fish turn together aided by the flow.

● **Further reading**
A Filella *et al.* 2018 *Phys. Rev. Lett.* **120** 198101.

A study of fish schooling shows that fluid effects influence properties like swimming speed. (Credit: iStock/Tammy616.)

Long-lived biohybrid robot

Biohybrid robots, which are based on heart or skeletal muscle tissue formed on flexible substrates, have suffered from poor agility and durability owing to tissue shrinkage and loss of function. Now, taking a cue from actual organisms, Yuya Morimoto of the University of Tokyo and colleagues have developed an "antagonistic" pair of skeletal muscle tissues, with one contracting and the other expanding, to make a biohybrid robot that overcomes these drawbacks. The device achieves about 90° of rotation of a joint through selective contractions of the tissues, and a lifetime of approximately a week, by balancing the tensions of the tissues to reduce tissue shrinkage. It can pick-and-place objects, and may lead to more life-like robots.

● **Further reading**
Y Morimoto *et al.* 2018 *Sci. Robot.* **3** eaat4440.

Neural network speedup

Artificial neural networks may get a huge boost from analogue memory. Much of the time and energy that goes into training such networks is due to the need to transfer weight data between conventional digital memory and processors. Stefano Ambrogio of IBM Research–Almaden in San Jose, California, and colleagues have now demonstrated a fast and energy-efficient artificial neural network based on a type of analogue memory called phase-change memory, showing that it is as accurate as those based on digital memories. The network has an energy efficiency of 28,065 billion operations per second per watt and a throughput per area of 3.6 trillion operations per second per square millimetre. These values are two orders of magnitude better than those obtained using today's GPU memories.

● **Further reading**
S Ambrogio *et al.* 2018 *Nature* **558** 60.

Astrowatch

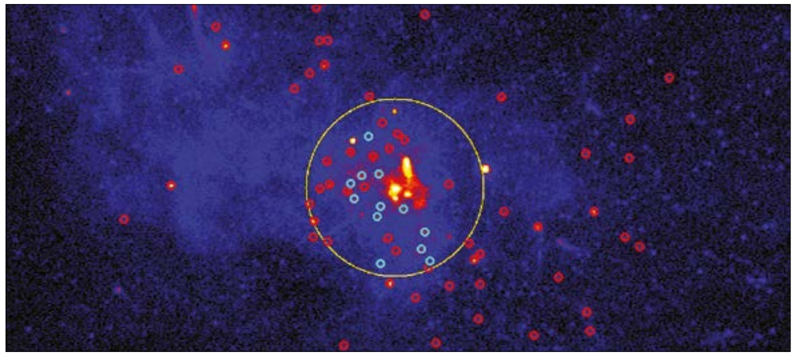
Compiled by Merlin Kole, Department of Particle Physics, University of Geneva

Black holes galore at galactic core

For decades, theoretical models of galaxy evolution have predicted that the supermassive black hole lying at the heart of the Milky Way is surrounded by thousands of smaller black holes left behind by dying stars. Testing such theories is important to understand our own galaxy and, more generally, to understand how galaxies evolve and how black holes are produced. Now, observations by NASA's Chandra X-ray Observatory have revealed a dozen stellar-mass black holes at the centre of the galaxy, providing the first observational evidence for such a black-hole cluster.

Black holes emit virtually no radiation, so it's not possible to detect them when they are isolated and located at large distances from Earth. But many black holes have close stellar companions from which they accrete matter and, as this matter is sucked into the black hole, it heats up and emits X-rays that can be detected on Earth. If only a few of the thousands of the stellar-mass black holes that are predicted to exist in the galactic centre had a companion star, at least this binary fraction of the total black-hole population would be detectable by X-ray telescopes.

Using Chandra data, a group led by Chuck Hailey of Columbia University in New York searched for such black-hole binary systems in a region extending several light years from the galactic centre. This type of search is confounded by two aspects: the high density of other X-ray-emitting objects in the same region, such as binary systems containing neutron stars or white dwarfs instead of black holes; and the relatively low intensity of the X-ray binary sources in the region. But in their study, Hailey and colleagues were able to distinguish between the different types of weak X-ray binary system in the region by studying their spectra.



Modified from C J Hailey *et al.*

Chandra image of the galactic centre showing the 12 sources whose spectra have the expected features of black-hole binaries (cyan circles) and other sources that have different spectral characteristics (red circles). The black-hole binaries are all contained within a radius of three light years (large yellow circle) from the central supermassive black hole. The background colours denote the strength of the X-ray emission, from low (black) to high (yellow).

The researchers examined the Chandra spectra of 415 weak X-ray point sources, containing as few as 100 counts, and looked for the expected spectral features of black-hole binaries. They found 12 sources that have the expected spectral characteristics of black-hole binaries, all within a radius of three light years from the supermassive black hole (see figure). Other X-ray sources whose spectra match well with those of white-dwarf binary systems were found to be distributed at larger distances from the galactic centre.

The researchers went on to estimate the total number of black-hole binary systems in the observed region, assuming that the 12 sources are the brightest in their family and using the known fluxes of brighter and well-studied black-hole binary systems. This resulted in about 300–1000 binary black holes, which is a lower limit on the total number because it only includes those with companion stars. According to theoretical follow-up work by Aleksey Generozov of Columbia and colleagues, the total number of black holes should be between 10,000 and 40,000.

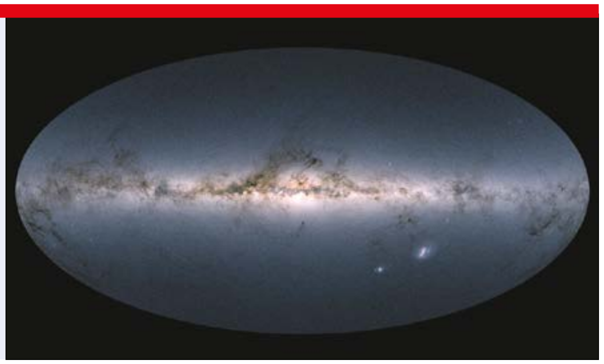
The results, published in *Nature*, agree with the theoretical predictions and therefore confirm the existing models of galaxy evolution. What's more, the findings allow astronomers to predict the number of black-hole mergers – and thus the number of gravitational waves – from this region.

● Further reading

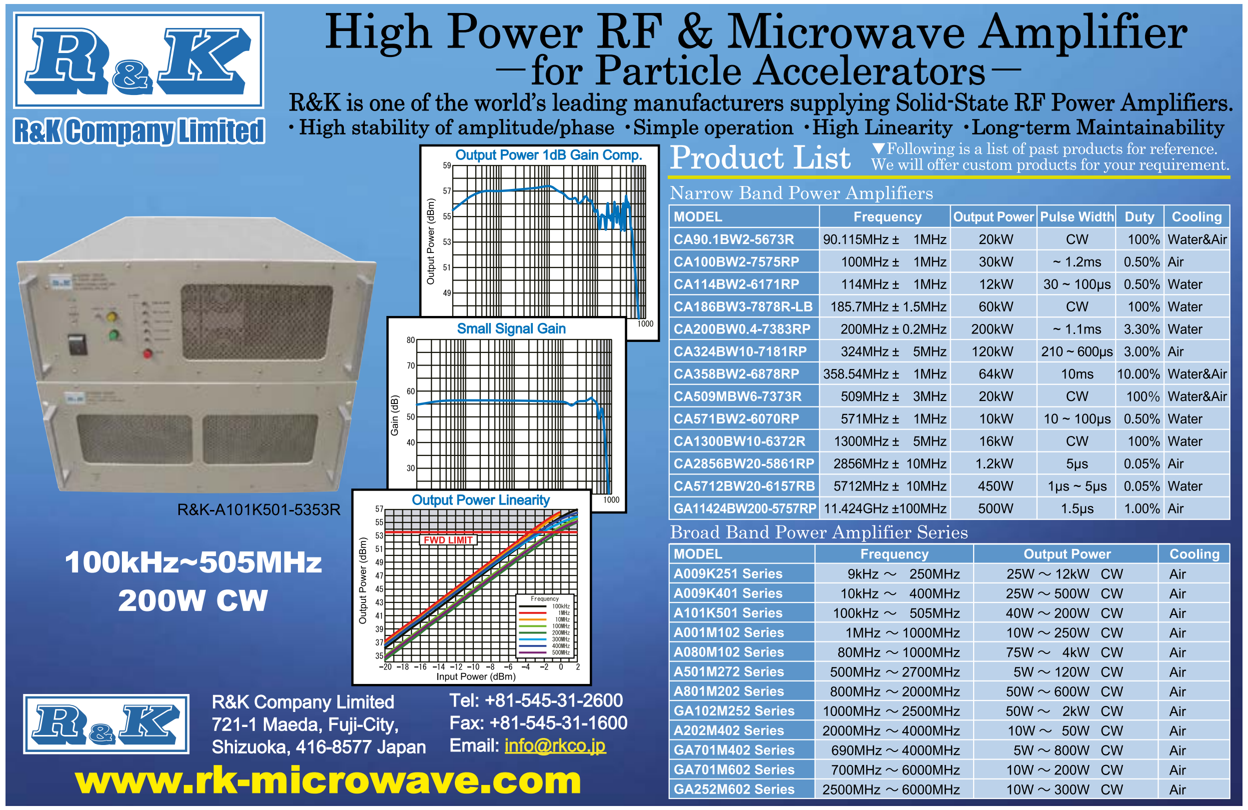
C J Hailey *et al.* 2018 *Nature* **556** 70.

Picture of the month

The second data release of the Gaia collaboration on 25 April resulted in this extremely detailed image of the sky, which contains nearly 1.7 billion stars. The data comprise information on the position of these stars as well as their colour, brightness and relative motion, which can be used to calculate their distance from Earth. The stars making up the Milky Way form the bright disc in the middle of the image. The red and blue shades of the disc, which in some parts is obstructed by dust, indicate regions with different types of star. Other galaxies can be seen in the image, including the Large and Small Magellanic Clouds in the bottom right. Gaia, a mission of the European Space Agency launched in December 2013, aims to create the largest 3D map of the Milky Way, encompassing about 1% of our galaxy's stellar population.



ESA/Gaia/DPAC



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CA1300BW10-6372R	1300MHz ± 5MHz	16kW	CW	100%	Water
CA2856BW20-5861RP	2856MHz ± 10MHz	1.2kW	5μs	0.05%	Air
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GA252M602 Series	2500MHz ～ 6000MHz	10W ～ 300W CW	Air

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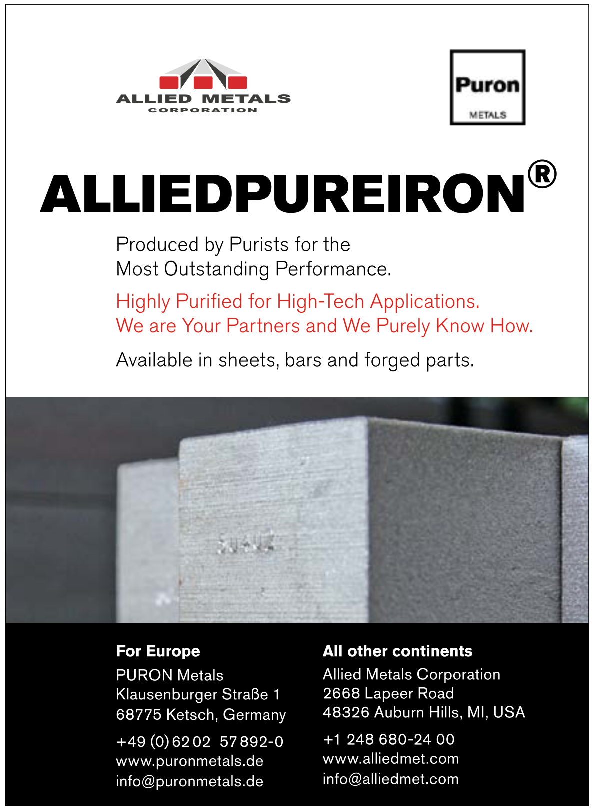

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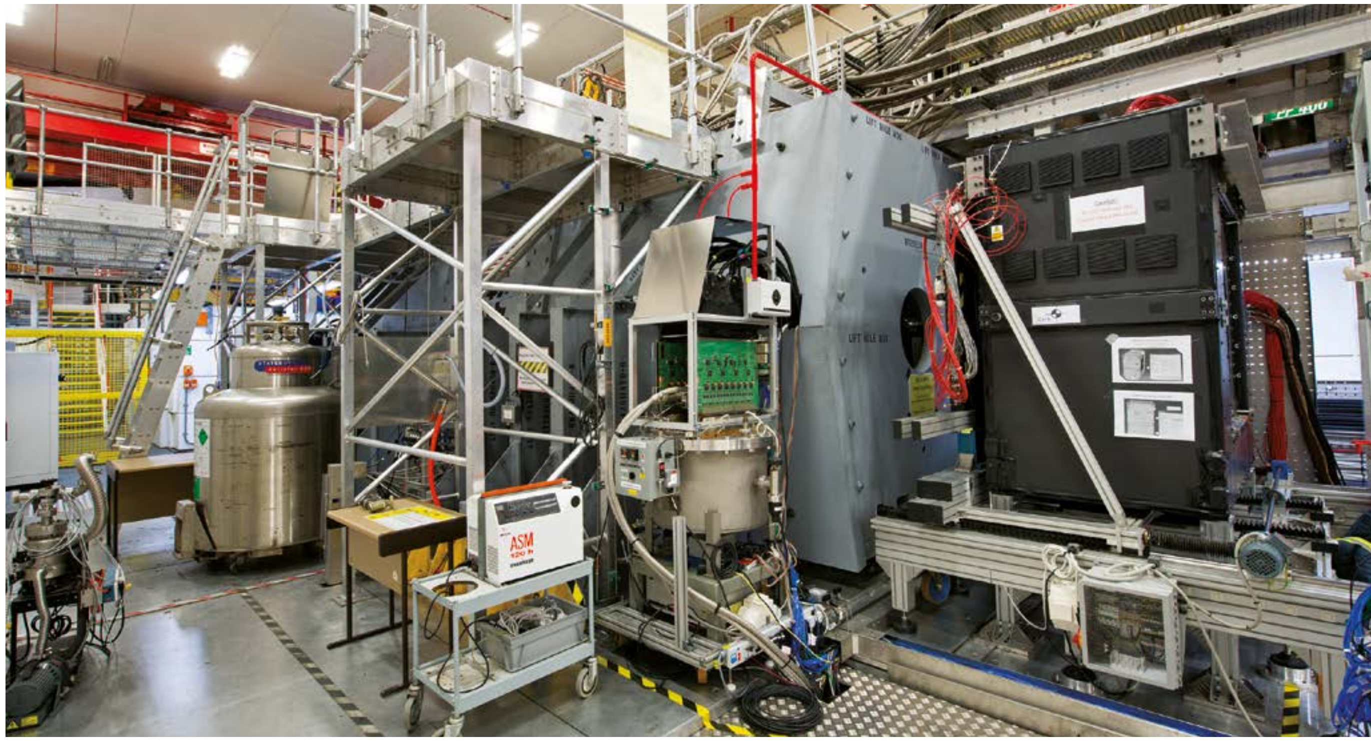


Muons cooled for action

The recent demonstration of muon ionisation-cooling by the MICE collaboration opens a path to a neutrino factory and muon collider.

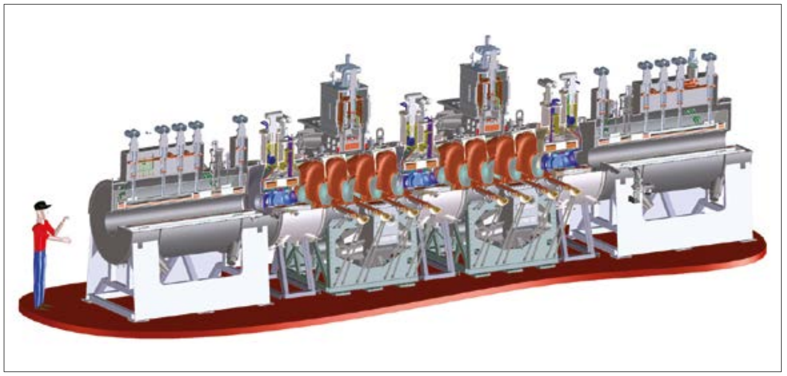
Fundamental insights into the constituents of matter have been gained by observing what happens when beams of high-energy particles collide. Electron–positron, proton–proton, proton–antiproton and electron–proton colliders have all contributed to the development of today's understanding, embodied in the Standard Model of particle physics (SM). The Large Hadron Collider (LHC) brings 6.5 TeV proton beams into collision, allowing the Higgs boson and other SM particles to be studied and searches for new physics to be carried out. To reach physics beyond the LHC will require hadronic colliders at higher energies and/or lepton colliders that can deliver substantially increased precision.

A variety of options are being explored to achieve these goals. For example, the Future Circular Collider study at CERN is investigating a 100 km-circumference proton–proton collider with beam energies of around 50 TeV the tunnel for which could also host an electron–positron collider (*CERN Courier* June 2018 p15). Electron–positron annihilation has the advantage that all of the beam energy is available in the collision, rather than being shared between the constituent quarks and gluons as it is in hadronic collisions. But to reach very high energies requires either a state-of-the-art linear accelerator, such as the proposed Compact Linear Collider or the International Linear Collider, or a circular accelerator with an extremely large bending radius.

Muons to the fore

A colliding-beam facility based on muons has a number of advantages. First, since the muon is a lepton, all of the beam energy is available in the collision. Second, since the muon is roughly 200 times heavier than the electron and thus emits around 10^9 times less synchrotron radiation than an electron beam of the same energy, it is possible to produce multi-TeV collisions in an LHC-sized circular collider. The large muon mass also enhances the direct "s-channel" Higgs-production rate by a factor of around 40,000 compared

Image: the MICE facility at the ISIS source. *(Image credit: S Kill/STFC/RAL.)*



MICE collaboration

Fig. 1. The original conceptual design of MICE, showing the ionisation-cooling cell sandwiched between the two spectrometer solenoid modules. The liquid-hydrogen absorbers (blue) are placed within the bore of the focus-coil modules and the energy lost in the absorbers is restored in the two, four-cavity 201 MHz linac modules. Beam transport through the linacs is provided by coupling coils. Not shown are the various detectors (including time-of-flight hodoscopes, Cherenkov counters and scintillating-fibre trackers), used to measure the muon's properties.

to that in electron–positron colliders, making it possible to scan the centre-of-mass energy to measure the Higgs-boson line shape directly and to search for closely spaced states.

Stored muon beams could also serve the long-term needs of neutrino physicists (see box 1). In a neutrino factory, beams of electron and muon neutrinos are produced from the decay of muons circulating in a storage ring. It is straightforward to tune the neutrino-beam energy because the neutrinos carry away a substantial fraction of the muon's energy. This, combined with the excellent knowledge of the beam composition and energy spectrum resulting from the very well-known characteristics of muon decays, makes the neutrino factory the ideal place to make precision measurements of neutrino properties and to look for oscillation phenomena that are outside the standard, three-neutrino-mixing paradigm.

Given the many benefits of a muon collider or neutrino factory, it is reasonable to ask why one has yet to be built. The answer is that muons are unstable, decaying with a mean lifetime at rest of 2.2 microseconds. This presents two main challenges: first, a high-intensity primary beam must be used to create the muons that will form the beam; and, second, once captured, the muon beam must be accelerated rapidly to high energy so that the effective lifetime of the muon can be extended by the relativistic effect of time dilation.

One way to produce beams for a muon collider or neutrino factory is to harness the muons produced from the decay of pions when a high-power (few-MW), multi-GeV proton beam strikes a target such as carbon or mercury. For this approach, new proton accelerators with the required performance are being developed at CERN, Fermilab, J-PARC and at the European Spallation Source. The principle of the mercury target was proved by the MERIT experiment that operated on the Proton Synchrotron at CERN. However, at the point of production, the tertiary muon beam emerging from such schemes occupies a large volume in phase space. To maximise the muon yield, the beam has to be "cooled" – i.e. its phase-space volume reduced – in a short period of time before it is accelerated.

Box 1: Stored muons promise neutrino beams of unprecedented intensity

Neutrinos, technically antineutrinos, were discovered in 1956 using a nuclear reactor as a source. Four years later, Simon van der Meer invented the magnetic horn to focus a secondary beam of pions. For more than half a century, reactors and horn-focused pion beams were the only way to achieve bright neutrino sources (the picture shows a horn at Fermilab's NuMI beamline). Neutrino factories are to today's neutrino beams what a free-electron laser is to an X-ray tube: a neutrino factory would revolutionise the way neutrinos are made, delivering beams of unprecedented intensity and purity and with sub-percent uncertainties on the neutrino flux. Until this technology becomes available, the neutrino community has to make do with pion-decay-based beams.

P Ginter/Fermilab

The Deep Underground Neutrino Experiment (DUNE) in the US and the Tokai-to-Hyper-Kamiokande (Hyper-K) experiment in Japan, will make use of neutrino beams produced using proton-beam powers in excess of 1 MW. At this power, finally, neutrino-beam science will no longer be limited by counting statistics and now must face the issue of systematic uncertainties. These uncertainties are dominated by our lack of a micro-physical understanding of neutrino–nucleus interactions, that is, cross sections for a neutrino to scatter off a complex nuclear bound-state such as argon or oxygen (*CERN Courier* October 2017 p23).

Current neutrino beams have flux uncertainties around 5%. The proposed Neutrinos from Stored Muons (nuSTORM) facility, a storage ring for muons in the few-GeV range, can produce neutrino and antineutrino fluxes of both electron and muon flavours, known with an absolute accuracy better than 1%. This is key to enable the cross-section measurements that are required to allow DUNE and Hyper-K to reach their full potential in the search for leptonic CP-violation and to maximise their sensitivity to physics beyond the Standard Model. At the same time, nuSTORM would allow for the most sensitive test of the eV-scale sterile neutrino hypothesis in both the muon-neutrino disappearance as well as electron-neutrino appearance channels. Eventually, nuSTORM would serve as a valuable test-bed for R&D towards a neutrino factory and a multi-TeV muon collider. An initial study for nuSTORM took place at Fermilab, and the proposal is now part of the Physics Beyond Colliders study at CERN.

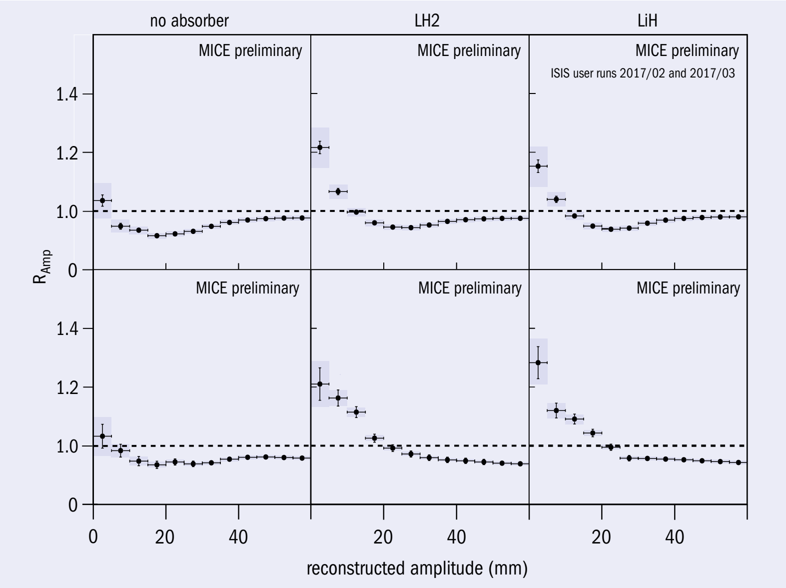


Fig. 2. MICE results obtained using liquid-hydrogen (LH2) and lithium-hydride (LiH) absorbers exposed to beams with a nominal momentum of 140 MeV/c and nominal initial normalised transverse emittance of 6 mm (top row) and 10 mm (bottom row). The results obtained with no absorber are also shown. The ratio of the cumulative amplitude distribution downstream of the absorber to that upstream of the absorber (R_{Amp}) is shown as a function of the reconstructed amplitude. The value of R_{Amp} for a particular bin will be greater than one if muons have been caused to migrate there by their passage through the absorber. R_{Amp} is observed to be greater than one for low-amplitude bins for both liquid- hydrogen and lithium-hydride absorbers, implying that the population of muons at low amplitude in the core of the beam has increased and therefore that the beam has been cooled.

The proposed solution is called ionisation cooling, which involves passing the beam through a material in which it loses energy via ionisation and then re-accelerating it in the longitudinal direction to replace the lost energy. Proving the principle of this technique is the goal of the Muon Ionization Cooling Experiment (MICE) collaboration, which, following a long period of development, has now reported its first observation of ionisation cooling.

An alternative path to a muon collider called the Low Emittance Muon Accelerator (LEMMA), recently proposed by accelerator physicists at INFN in Italy and the ESRF in France, provides a naturally cooled muon beam with a long lifetime in the laboratory by capturing muon–antimuon pairs created in electron–positron annihilation (see box 2).

Cool beginnings

The benefits of a collider based on stored muon beams were first recognised by Budker and Tikhonin at the end of the 1960s. In 1974, when CERN's Super Proton Synchrotron (SPS) was being brought into operation, Koshkarev and Globenko showed how muons confined within a racetrack-shaped storage ring could be used to provide intense neutrino beams. The following year, the SPS proton beam was identified as a potential muon source and the basic parameters of the muon beam, storage ring and neutrino beam were defined. It was quickly recognised that the performance of this facility—the first neutrino factory to be proposed – could be enhanced if the muon beam was cooled. In 1978, Budker and Skrinsky identified ionisation cooling as a technique that could produce sufficient cooling in a timeframe short compared to the muon lifetime and, the following year, Neuffer proposed a muon collider that exploited ionisation cooling to increase the luminosity.

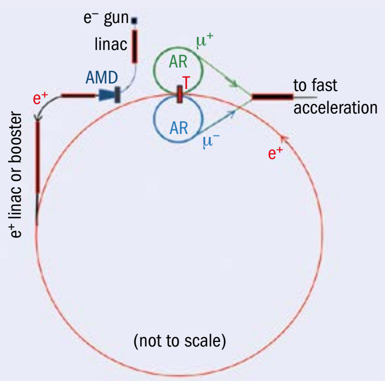
The study of intense, low-emittance muon beams as the basis of a muon collider and/or neutrino factory was re-initiated in the 1990s, first in the US and then in Europe and Japan. Initial studies of muon production and capture, phase-space manipulation, cooling and acceleration were carried out and neutrino- and energy-frontier physics opportunities evaluated. The reduction of the tertiary muon-beam phase space was recognised as a key technological challenge and at the 2001 NuFact workshop the international MICE collaboration was created, comprising 136 physicists and engineers from 40 institutes in Asia, Europe and the US.

The MICE cooling cell, in common with the cooling channels studied since the seminal work of the 1990s, is designed to operate at a beam momentum of around 200 MeV/c. This choice is a compromise between the size of the ionisation-cooling effect and its dependence on the muon energy, the loss rate of muon-beam intensity through decay, and the ease of acceleration following the cooling channel. The ideal absorber has, at the same time, a large ionisation energy loss per unit length (to maximise ionisation cooling) and a large radiation length (to minimise heating through multiple Coulomb scattering). Liquid hydrogen meets these requirements and is an excellent absorber material; a close runner-up, with the practical advantage of being solid, is lithium hydride. MICE was designed to study the properties of both. The critical challenges faced by the collaboration therefore included: the integration of high-field superconducting magnets operating in a magnetically coupled lattice; high-gradient accelerating cavities capable of operation in a strong magnetic

Neutrino factories are to today's neutrino beams what a free-electron laser is to an X-ray tube

Box 2: An alternative path to a muon collider from electron–positron annihilation

The Low Emittance Muon Accelerator (LEMMA) is a proposal to produce very low-emittance muon beams without the need for ionisation cooling. By causing a positron beam to impinge on electrons at rest in a target, LEMMA exploits the fact that muons produced in electron–positron interactions close to threshold are constrained into a small phase-space region, effectively producing a cold muon beam with a long laboratory lifetime. A beam emittance comparable to those typically obtained with electrons can be obtained, and potentially high luminosities and high energies could be reached with relatively small muon fluxes. Muon pairs from positrons-on-target were produced in the 1980s, showing that the process is feasible. For application to a muon collider, however, very intense positron beams need to be accumulated in a storage ring to produce muons at a suitable rate. The design of this system – which requires a positron source with an adiabatic matching device (AMD), positron ring plus target (T) for $\mu^+\mu^-$ production, two $\mu^+\mu^-$ accumulator rings (AR), and a fast-acceleration section to be followed by the muon collider – places challenging requirements on the accelerator and target in order to produce and maintain the high muon rates that are required.



field; and the safe implementation of liquid-hydrogen absorber modules – all solved through more than a decade of R&D (see box 3).

In 2003 the MICE collaboration submitted a proposal to mount the experiment (figure 1) on a new beamline at the ISIS proton and muon source at the Science and Technology Facilities Council's (STFC) Rutherford Appleton Laboratory in the UK. Construction began in 2005 and first beam was delivered on 29 March 2008. The detailed design of the spectrometer solenoids was also carried out at this time and the procurement process was started. During the period from 2008 to 2012, the collaboration carried out detailed studies of the properties of the beam delivered to the experiment and, in parallel, designed and fabricated the focus-coil magnets and a first coupling coil.

Delays were incurred in addressing issues that arose in the manufacture of the spectrometer solenoids. This, combined with the challenges of integrating the four-cavity linac module with the coupling coil, led, in November 2014, to a reconfiguration of the MICE cooling cell. The simplified experiment required two, single-cavity modules and beam transport was provided by the focus-coil modules. An intense period of construction followed, culminating with the installation of the spectrometer solenoids and the focus-coil module in the summer of 2015. Magnet commissioning progressed well until, a couple of months later, a coil in the downstream solenoid failed during a training quench. The modular design of the apparatus meant the collaboration was able to devise new settings rapidly, but it proved not to be possible to restore the downstream spectrometer magnet to full functionality. This, combined with the additional delays incurred in the recovery of the magnet, eventually led to the cancellation of the installation of the RF cavities in favour of the extended operation of a configuration of the experiment without the cavities (see schematic in box 3).

It is interesting to reflect, as was done in a recent lessons-learnt exercise convened by the STFC, whether a robust evaluation of alternative options for the cooling-demonstration lattice at the outset of MICE might have identified the simplified lattice as a "less-risky" option and allowed some of the delays in implementing the experiment to be avoided.

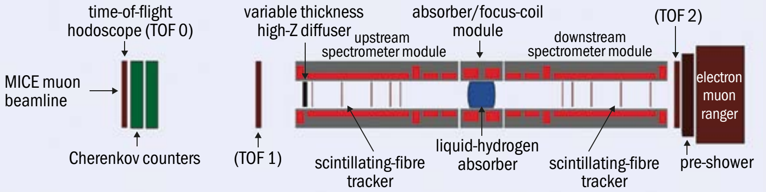
The bulk of the data-taking for MICE was carried out between November 2015 and December 2017, using lithium-hydride and liquid-hydrogen absorbers. The campaign was successful: more than 5×10^8 triggers were collected over a range of initial beam momentum and emittance for a variety of configurations of the magnetic channel for each absorber material. The key parameter to measure when demonstrating ionisation cooling is the "amplitude" of each muon – the distance from the beam centre in transverse phase space, reconstructed from its position and momentum. The muon's amplitude is measured before it enters the absorber and again as it leaves, and the distributions of amplitudes are then examined for evidence of cooling: a net migration of muons from high to low amplitudes. As can be seen (figure 2), the particle density in the core of the MICE beam is increased as a result of the beam's passage through the absorber, leading to a lower transverse emittance and thereby providing a higher neutrino flux or a larger luminosity.

The MICE observation of the ionisation-cooling of muon beams is an important breakthrough, achieved through the creativity and tenacity of the collaboration and the continuous support of the funding agencies and host laboratory. The results match expectations, and the next step would be to design an experiment to demonstrate cooling in all six phase-space dimensions.

Completing the MICE programme

Having completed its experimental programme, MICE will now focus on the detailed analysis of the factors that determine ionisation-cooling performance over a range of momentum, initial emittance and lattice configurations for both liquid-hydrogen and lithium-hydride absorbers. MICE was operated such that data were recorded one particle at a time. This single-particle technique will allow the collaboration to study the impact of transverse-emittance growth in rapidly varying magnetic fields and to devise mechanisms to mitigate such effects. Furthermore, MICE has taken data to explore a scheme in which a wedge-shaped absorber is used to decrease the beam's longitudinal emittance while allowing a controlled growth in its transverse emittance. This is required for a proton-based muon collider to reach the highest luminosities.

Box 3: Cooling muons took 15 years of accelerator R&D



A proton-based neutrino factory or muon collider will need: a proton driver; a pion production-and-capture system; a "front-end" to collect muons produced in pion decay and form the beam into a train of bunches; an ionisation-cooling channel; rapid muon-beam acceleration; and a muon storage or collider ring. Cooling is perhaps the most critical of these elements.

The concept for the Muon Ionization Cooling Experiment (MICE) was based on a single cell of the ionisation-cooling-channel lattice, in which the beam is focussed at the centre of the absorber to enhance the net cooling effect by suppressing the heating from multiple Coulomb scattering (see figure 1). At either side of the absorber/focus-coil modules, short four-cavity linac modules were proposed. A large coupling coil surrounded the cavities to transport the beam, and acceleration was provided by four 201 MHz copper cavities that delivered a gradient of 8 MV/m.

A new muon beamline on the UK's 800 MeV ISIS facility was built to serve MICE, featuring a novel target that intercepts the ISIS proton beam approximately 2 ms before it is extracted. To do this, a linear motor was developed that accelerates the target shaft at 80 g into and out of the proton beam. Such extreme accelerations place high demands on the design and build-quality of the shaft and bearings. Reliable operation was achieved using a diamond-like graphite coating on the titanium shaft and high performance Vespel polymer for the bearings; high precision in the size and form of the components was critical to achieve reliable operation over millions of cycles.

The cavity-development programme for MICE was carried out in the US, including an elegant series of experiments at the MuCOOL test area at Fermilab. A prototype 201 MHz cavity was constructed and careful attention paid to the preparation of the cavity surface, leading to a performance exceeding expectations: a gradient in excess of 20 MV/m without the need to condition the cavity, and with no degradation of performance observed in the presence of magnetic field.

An innovative modular design was adopted for the superconducting solenoids to create flexibility and to allow magnet procurement to be distributed across the collaboration. Each magnet was cooled using closed-cycle cryo-coolers. Space inside the cryostats was at a premium as the compact magnetic lattice of the cooling cell required inter-coil distances to be kept acceptably small.

Three superconducting-magnet modules were conceived: the spectrometer-solenoid, focus-coil and coupling-coil modules. Each spectrometer solenoid contained five coils, the largest being a 120 cm-long central coil with a uniform field of up to 4 T in the tracking volume. The challenges associated with the tight internal tolerances within the magnet cryostats were successfully overcome and by the autumn of 2015, the collaboration had begun to take data in the configuration shown in the figure above.

The MICE muon beamline can be set to deliver beams of nominal momentum from 120–260 MeV/c. Since muon beams are inevitably contaminated with charged pions, and all positive (negative) beams contain a small flux of positrons (electrons), the instrumentation upstream of the MICE experiment is required to reject these particles to deliver a muon purity >99.9%. This was achieved using time-of-flight hodoscopes and Cherenkov counters. The momentum of each muon is measured upstream and downstream of the cooling cell using two scintillating-fibre trackers read out using visible-light photon counters developed for the DØ experiment at Fermilab.

With the MICE observation of ionisation cooling, the last of the proof-of-principle demonstrations of the novel technologies that underpin a proton-based neutrino factory or muon collider has now been delivered. The drive to produce lepton–antilepton collisions at centre-of-mass energies in the multi-TeV range can now include consideration of the muon collider, for which two routes are offered: one, for which the R&D is well advanced, that exploits muons produced using a high-power proton beam and which requires ionisation cooling; and one that exploits positron annihilation with electrons at rest to create a high-energy cold muon source. The high muon flux that can be achieved using the proton-based technique has the potential to serve a neutrino-physics programme of unprecedented sensitivity, and the MICE collaboration's timely results will inform the coming update of the European Strategy for Particle Physics.

● Further reading

MICE Collaboration 2018 arXiv:1806.01807.
D Adey *et al.* 2013 arXiv:1305.1419
M Boscolo *et al.* 2018 arXiv:1803.06696.

Résumé

Des muons refroidis avant d'entrer en action

Avec un collisionneur circulaire de la taille du LHC, il serait possible de produire des collisions entre des faisceaux de muons à une énergie de plusieurs TeV, ce qui ferait augmenter la production de bosons de Higgs d'un facteur très élevé et fournirait des collisions propres, adaptées pour des mesures de précision. La courte durée de vie des muons représente toutefois un défi pour la science des accélérateurs. L'expérience MICE, basée au Royaume-Uni, vient de faire la démonstration d'une étape cruciale en observant le refroidissement par ionisation de faisceaux de muons. Cette avancée, rendue possible grâce à la créativité et à la ténacité de la collaboration MICE ces 15 dernières années, ouvre des perspectives pour une usine de neutrinos ou un collisionneur de muons.

Manuela Boscolo, INFN-LNF; **Patrick Huber**, Virginia Tech; and **Kenneth Long**, Imperial College London and STFC.

Learning machine learning

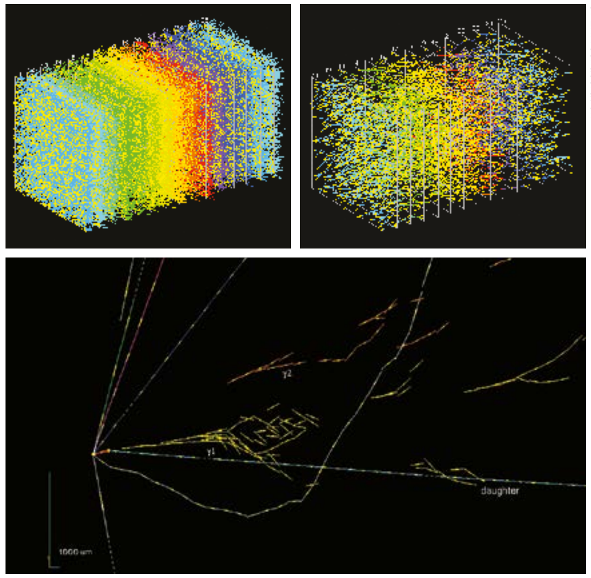
The Yandex machine-learning school for high-energy physics is teaming up with experiments at CERN and beyond to train young researchers in the arts of deep learning.

Machine learning, whereby the ability of a computer to perform an intelligent task progressively improves, has penetrated many scientific domains. It allows researchers to tackle problems from a completely new perspective, enabling improvements to things previously thought solved for good. The downside of machine learning is that the field itself is developing so quickly, with new techniques popping up at an incredible rate, that it is hard to keep up. What is needed is some sort of high-level trigger to discriminate between good and bad, and to guide a growing community of users in a systematic way.

Machine-learning techniques are already in wide use in particle physics, and they will only become more prevalent during the coming years of the high-luminosity LHC and future colliders. Online data processing, offline data analysis, fast Monte Carlo generation techniques and detector-upgrade optimisation are just a few examples of the areas that could profit significantly from smarter algorithms (see p31).

The most remarkable growth trend in machine learning today, and one that has also been heavily hyped, concerns so-called deep learning. Although there is no strict boundary, a neural network with less than four layers is considered "shallow", while one with more than 10 layers and many thousands of connections is considered "deep". Using deep-learning algorithms, plus performative computing resources and extremely large datasets, researchers have managed to break important barriers for such tasks as text translation, voice recognition, image segmentation and even to master the game Go. Many of the educational materials one can find on the Internet are thus focused around typical tasks such as image recognition, annotation, segmentation, text processing and pattern generation.

Since most of these are conveyed in computer-science language, there is an obvious language barrier for domain-specific scientists, such as particle physicists, who have to learn a new technique and apply it to their own research. Another complication is that there are a variety of machine-learning methods capable of solving particular problems and a plenitude of tools (i.e. different languages, packages and platforms) out there – almost all of which are online – with which to implement those methods.



Electromagnetic shower identification for the OPERA experiment, showing a detector element filled with background tracks (top left), the same volume after pre-filtering by OPERA's tracking algorithm (top right), and finally the shower revealed after even more thorough filtering (bottom).

OPERA collaboration

Targeting particle physics

As machine learning spreads into new domains such as astrophysics or biology, schools that focus on problems in specific areas are becoming more popular. Historically there are several summer schools for particle physicists focused around data analysis, computing and statistical learning – in particular the CERN School for computing, INFN School of Statistics and the CMS Data Analysis School. But, until 2014, none focused specifically on machine learning. In that year, a series with the straightforward title Machine-Learning school for High-Energy Physics (MLHEP) was launched.

MLHEP grew out of the well-established Yandex School of Data Analysis (YSDA), a non-commercial educational organisation funded by the Russia-based internet firm Yandex. Over the past decade, YSDA has grown to receive several thousand applications per year, out of which around 200 people pass the entrance exams and around 50 graduate in conjunction with leading Russian universities – almost all of them finding data-science positions in the private sector.

In 2015, YSDA joined the LHCb collaboration. The goal was to help optimise LHCb's high-level trigger system to improve its efficiency for selecting B-decay events, and the result of the LHCb-YSDA collaboration was an efficiency gain of up to 60% compared to that obtained during LHC Run I. Another early joint effort between YSDA, CERN and MIT within LHCb was the design of decision-tree algorithms capable of decorrelating their output from a given variable, such as invariant mass.

The first MLHEP schools in 2015 and 2016 were satellite events at the Large Hadron Collider Physics (LHCP) conference held in St. Petersburg and Lund, respectively. Another key contributor to the school was the faculty of computer science at Russia's Higher School of Economics (HSE), which was founded in 2014 by Yandex. MLHEP 2017 was organised by Imperial College London in the UK, and the 2018 school takes place in Oxford at the beginning of August.

The topics covered during the schools usually start from the basic aspects of machine learning, such as loss functions, optimisation methods, predictive-model quality validation, and stretch towards advanced techniques like generative adversarial networks and Bayesian optimisation. The curriculum is not static, and each year the focus changes to address the most interesting and promising trends in deep learning while providing an overview of various techniques available on the market. At the 2018 school, speakers were invited from both academia and from companies, including Oracle, Nvidia, Yandex and DeepMind.

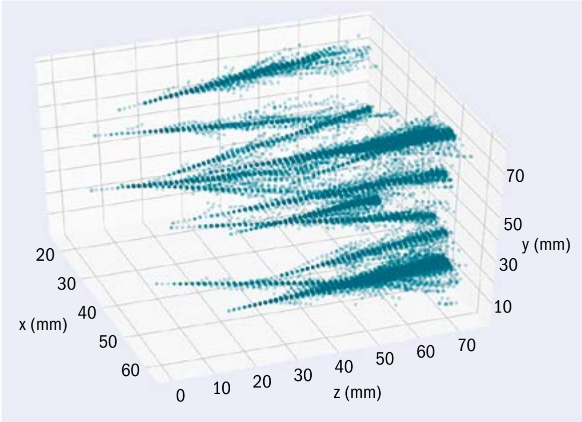
Breaking the language barrier

Some people compare deep learning not with a tool or platform, but with a language that allows a researcher to express computational "sentences" addressing a particular problem.

To reinforce the language analogy, recall that there is no solid theory of deep learning yet; in a sense it is just a bunch of best-practices and approaches that has proven to work in several important cases. A lot of the time during MLHEP classes is therefore devoted to practical exercises. School students are also encouraged to enter a data-science competition that is related to particle physics – e.g. tracking for the Coherent Muon to Electron Transition (COMET) experiment and event selection for the Higgs-boson discovery by the ATLAS and CMS experiments. The competition is published on the machine-learning competition platform kaggle.com at the start of the school, and is open for anyone who wants to get more machine-learning practice.

For summer 2017, the competition was organised together with the OPERA and SHiP collaborations. The goal was to analyse volumes of nuclear emulsions collected by OPERA that contain lots of cosmic-background tracks as well as tracks from electromagnetic showers. These shower-like structures are of interest for OPERA for the analysis of tau-neutrino interactions, so special algorithms have to be developed. Such algorithms are also very relevant to the SHiP experiment, which aims to use emulsion-based detectors for finding hidden-sector particles at CERN. According to some theoretical models, such showers might be closely related to hidden-sector particle interaction with regular matter (e.g. elastic scattering of very weakly-interacting particles off electrons or nuclei), so a separate task would be to discriminate these showers from neutrino interactions. The performance of the algorithms designed by participants was amazing. The winner of the challenge presented his solution at the SHiP collaboration meeting in November 2017 and was invited by OPERA to continue the collaboration.

A major part of the MLHEP curriculum is given by YSDA/HSE lecturers, and guest speakers help to broaden the view on the machine-learning challenges and methods. The school is non-commercial, and its success depends on external contributions from the HSE, YSDA, local organisers and commercial sponsors. For the past two years we have been supported by the Marie Skłodowska-Curie training network AMVA4NewPhysics, which has also sent several PhD students to the school.



Simulated overlapping electromagnetic showers in the proposed SHiP detector, which participants of MLHEP-2017 had to recognise against dense background settings using machine-learning methods.

The format of the summer school is very productive, allowing students to dive into the topics without distraction. The school materials also remain available at GitHub, allowing students to access them whenever they want. As time goes by, basic machine-learning courses are becoming more readily available online, giving us a chance to introduce more advanced topics every year and to keep up with the rapid developments in this field.

● Further reading

bit.ly/mlhep2018.

A Rogozhnikov *et al.* 2014 arXiv:1410.4140.

Résumé

Se former sur l'apprentissage automatique

L'apprentissage automatique permet aux scientifiques de s'attaquer à des problèmes depuis une perspective entièrement nouvelle, et d'approfondir des questions que l'on croyait jusqu'ici résolues pour de bon. Le revers de la médaille est que le domaine lui-même se développe tellement rapidement, avec des nouvelles techniques qui apparaissent à un rythme effréné, qu'il est difficile de suivre son évolution. Au sein de l'apprentissage automatique, le sous-domaine présentant aujourd'hui la croissance la plus remarquable est l'apprentissage approfondi, qui a par ailleurs été très médiatisé. Afin de former des jeunes chercheurs à l'art de l'apprentissage approfondi, l'école d'apprentissage automatique pour la physique des hautes énergies de Yandex s'associe à des expériences au CERN et dans d'autres laboratoires.

Andrey Ustyuzhanin, YSDA, HSE, ICL.

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HALO consists of a 10 m-wide cylinder defined by vertical piano wires, within which a 4 m-tall screen displays particle collisions. The data also trigger hammers that strike the vertical wires and set up vibrations to create a multisensory experience. (Credit: M Giesbrecht/Audemars Piguet.)

Creativity across cultures

Data from the ATLAS experiment is a key element in *HALO*, an important new commission undertaken for Art Basel, the world's premier fair for contemporary art. It's the latest exciting outcome of Arts at CERN, which has become a major player in the world where art and science meet.

Lift up your eyes as you walk through the principal entrance to CERN's main building and you will see a tangled iron coil suspended above the central staircase. Rather like electron orbitals marking out the shape of an atom, the structure's overlapping lines form hints of something more tangible that changes as you move – a human body. Here, in his sculpture *Feeling Material XXXIV*, the artist Antony Gormley has spun a chaotic spiralling line that envelopes the body's space.

Every bit of time spent in and researching around CERN encourages me to reconsider the intangible peripheries of micro and macro.
Mariele Neudecker, artist

Artists, like scientists, have always been keen observers of the world about them and Gormley is no exception. It was his interest in how spaces are delineated that led to his first contacts with CERN physicist Michael Doser in 2006, and ultimately to his donation of *Feeling Material XXXIV* to the Organization in 2008. Over the years many artists have visited CERN, intrigued by its research; the American performance artist James Lee Byars even featured on the cover of *CERN Courier* in September 1972. And in the 1990s, British artist and film-maker Ken McMullen visited the laboratory as a result of his friendship with the daughter of the late Maurice Jacob, a well-known CERN theorist. The visit sowed the seeds for a major project, *Signatures of the Invisible*, based on a collaboration between the London Institute and CERN. This project brought 11 established artists from various countries, including McMullen, to work with scientists and technicians at CERN during 1999–2000, resulting in works of art that were exhibited worldwide (*CERN Courier* May 2001 p23).

The experience proved rewarding for both sides. Writing in the *Courier* (July 2001, p30), Ian Sexton, the CERN technician who worked with laser cutting and other techniques on McMullen's piece *Crumpled Theory*, described his pleasure at seeing the artist's first sight of the completed work "simply presented on the workshop floor, with sunlight streaming through the blinds. Ken was … delighted. His enthusiasm was a most unusual experience for me. Normally on completion of a job at CERN a perfunctory 'thank you' is the only response."

The project had involved a significant commitment by CERN. The Press Office managed the project on the Organization's behalf, a number of scientists became deeply involved, and the artists were offered the use of the laboratory's workshop – all of which implied a great deal of disruption and additional work for those concerned. So perhaps there were reservations in the minds of some at CERN when a new "science and art" initiative began to take shape. In 2009, cultural expert Ariane Koek decided to use the award of a Clore Fellowship to come to CERN and – with the encouragement of the Director-General at the time, Rolf Heuer – work out how to establish and fund an artists' residency scheme. Heuer was suitably impressed by her proposals and the following year, after a selection process, Koek was taken on to set up Arts at CERN.

Cultural policy

These efforts bore fruit in August 2011 with the launch of CERN's first-ever cultural policy. Its central element is a selection process for arts engagement with CERN, with a cultural board for the arts to advise on and oversee projects and collaborations involving CERN. The initiative brought order and direction to what had been an ad-hoc approach to CERN's involvement with the arts.

The first outwardly visible outcome of Arts at CERN was a competition, now called Collide International, open to artists from anywhere in the world. A key element is to pair winning artists with scientists at CERN during a residency lasting up to three months. The first such award, announced in 2011, was set up in collaboration with Austria-based digital arts organisation Ars Electronica, and the residency consisted of two months at CERN and one month at Ars Electronica's research and development lab. This was a coup for CERN and the new cultural policy, as Ars Electronica had for 40 years built up a formidable reputation in bringing artists, scientists and engineers together. Widely publicised by CERN, the partnership was well received in the arts world, but it was perhaps not so well understood at CERN. Was this something that CERN should be doing and who was paying for it all?

Heuer, who was instrumental in initiating Arts at CERN, was always clear on the first point. "The arts and science are inextricably linked; both are ways of exploring our existence, what it is to be human and what is our place in the universe," he said on launching the cultural policy. Commenting later after three years of successful part-

Engaging with artists stops research becoming a day job, and fills you with awe again.
Tara Shears, physicist


Head of Arts at CERN, Mónica Bello, with the 2016 Collide International winner, Yunchal Kim.

CERN-PHOTO-201611-291-8


Sound artist Antye Greie-Ripatti recording during her visit to CERN as a Guest Artist in 2016.

CERN-PHOTO-201610-267-21

nership with Ars Electronica, he wrote: "The level of heated debate about the so-called two-cultures is a constant source of bafflement to me. Of course arts and science are linked. Both are about creativity. Both require technical mastery. And both are about exploring the limits of human potential."

Regarding the second point, Arts at CERN was conceived from the start to be mainly self-funding. Support from CERN initially came through its programmes for fellows and students. Funding for the original international residency came principally from Ars Electronica, as well as from the UNIQA Insurance Group, which has a long association with CERN. Currently, FACT (Foundation for Art and Creative Technology), based in Liverpool in the UK, is the main partner for the Collide International award. Two further strands in the programme follow a similar formula. Artists from across Switzerland can compete for a residency funded principally by Pro Helvetia, the Swiss Arts Council, while those from Geneva are eligible for an award set up in partnership with the Republic and Canton of Geneva and the City of Geneva. The two residencies – Collide Pro Helvetia and Collide Geneva – are awarded in alternate years. In addition, via a slightly different scheme called Accelerate, each year ministries or foundations in a specific country fund artists working in different domains to come to CERN for one month.

A new era begins

By 2014, when the call went out for a new person to head Arts at CERN, the programme had already earned a global reputation. Two internationally known artists and recipients of the Collide International award epitomise this reach: Bill Fontana and Ryoji Ikeda. Sound-sculptor Fontana, from the US, had produced works based on sounds across the globe when he was awarded the 2013 international residency. He explored sounds recorded in the LHC tunnel in works such as *Acoustic Time Travel* (*CERN Courier* December 2012 p32), and was followed a year later by Ikeda, Japan's leading electronic composer and visual artist, who used his residency to inform his works *supersymmetry* and *micro|macro*.

This growing reputation within the science and art scene appealed in particular to the art historian and curator Mónica Bello, who had more than 15 years' experience in curating and managing cultural programmes in art, science and technology institutions in different countries and had spent five years as artistic director of the VIDA International Art and Artificial Life Awards. Educated in modern and contemporary art history, she had been exposed to new ideas emerging at the boundaries of modern art and become passionate about the fusion between science and art. "I like art that is based on open processes, where different agents – the artists, researchers, even the audience – can join together to become the project," she explains. "Experimentation with openness is the most exciting thing that's happening in the arts right now – and CERN is the place to be for that."

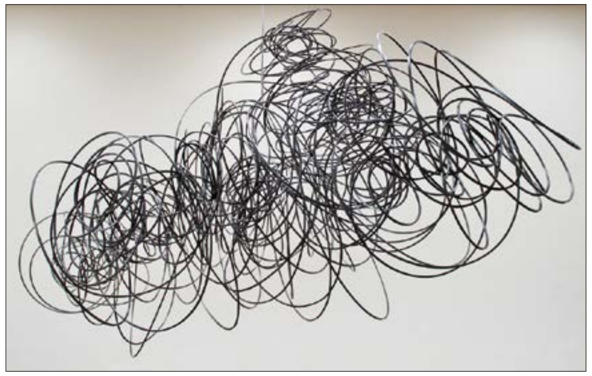
Bello took up her position at CERN in March 2015, joining co-ordinator Julian Caló. In accelerator terms, by the following year, Arts at CERN was running at its design energy and beyond. The programme was bringing artists to the laboratory for as many as four residencies a year, and the number of entries for the Collide International award had risen from some 150 when it was launched in 2011 to around 1000. In addition, the sheer number of artists from all over the world wishing to see CERN had pushed the existing programme of individual visits almost to breaking point. So, in 2016, Bello initiated a Guest Artist programme for 10 selected artists per year. It is the unique strand of Arts at CERN where artists visit by invitation only and where they underwrite the visits themselves.

Mad passion, courage and an immense amount of creativity is what I found in common between scientists and spiritual seekers. One search outwards, the other search inwards, yet both learn the same truth about the magnificent nature of nothingness.
Aisha Juma, artist

However, Bello's main vision is to move beyond exploration and artistic research to develop new art commissions and exhibitions. Continuing to support the artists once they finish their residencies at CERN is essential for this, and one way is to connect the artists with CERN scientists that have links to the cities of the programmes' partners. This was initiated with Liverpool, where artists spent a one-month residency at FACT after being at CERN and where they were connected with research groups at Liverpool University led by LHCb physicist Tara Shears. Connecting CERN to international cultural organisations is part of the same objective, through links formed with different cities and countries.

These new developments are fully supported by CERN's current management. Earlier this year, Director-General Fabiola Gianotti made her views on the "two cultures" clear at the World Economic Forum in Davos: "Too often people put science and humanities, or science and the arts, in different compartments… but they do have much in common. They are the highest expression of the creativity and the curiosity of humanity. We should really talk about culture in general, and not focus on one particular sector of culture. This is an important message we should be giving to teachers and to young people, for a better world, so they can grow to face the challenges of society."

Arts at CERN currently has a clear home within CERN's international relations sector. The aim is to provide stability for the programme, with a view to making it self-sustaining with separate funding within the context of the CERN & Society Foundation. At the same time, Arts at CERN forms part of a broader interest at CERN in the arts, which includes a distinctive and complementary programme Arts@CMS. This education and outreach initiative of the CMS collaboration has set up school-based projects and collaborations with artists with the aim of inspiring a greater appreciation of CERN's science within the public at large.


Antony Gormley's Feeling Material XXXIV, *which hangs in building 500.*

CERN-GE-1108207-16


A performance of the production Quantum *in the CMS surface building during CERN's open days in 2013.*

CERN-PHOTOLAB-2013-052-14

A new production scheme

Arts at CERN has clearly been a resounding success with the arts community, and reaching audiences beyond the confines of the laboratory has proved no problem at all. Nor has it been difficult to find scientists willing to work with the artists; more than 200 have so far been involved. But it is by no means easy to mount an exhibition at a scientific laboratory – in places almost an industrial site – where health and safety are of paramount importance. There have been some obvious artistic interventions, such as when choreographer Gilles Jobin, winner of the 2012 Collide Geneva award, installed dancers in the CERN restaurant and computer centre, and even the library; and his project *Quantum* – a fusion of dance and lighting installation developed with Julius von Bismarck, the first Collide International artist-in-residence – debuted in the CMS cavern during CERN's open days in 2013, before embarking on an international tour (*CERN Courier* November 2013 p29).

More recently, as part of Geneva's annual Electron Festival in 2016, the winners of the 2014 Collide Geneva award, Rudy Decelière and Vincent Hänni, showed work developed with experimentalist Robert Kieffer and theorist Diego Blas. Their sound installation *Horizons Irrésolus* (2016) – which consists of 888 micro-synthesisers and speakers, network cable and nylon thread – was installed at CERN for visits during the Easter weekend when the festival traditionally takes place. The effort required by many people at CERN included registration to allow access to the Meyrin site and a shuttle bus to take visitors to see the installation. The response was enthusiastic, but not large.

It is to address such problems that Bello has introduced a production and exhibition stage into the residencies. Rather as a scientific experiment evolves from conception to data-collection, analysis and publication, so does an artistic endeavour evolve from exploration to production and exhibition. The original focus of the residencies at CERN was on exploration: having artists and scientists come together to evolve ideas. The goal was to gain knowledge but not necessarily to produce artworks. In the new phase for Arts at CERN, at the end of their residencies, artists will be invited to propose a work to be considered for additional funding for production. The aim is to collaborate with other institutes to co-produce cultural works for ideas that are worth developing, and to curate the resulting work so that it can be shown and shared with the CERN community.

We do not need to patronise [artists], in the same way they do not patronise us. It is interesting to share the perception we have of each other's work and insights.
Luis Álvarez-Gaumé, physicist

In 2016 CERN began a new collaboration for the Collide

CERN-PHOTO-BUL-NA-2015-192

Semiconductor duo Ruth Jarman (left) and Joe Gerhardt (right) talk with Peter Jenni of ATLAS during their residency.

Documentary film-maker Jan Peters at the ATLAS pixel detector during his residency in 2013, as part of his Collide Geneva award.

International award involving FACT, ushering in the production phase. To support production of the artworks, CERN and FACT have brought together several important European cultural organisations under the umbrella of ScANNER (Science and Art Network for New Exhibitions and Research). Supported by ScANNER, a major exhibition will open at FACT in November 2018 showcasing artworks from, among others, the 2018 Collide International award winner and four previous winners: Semiconductor (2015), Yunchul Kim (2016), studio hrm199 led by Haroon Mirza (2017) and Suzanne Triester (2018). The exhibition will then tour all venues of the ScANNER members during 2019 and 2020.

Meanwhile, Arts at CERN continues to be a major influence across an impressive range of artistic areas. For example, in her project *Quantum Nuggets*, designer Laura Couto (Collide Pro Helvetia award 2017) has developed a computer program to enable other artists and designers to produce 3D shapes based on collision data from the LHC, thus creating real objects, such as furniture, that echo the invisible quantum world of particle physics. And in February this year Cheolwon Chang (Accelerate Korea) spent time at CERN finding out about the geometric properties of nature and how mathematics influences our further understanding of the universe. The winners of two awards for 2018 were announced in March: Suzanne Treister (Collide International) and Anne Sylvie Henchoz and Julie Lang (Collide Geneva).

Residing (artistically) at CERN was akin to inhabiting a hard-core sci-fi film set of unearthly scale and complexity, radiating with an infinite number of narratives of mind-boggling depth.
Julijonas Urbonas, artist

Most recently, a prestigious commission for Art Basel held on 11–17 June and guest-curated by Bello, has highlighted the pinnacles that Arts at CERN is reaching. Swiss watchmakers, Audemars Piguet, a partner of Art Basel, chose the British artist-duo Semiconductor to create the Audemars Piguet Art Commission for the 2018 fair. Ruth Jarman and Joe Gerhardt, who work together under the name Semiconductor, were the recipients of the 2015 Collide International award and for Art Basel they created *HALO* – an installation that surrounds visitors with data collected by the ATLAS experiment at the LHC. *HALO* consists of a 10 m-wide cylinder defined by vertical piano wires, within which a 4 m-tall screen displays particle collisions. The data also trigger hammers that strike the wires and set up vibrations to create a multisensory experience.

This important commission is testament to the impact that the Arts at CERN programme is having in the world of contemporary art, and underlines its importance in bringing together apparently disparate ways in viewing and making sense of the world, the universe in which we live. There are many people who say they do not appreciate modern art, just as there are many who say that they never liked physics. But with modern art, just as with modern physics, making a little effort can open up remarkable new ways of thinking about our place in space and time. Arts at CERN is very clearly bringing people together in ways that open their minds and allow them not necessarily to understand but to appreciate how others view the world about us.

Résumé

La créativité au-delà des frontières culturelles

Au fil des années, le CERN a reçu la visite de nombreux artistes, curieux des recherches menées par le Laboratoire. En 2011, l'Organisation a établi sa toute première politique culturelle, dont l'objectif central est d'apporter un cadre et une orientation à l'approche au cas par cas qui avait jusque-là régi la participation du CERN à des activités artistiques. Aujourd'hui, le programme Arts at CERN est devenu un acteur majeur dans l'univers où l'art et la science se rencontrent ; il s'articule autour d'un concours appelé Collide International, grâce auquel les artistes peuvent gagner une résidence au CERN pouvant durer jusqu'à trois mois. La dernière création issue de ces interactions, HALO, un projet d'envergure entrepris cette année pour Art Basel, a pour ingrédient essentiel les données de l'expérience ATLAS.

Christine Sutton, former editor of *CERN Courier*.

The rise of deep learning

Deep learning is bringing new levels of performance to the analysis of growing datasets in high-energy physics.

It is 1965 and workers at CERN are busy analysing photographs of trajectories of particles travelling through a bubble chamber. These and other scanning workers were employed by CERN and laboratories across the world to manually scan countless such photographs, seeking to identify specific patterns contained in them. It was their painstaking work – which required significant skill and a lot of visual effort – that put particle physics in high gear. Researchers used the photographs (see figures 1 and 3) to make discoveries that would form a cornerstone of the Standard Model of particle physics, such as the observation of weak neutral currents with the Gargamelle bubble chamber in 1973.

In the subsequent decades the field moved away from photographs to collision data collected with electronic detectors. Not only had data volumes become unmanageable, but Moore's law had begun to take hold and a revolution in computing power was under way. The marriage between high-energy physics and computing was to become one of the most fruitful in science. Today, the Large Hadron Collider (LHC), with its hundreds of millions of proton–proton collisions per second, generates data at a rate of 25 GB/s – leading the CERN data centre to pass the milestone of 200 PB of permanently archived data last summer. Modelling, filtering and analysing such datasets would be impossible had the high-energy-physics community not invested heavily in computing and a distributed-computing network called the Grid.

Learning revolution

The next paradigm change in computing, now under way, is based on artificial intelligence. The so-called deep learning revolution of the late 2000s has significantly changed how scientific data analysis is performed, and has brought machine-learning techniques to the forefront of particle-physics analysis. Such techniques offer advances in areas ranging from event selection to particle identification to event simulation, accelerating progress in the field while offering considerable savings in resources. In many cases, images of particle tracks are making a comeback – although in a slightly different form from their 1960s counterparts.

Artificial neural networks are at the centre of the deep learning revolution. These algorithms are loosely based on the structure of biological brains, which consist of networks of neurons interconnected by signal-carrying synapses. In artificial neural networks these two entities – neurons and synapses – are represented by mathematical equivalents. During the algorithm's "training" stage, the values of parameters such as the weights representing the synapses are modified to lower the overall error

Image credit: iStock/ktsimage.

rate and improve the performance of the network for a particular task. Possible tasks vary from identifying images of people's faces to isolating the particles into which the Higgs boson decays from a background of identical particles produced by other Standard Model processes.

Artificial neural networks have been around since the 1960s. But it took several decades of theoretical and computational development for these algorithms to outperform humans, in some specific tasks. For example: in 1996, IBM's chess-playing computer Deep Blue won its first game against the then world chess champion Garry Kasparov; in 2016 Google DeepMind's AlphaGo deep neutral-network algorithm defeated the best human players in the game of Go; modern self-driving cars are powered by deep neural networks; and in December 2017 the latest DeepMind algorithm, called AlphaZero, learned how to play chess in just four hours and defeated the world's best chess-playing computer program. So important is artificial intelligence in potentially addressing intractable challenges that the world's leading economies are establishing dedicated investment programmes to better harness its power.

Computer vision

The immense computing and data challenges of high-energy physics are ideally suited to modern machine-learning algorithms. Because the signals measured by particle detectors are stored digitally, it is possible to recreate an image from the outcome of particle collisions. This is most easily seen for cases where detectors offer discrete pixelised position information, such as in some neutrino experiments, but it also applies, on a more complex basis, to collider experiments. It was not long after computer-vision techniques, which are based on so-called convolutional neural networks (figure 2), were applied to the analysis of images that particle physicists applied them to detector images – first of jets and then of photons, muons and neutrinos, simplifying and making the task of understanding ever-larger and more abstract datasets more intuitive.

Particle physicists were among the first to use artificial-intelligence techniques in software development, data analysis and theoretical calculations. The first of a series of workshops on this topic, titled Artificial Intelligence in High-Energy and Nuclear Physics (AIHENP), was held in 1990. At the time, several changes were taking effect. For example, neural networks were being evaluated for event-selection and analysis purposes, and theorists were calling on algebraic or symbolic artificial-intelligence tools to cope with a dramatic increase in the number of terms in perturbation-theory calculations.

Over the years, the AIHENP series was renamed ACAT (Advanced Computing and Analysis Techniques) and expanded to span a broader range of topics. However, following a new wave of adoption of machine learning in particle physics, the focus of the 18th edition of the workshop, ACAT 2017, was again machine learning – featuring its role in event reconstruction and classification, fast simulation of detector response, measurements of particle properties, and AlphaGo-inspired calculations of Feynman loop integrals, to name a few examples.

The availability of more powerful computer systems together with deep learning will likely allow particle physicists to think bigger.

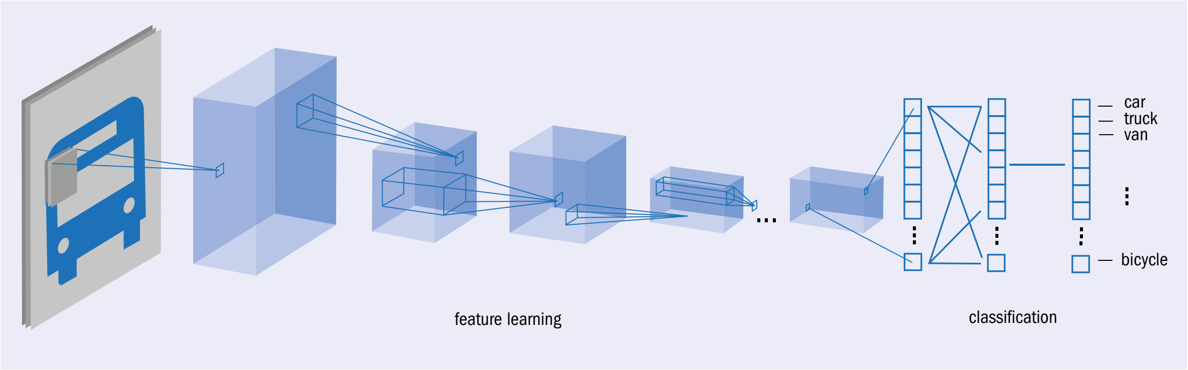

CERN

Fig. 1. A scanning worker analysing a bubble-chamber photograph in 1980.

Learning challenge

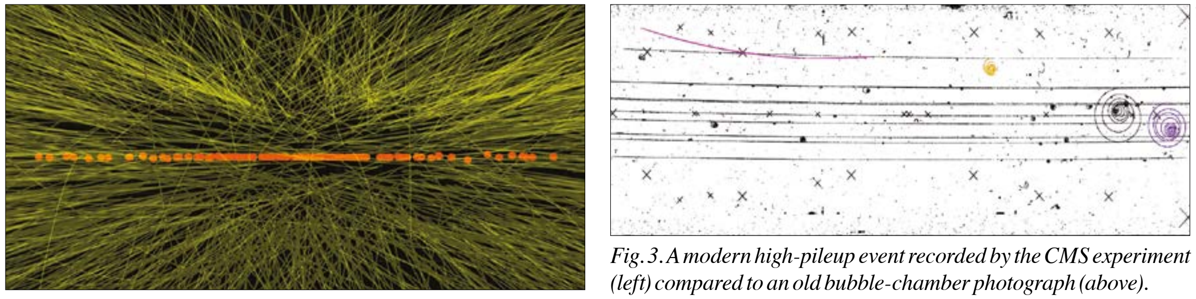
For these advances to happen, machine-learning algorithms had to improve and a physics community dedicated to machine learning needed to be built. In 2014 a machine-learning challenge set up by the ATLAS experiment to identify the Higgs boson garnered close to 2000 participants on the machine-learning competition platform Kaggle. To the surprise of many, the challenge was won by a computer scientist armed with an ensemble of artificial neural networks. In 2015 the Inter-experimental LHC Machine Learning working group was born at CERN out of a desire of physicists from across the LHC to have a platform for machine-learning work and discussions. The group quickly grew to include all the LHC experiments and to involve others outside CERN, like the Belle II experiment in Japan and neutrino experiments worldwide. More dedicated training efforts in machine learning are now emerging, including the Yandex machine learning school for high-energy physics and the INSIGHTS and AMVA4NewPhysics Marie Skłodowska-Curie Innovative Training Networks (see p24).

Event selection, reconstruction and classification are arguably the most important particle-physics tasks to which machine learning has been applied. As in the time of manual scanning, when the photographs of particle trajectories were analysed to select events of potential physics interest, modern trigger systems are used by many particle-physics experiments, including those at the LHC, to select events for further analysis (figure 3). The decision of whether to save or throw away an event has to be made in a split microsecond and requires specialised hardware located directly on the trigger systems' logic boards. In 2010 the CMS experiment introduced machine-learning algorithms to its trigger system to better estimate the momentum of muons, which may help identify physics beyond the Standard Model. At around the same time, the LHCb experiment also began to use such algorithms in their trigger system for event selection.



Modified from MathWorks

Fig. 2. Convolutional neural networks automatically extract features from input images in stages, drawing inspiration from the structure of biological visual systems. Spatiotemporal convolutions over the image (blue boxes) lead to increasingly higher-order feature abstractions while fully connected layers learn how to best combine them to perform image classification.


CERN

CERN

Fig. 3. A modern high-pileup event recorded by the CMS experiment (left) compared to an old bubble-chamber photograph (above).

Neutrino experiments such as NOvA and MicroBooNE at Fermilab in the US have also used computer-vision techniques to reconstruct and classify various types of neutrino events. In the NOvA experiment, using deep learning techniques for such tasks is equivalent to collecting 30% more data, or alternatively building and using more expensive detectors – potentially saving global taxpayers significant amounts of money. Similar efficiency gains are observed by the LHC experiments.

Currently, about half of the Worldwide LHC Computing Grid budget in computing is spent simulating the numerous possible outcomes of high-energy proton–proton collisions. To achieve a detailed understanding of the Standard Model and any physics beyond it, a tremendous number of such Monte Carlo events needs to be simulated. But despite the best efforts by the community worldwide to optimise these simulations, the speed is still a factor of 100 short of the needs of the High-Luminosity LHC, which is scheduled to start taking data around 2026. If a machine-learning model could directly learn the properties of the reconstructed particles and bypass the complicated simulation process of the interactions between the particles and the material of the detectors, it could lead to simulations orders of magnitude faster than those currently available.

Competing networks

One idea for such a model relies on algorithms called generative adversarial networks (GANs). In these algorithms, two neural networks compete with each other for a particular goal, with one of them acting as an adversary that the other network is trying to fool. CERN's openlab and software for experiments group, along with others in the LHC community and industry partners, are starting to see the first results of using GANs for faster event and detector simulations.

Particle physics has come a long way from the heyday of manual scanners in understanding elementary particles and their interactions. But there are gaps in our understanding of the universe that need to be filled – the nature of dark matter, dark energy, matter–antimatter asymmetry, neutrinos and colour confinement, to name a few. High-energy physicists hope to find answers to these questions using the LHC and its upcoming upgrades, as well as future lepton colliders and neutrino experiments. In this endeavour, machine learning will most likely play a significant part in making data processing, data analysis and simulation, and many other tasks, more efficient.

Driven by the promise of great returns, big companies such as Google, Apple, Microsoft, IBM, Intel, Nvidia and Facebook are investing hundreds of millions of dollars in deep learning technology including dedicated software and hardware. As these technologies find their way into particle physics, together with high-performance computing, they will boost the performance of current machine-learning algorithms. Another way to increase the performance is through collaborative machine learning, which involves several machine-learning units operating in parallel. Quantum algorithms running on quantum computers might also bring orders-of-magnitude improvement in algorithm acceleration, and there are probably more advances in store that are difficult to predict today. The availability of more powerful computer systems together with deep learning will likely allow particle physicists to think bigger and perhaps come up with new types of searches for new physics or with ideas to automatically extract and learn physics from the data.

That said, machine learning in particle physics still faces several challenges. Some of the most significant include understanding how to treat systematic uncertainties while employing machine-learning models and interpreting what the models learn. Another challenge is how to make complex deep learning algorithms work in the tight time window of modern trigger systems, to take advantage of the deluge of data that is currently thrown away. These challenges aside, the progress we are seeing today in machine learning and in its application to particle physics is probably just the beginning of the revolution to come.

Résumé

L'apprentissage approfondi a le vent en poupe

Le mariage entre la physique des hautes énergies et l'informatique est l'un des plus fructueux de la science ; il permet à des scientifiques basés dans le monde entier d'accéder aux immenses volumes de données des expériences LHC et d'autres expériences, et de leur donner un sens. Le changement de paradigme qui a lieu actuellement dans l'informatique s'appuie sur l'intelligence artificielle : la « révolution de l'apprentissage approfondi », qui s'est amorcée à la fin des années 2000, transforme la manière dont les données sont traitées et analysées. Des techniques d'apprentissage approfondi sont utilisées aujourd'hui dans une multitude de domaines, allant de la sélection des événements à l'identification des particules et à la simulation d'événements. En plus d'accélérer les progrès de la discipline, l'apprentissage automatique permet des économies considérables en matière de ressources.

Sergei Gleyzer, University of Florida, **Federico Carminati**, CERN, **Sofia Vallecorsa**, Gangneung-Wonju National University, and **Denis Perret-Gallix**, LAPP/IN2P3/CNRS-KEK.

Faces & Places

APPOINTMENTS

Committee to find next ERC president

On 30 May, the European commissioner for research, science and innovation, Carlos Moedas, appointed seven experts, including CERN Director-General Fabiola Gianotti, to conduct a search for the next president of the European Research Council (ERC). Established in 2007, the ERC is the European Union's funding body for frontier research and offers a number of grants as part of the European Union framework programme for research and innovation.

The committee, chaired by former European commissioner and also former prime minister of Italy, Mario Monti (pictured), will make recommendations to the European Commission in time for the next ERC president to take up duties on 1 January 2020, as successor to the current president Jean-Pierre Bourguignon. About the appointed committee, Moedas said: "The ERC has become a powerhouse of science, and will be a key pillar in an even more ambitious research and innovation framework programme that will follow Horizon 2020. I am confident that Mr Monti and his distinguished group of people from European science and research can help us find the right person to lead the ERC to even greater success."

Wikimedia Commons

Mario Monti will chair the committee appointed to search for the next European Research Council president.

AWARDS

Hamburg Prize for Theoretical Physics goes to Ooguri

Hirosi Ooguri from the California Institute of Technology and the Aspen Center for Physics in the US, and the University of Tokyo in Japan, has been awarded the 2018 Hamburg Prize for Theoretical Physics. The prize is one of the most valuable science prizes in Germany, and is awarded by the Joachim Herz Foundation in partnership with the Wolfgang Pauli Centre of the University of Hamburg, DESY, and the Hamburg Centre for Ultrafast Imaging at the University of Hamburg. This year the prize covers all areas of theoretical physics (in previous years it was given to theorists in quantum information, quantum optics and quantum many-body systems), and, additionally, the prize money has been increased from €40,000 to €100,000.

Ooguri is recognised for his successful mathematical work on topological string theory, as well as for making his research more publicly available. The researcher is also the author of six books in Japanese, which have sold more than 300,000 copies and have been translated into Chinese and Korean. Ooguri's work and related science will be the subject of a three-day symposium that will take place in November at the University of Hamburg.

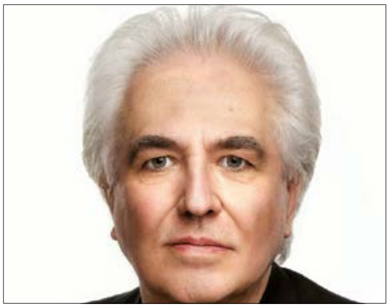
B Youngblood/Caltech

Ooguri will receive his award on 7 November at the Hamburg Planetarium.

James Pinfold wins a Killam Prize

James Pinfold from the University of Alberta, Canada, has received one of this year's Killam Prizes, in the natural-sciences category. The five awards, each worth C$100,000, are given by the Canada Council for the Arts and recognise the career achievements of eminent Canadian scholars and scientists actively engaged in research.

Pinfold, who completed his PhD at University College London in 1977, has held senior roles in particle-physics experiments, and was a founding member of the ATLAS experiment at CERN. He was also a leader in four major advances in particle physics, including the discovery of neutral currents, the first observation of charm particle production and the discovery of the Higgs boson. He now leads the MoEDAL experiment at the LHC, which is designed to search for highly ionising harbingers of new physics such as magnetic monopoles.



University of Alberta

Pinfold won his award in the natural-sciences category.

Hannah Petersen awarded Zimányi Medal

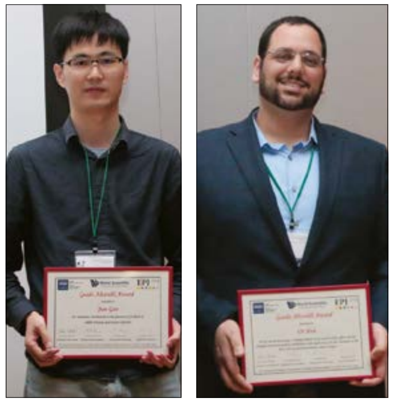
Hannah Petersen from Goethe University in Frankfurt, Germany, was awarded the Zimányi Medal at the 2018 Quark Matter conference in Venice, Italy. Created in memory of the nuclear physicist József Zimányi, the prize is awarded by the Wigner Research Center for Physics of the Hungarian Academy of Sciences in Budapest, and is given to theoretical physicists under the age of 40 who have achieved international recognition in the area of theoretical high-energy physics. Petersen is recognised for her pioneering development of an event-by-event hybrid description of high-energy heavy-ion collisions, which couples fluid dynamics in the quark–gluon plasma with hadron transport.

R Turrisi

Hannah Petersen with Tamás Sándor Bíró from the Zimányi Foundation during the award ceremony in Venice.

Guido Altarelli Award goes to Gao and Hen

The third Guido Altarelli Award was presented to two researchers during the 2018 international workshop on deep-inelastic scattering and related subjects (DIS18), which took place in Kobe, Japan, on 16–20 April. The award, which honours the memory of CERN theorist Guido Altarelli, recognises exceptional achievements from young scientists in the field of deep-inelastic scattering and related subjects. Jun Gao from Shanghai Jiao Tong University, China, is one of the main developers of the so-called CTEQ family of parton densities, and was recognised for his innovative contributions to precise QCD calculations. The other recipient, Or Hen from the Massachusetts Institute of Technology, US, received the award for his role in uncovering a striking relation between the nuclear "EMC effect" and nucleon–nucleon correlations, with implications for valence up- and down-quark distributions.


H Hiramoto

Jun Gao (left) and Or Hen (right) received their prizes at the DIS18 workshop.

High-energy physicists elected to Royal Society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CERN-201512-261-8
CERN-201611-285-3

From left to right, Jim Al-Khalili, Fabiola Gianotti and Guy Wilkinson.

Jim Al-Khalili, Fabiola Gianotti and Guy Wilkinson were among several physicists elected as 2018 Fellows and Foreign Members of the Royal Society. Gianotti, CERN Director-General, has worked on several CERN experiments, and was the spokesperson of the ATLAS experiment at the time of the discovery of the Higgs boson in 2012. She was included among *The Guardian* newspaper's "Top 100 most inspirational women" in 2011 and ranked fifth in *Time* magazine's Personality of the Year in 2012.

Guy Wilkinson, from the University of Oxford, studies CP violation and related open questions of the Standard Model through measurements of rare processes involving the decays of hadrons containing beauty or charm quarks. He was a founding member of the LHCb experiment and a spokesperson for the experiment between 2014 and 2017.

Jim Al-Khalili holds a joint chair in physics and in the public engagement in science at the University of Surrey, UK. His current interest is in the application of quantum mechanics in biology and, together with colleagues, has set up the world's first doctoral training centre in quantum biology at Surrey. He has also written 14 books, between them translated into 26 languages, is a regular presenter of TV science documentaries, and for the past seven years has hosted the weekly BBC Radio 4 programme, *The Life Scientific*.

Event

Laureates mark Standard Model anniversary

On June 1–4, several Nobel Prize winners in physics attended a symposium at Case Western Reserve University to mark 50 years of the Standard Model. The event included a free public lecture by 2004 laureate and co-inventor of QCD David Gross (pictured), and a concluding talk by 1979 laureate Steven Weinberg, whose 1967 paper "A Model of Leptons" established electroweak theory. Other contributors to the Standard Model attended the symposium, including 1984 laureate and former CERN Director-General Carlo Rubbia. Glenn Starkman of Case Western Reserve remarked: "It's a pretty amazing group of men and women who have contributed immeasurably to our understanding of the world."


R Wetzler/CWR

Nobel Prize laureate David Gross speaking at the symposium marking 50 years of the Standard Model.

Meetings

Neutrino physics shines bright in Heidelberg


R Harvey/Wikimedia Commons

Heidelberg was the setting for Neutrino 2018, the best attended edition in the series so far.

The 28th International Conference on Neutrino Physics and Astrophysics took place in Heidelberg, Germany, on 4–9 June. It was organised by the Max Planck Institute for Nuclear Physics and the Karlsruhe Institute of Technology. With 814 registrations, 400 posters and the presence of Nobel laureates, Art McDonald and Takaaki Kajita, it was the most attended of the series to date – showcasing many new results.

Several experiments presented their results for the first time at Neutrino 2018. T2K in Japan and NOvA in the US updated their results, strengthening their indication of leptonic CP violation and normal-neutrino mass ordering, and improving their precision in measuring the atmospheric oscillation parameters. Taken together with the Super-Kamiokande results of atmospheric neutrino oscillations, these experiments provide a 2σ indication of leptonic CP violation and a 3σ indication of normal mass ordering. In particular, NOvA presented the first 4σ evidence of $\bar{\nu}_\mu - \bar{\nu}_e$ transitions compatible with three-neutrino oscillations.

The next-generation long-baseline experiments DUNE and Hyper-Kamiokande in the US and Japan, respectively, were discussed in depth. These experiments have the capability to measure CP violation and mass ordering in the neutrino sector with a sensitivity of more than 5σ, with great potential in other searches like proton decay, supernovae, solar and atmospheric neutrinos, and indirect dark-matter searches.

All the reactor experiments – Daya Bay, Double Chooz and Reno – have improved their results, providing precision measurements of the oscillation parameter θ_{13} and of the reactor antineutrino spectrum. The Daya Bay experiment, integrating 1958 days of data taking, with more than four million antineutrino events on tape, is capable of measuring the reactor mixing angle and the effective mass splitting with a precision of 3.4% and 2.8%, respectively. The next-generation reactor experiment JUNO, aiming at taking data in 2021, was also presented.

The third day of the conference focused on neutrinoless double-beta decay (NDBD) experiments and neutrino telescopes. EXO, KamLAND-Zen, GERDA, Majorana Demonstrator, CUORE and SNO+ presented their latest NDBD search results, which probe whether neutrinos are Majorana particles, and their plans for the short-term future. The new GERDA results pushed their NDBD lifetime limit based on germanium detectors to 0.9×10^{26} years (90% CL), which represents the best real measurement towards a zero-background next-generation NDBD experiment. CUORE also updated its results based on tellurium to 0.15×10^{26} years.

Neutrino telescopes are of great interest for multi-messenger studies of astrophysical objects at high energies. Both IceCube in Antarctica and ANTARES in the Mediterranean were discussed, together with their follow-up IceCube Gen2 and KM3NeT facilities. IceCube has already collected 7.5 years of data, selecting 103 events (60 of which have an energy of more than 60 TeV) and a best-fit power law of $E^{-2.87}$. IceCube does not provide any evidence for neutrino point sources and the measured $\nu_e:\nu_\mu:\nu_\tau$ neutrino-flavour composition is 0.35:0.45:0.2. A recent development in neutrino physics has been the first observation of coherent elastic neutrino–nucleus scattering as discussed by the COHERENT experiment (*CERN Courier* October 2017 p8), which opens the possibility of searches for new physics.

A very welcome development at Neutrino 2018 was the presentation of preliminary results from the KATRIN collaboration about the tritium beta-decay end-point spectrum measurement, which allows a

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direct measurement of neutrino masses. The experiment has just been inaugurated at KIT in Germany and aims to start data taking in early 2019 with a sensitivity of about 0.24 eV after five years. The strategic importance of a laboratory measurement of neutrino masses cannot be overestimated.

A particularly lively session at this year's event was the one devoted to sterile-neutrino searches. Five short-baseline nuclear reactor experiments (DANSS, NEOS, STEREO, PROSPECT and SoLid) presented their latest results and plans regarding the so-called reactor antineutrino anomaly. These are experiments aimed at detecting the oscillation effects of sterile neutrinos at reactors free from any assumption about antineutrino fluxes. There was no reported evidence for sterile oscillations, with the exception of the DANSS experiment reporting a 2.8σ effect, which is not in good agreement with previous measurements of this anomaly. These experiments are only at the beginning of data taking and more refined results are expected in the near future, even though it is unlikely that any of them will be able to provide a final sterile-neutrino measurement with a sensitivity much greater than 3σ.

Further discussion was raised by the results reported by MiniBooNE at Fermilab, which reports a 4.8σ excess of electron-like events by combining their neutrino and antineutrino runs. The result is compatible with the 3.8σ excess reported by the LSND experiment about 20 years ago in an experiment taking data in a neutrino beam created by pion decays at rest at Los Alamos. Concerns are raised by the fact that even sterile-neutrino oscillations do not fit the data very well, while backgrounds potentially do (and the MicroBooNE experiment is taking data at Fermilab with the specific purpose of precisely measuring the MiniBooNE backgrounds). Furthermore, as discussed by Michele Maltoni in his talk about the global picture of sterile neutrinos, no sterile neutrino model can, at the same time, accommodate the presumed evidence of $\nu_\mu - \nu_e$ oscillations by MiniBooNE and the null results reported by several different experiments (among which is MiniBooNE itself) regarding ν_μ disappearance at the same Δm^2.

The lively sessions at Neutrino 2018, summarised in the final two beautiful talks by Francesco Vissani (theory) and Takaaki Kajita (experiment), reinforce the vitality of this field at this time (see p5).

- *Mauro Mezzetto, INFN University of Padova.*

LHCP reports from Bologna

R Serra/FotoBouque

The LHCP participants in the San Domenico Centre.

Some 450 researchers from around the world headed to historic Bologna, Italy, on 4–9 June to attend the sixth Large Hadron Collider Physics (LHCP) conference. The many talks demonstrated the breadth of the LHC physics programme, as the collider's experiments dig deep into the high-energy 13 TeV dataset and look ahead to opportunities following the high-luminosity LHC upgrade.

Both ATLAS and CMS have now detected the Higgs boson's direct Yukawa coupling to the top quark, following earlier analyses, and the results are in agreement with the prediction from the Standard Model (SM). Further results on Higgs interactions included the determination by ATLAS of the boson's coupling to the tau lepton with high significance, which agrees well with the previous observation by CMS. Measuring the coupling between the Higgs and the other SM particles is a key element of the LHC physics programme, with bottom quarks now in the collaborations' sights.

The Bologna event also saw news on the spectroscopy front. CMS reported that it has resolved, for the first time, the $J=1$ and $J=2$ states of the Xi$_b$(3P) particle, using 13 TeV data corresponding to an integrated luminosity of 80 fb^{-1}. The measured mass difference between the two states, 10.60 ± 0.64 (stat) ± 0.17 (syst) MeV, is consistent with most theoretical calculations (see p10). Meanwhile, the LHCb collaboration reported the measurement of the lifetime of the doubly charmed baryon Xi$_{cc}^{++}$ discovered by the collaboration last year, obtaining a value of $0.256^{+0.024}_{-0.022}$ (stat) ± 0.014 (syst) ps, which is within the predicted SM range (see p11).

The Cabibbo–Kobayashi–Maskawa (CKM) matrix, which quantifies the couplings between quarks of different flavours and possible charge-parity (CP) violation in the quark system, was another focus of the conference. LHCb presented a new measurement of the gamma angle, which is the least well measured of the three angles defining the CKM unitary triangle and is associated with the up–bottom quark matrix element. The collaboration obtained a value of 74° with an uncertainty of about 5°, making it the most precise measurement of gamma from a single experiment.

Nuclei–nuclei collisions also shone, with the ALICE collaboration showcasing measurements of the charged-particle multiplicity density, nuclear modification factor and anisotropic flow in Xe–Xe collisons at an energy of 5.44 TeV per nucleon (see p12). These and other nuclei–nuclei measurements are providing a deeper insight into extreme states of matter such as the quark–gluon plasma.

Searches for physics beyond the SM by the LHC experiments so far continue to come up empty-handed, slicing into the allowed parameter space of many theoretical models such as those involving dark matter. However, as was also emphasised at this years' LHCP, there are many possible models and the range of parameters they span is large, requiring researchers to deploy "full ingenuity" in searching for new physics.

These are just a few of the many highlights of this year's LHCP, which also included updates on the experiments' planned upgrades for the high-luminosity LHC and perspectives on physics opportunities at future colliders.

- *Ana Lopes, CERN.*

Heavy-flavour highlights from Beauty 2018

C Raso

The participants at Beauty 2018 in La Biodola.

The international conference devoted to B physics at frontier machines, Beauty 2018, was held in La Biodola, Isola d'Elba, Italy, from 6–11 May, organised by INFN Pisa. 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 17th in the series, attracted around 80 scientists from all over the world. The programme comprised 58 invited talks, of which 13 were theory-based.

Heavy-flavour decays, in particular those of hadrons that contain b quarks, offer powerful probes of physics beyond the Standard Model (SM). In recent years, several puzzling anomalies have emerged from LHCb and b-factory data (*CERN Courier* April 2018 p23), and discussion of these set the scene for a very inspiring atmosphere at the conference. In particular, the ratio of branching fractions $R_{D^{(*)}} = BR(B \rightarrow D^{(*)}\tau\nu)/BR(B \rightarrow D^{(*)}l\nu)$, where $l = \mu, e$, provide a test of lepton universality and, intriguingly, now give combined experimental values which are about 4σ away from the SM expectations. Furthermore, the ratios $R_K = BR(B^+ \rightarrow K^+\mu^+\mu^-)/BR(B^+ \rightarrow K^+e^+e^-)$ and the corresponding measurement, R_{K^*}, yield results that are each around 2.5σ away from unity. Other potential deviations from the SM are seen in the observable, P_5', of the angular distribution of decay products in the rare decay $B^0 \rightarrow K^*\mu^+\mu^-$, and also measurements in related decay channels. Hence, the release of new LHCb results from LHC Run 2 is eagerly awaited later this year.

The rare decay $B_s \rightarrow \mu^+\mu^-$, already observed at the 6σ level two years ago by a combined analysis of CMS and LHCb data, has now been observed by LHCb alone at a level greater than 5σ, and is consistent with the SM. The effective lifetime of the decay offers additional tests of new physics, and a first measurement has now been made: 2.04 ± 0.44 (stat) ± 0.05 (syst) ps – also consistent with the SM but with large uncertainties.

Theoretical overview talks put recent results such as those above in context. Regarding the flavour anomalies, models involving leptoquarks and new Z' bosons are currently receiving much attention. Impressive progress has also been made in lattice-QCD calculations and in our understanding of hadronic form factors, which are crucial as inputs for theoretical predictions. Continued interplay between theory and experiment will be essential to understand the emerging data from the LHC and also from the Belle-II experiment in Japan, which has recently started taking data *(CERN Courier* June 2018 p7).

Concerning CP violation in the b sector, LHCb reported a new world-best determination of the angle γ of the unitarity triangle from a combination of measurements: $74.0^{+5.0}_{-5.8}$ degrees, which differs from the prediction from other unitarity-triangle constraints by around 2σ. Regarding CP violation in $B_s^0 \rightarrow J/\psi\, \phi$ decays, which is predicted to be very small in the SM, the experimental knowledge from a combination of LHC experiments has now reached $\phi_s = 21 \pm 31$ mrad, which is compatible with the SM.

Presentations were also devoted to hadron spectroscopy and exotic states, where there has been huge interest since the recent discovery of pentaquark-like states by LHCb (*CERN Courier* April 207 p31). The udsb tetraquark candidate reported by the D0 experiment at Fermilab just over two years ago has not been confirmed in LHC data and, significantly, neither by its sister experiment CDF. A plethora of other new results were reported at Beauty 2018, including from LHCb: a doubly-charmed baryon, Ξ_{cc}^{++}, and a Ξ_b^{**-} state, as well as a spectroscopy "gold mine" of X, Y and Z states from BES-III in China. Kaon physics was also discussed. With the completion of 2016 data analysis, the NA62 experiment at CERN has reached SM-sensitivity for the ultra-rare $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay channel. A single candidate event was found with 0.15 background events expected, and a lower limit on the branching ratio of 14×10^{-10} at 95% confidence has been set.

The future experimental programme of flavour physics is full of promise. One of the highlights of the conference was a report on first data from Belle-II; further exciting options will emerge beyond 2021 when LHC Run 3 commences, with LHCb running at an increased luminosity of 2×10^{33} cm^{-2}s^{-1} with an improved trigger, and high-luminosity upgrades to ATLAS and CMS to follow. The scientific programme of Beauty 2018 was complemented by a variety of social events, which, coupled with the stimulating presentations, made the conference a huge success at this exciting time for B physics.

- *Robert Fleischer, Nikhef and Vrije Universiteit Amsterdam; Neville Harnew and Guy Wilkinson, University of Oxford; and Giovanni Punzi, University and INFN Pisa.*

LETTER

Chalk River operations

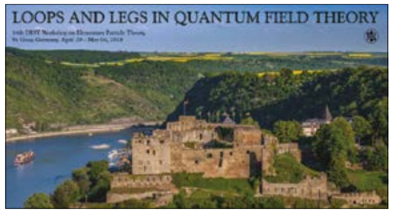
Your article "Tales from TRIUMF" (*CERN Courier* May 2018 p31), mentions, in paragraph 19, "…the shutdown of the Chalk River reactor facility."

The National Research Universal (NRU) reactor was indeed shutdown for the last time on 31 March this year. However, the NRU facility is but one of many facilities (nuclear and non-nuclear) at the Canadian Nuclear Laboratories Chalk River campus, which will continue to operate without NRU. I'm afraid the wording in the article implies that Chalk River, which is a known reactor laboratory/site, is closing or ceasing research operations entirely. This is definitely not the case.

- *Andrew Erlandson, Canadian Nuclear Laboratories.*

MEETINGS

Loops and legs in quantum field theory



The meeting poster.

H Klaes

The international conference Loops and Legs in Quantum Field Theory 2018 took place from 29 April to 4 May near Rheinfels Castle in St Goar, Rhine, Germany. The conference brought together more than 100 researchers from 18 countries to discuss the latest results in precision calculations for particle physics at colliders and associated mathematical, computer-algebraic and numerical calculation technologies. It was the 14th conference in the series, with 87 talks delivered.

Organised biennially by the theory group of DESY at Zeuthen, the locations for Loops and Legs are usually remote parts of the German countryside to provide a quiet atmosphere and room for intense scientific discussions. The first conference took place in 1992, just as the HERA collider started up, and the next event, close to the start of LEP2 in 1994, concentrated on precision physics at e^+e^- colliders. Since 1996, general precision calculations for physics at high-energy colliders form its focus.

This year, the topics covered new results on: the physics of jets; hadronic Higgs-boson and top-quark production; multi-gluon amplitudes; multi-leg two-loop QCD corrections; electroweak corrections at hadron colliders; the Z resonance in e^+e^- scattering; soft resummation, $e^+e^- \rightarrow t\bar{t}$; precision determinations of parton distribution functions; the heavy quark masses and the fundamental coupling constants; g-2; and NNLO and N^{3}LO QCD corrections for various hard processes.

On the technologies side, analytic multi-summation methods, Mellin–Barnes techniques, the solution of large systems of ordinary differential equations and large-scale computer algebra methods were discussed, as well as unitarity methods, cut-methods in integrating Feynman integrals, and new developments in the field of elliptic integral solutions. These techniques finally allow analytic and numeric calculations of the scattering cross-sections for the key processes measured at the LHC.

All of these results are indispensable to make the LHC, in its high-luminosity phase, a real success and to help hunt down signs of physics beyond the Standard Model (*CERN Courier* April 2017 p18). The calculations need to match the experimental precision in measuring the couplings and masses, in particular for the top-quark and the Higgs sector, and an even more precise understanding of the strong interactions.

Since the first event, when the most advanced results were single-scale two-loop corrections in QCD, the field has taken a breath-taking leap to inclusive five-loop results – like the β functions of the Standard Model, which control the running of the coupling constant to high precision – to mention only one example. In general, the various subfields of this discipline witness a significant advance every two years or so. Many promising young physicists and mathematicians participate and present results. The field became interdisciplinary very rapidly because of the technologies needed, and now attracts many scientists from computing and mathematics.

The theoretical problems, on the other hand, also trigger new research, for example in algebraic geometry, number theory and combinatorics. This will be the case even more with future projects, like an ILC, and planned machines such as the FCC, which needs even higher precision. The next conference will be held at the beginning of May 2020.

- *Johannes Bluemlein, Peter Marquard and Tord Riemann, DESY.*

KEK hosts hadron-therapy symposium

Participants at the event in Japan.

KEK

The first International Symposium on the Next Generation of Hadron Therapy and its Drivers was held in Tsukuba, Japan, on 13–15 March. Around 40 participants from research institutes, universities and the private sector in Japan, Europe, India, Taiwan and Indonesia, attended. Leading companies in this field, such as Hitachi, Toshiba and Sumitomo Heavy Industries, presented details of their synchrotron- or cyclotron-based cancer-therapy systems, and introduced their own original irradiation methods, including spot-scanning techniques. The symposium was organised by the KEK Accelerator Laboratory and University of Tsukuba Proton Beam Therapy Center, and was sponsored by Tsukuba Innovation Arena.

To mention a few of the systems presented, the National Centre of Oncological Hadron Therapy in Pavia, Italy and the Gunma University Heavy-Ion Medical Center in Maebashi, Japan, both reported progress achieved with their carbon-based therapy systems. Comparing these two therapy systems offers interesting insights. Meanwhile, the National Institute of Radiological Sciences in Chiba, Japan, described the long-anticipated compact superconducting gantry for its carbon-therapy system and its ^{11}C ion source, which allows direct beam irradiation for PET imaging as well as cancer treatment.

The conference saw three systems presented to meet the demands of next-generation hadron-therapy systems, such as freedom in beam handling, different beam species and low cost. LIGHT, which was developed by the CERN spin-off ADAM, was also discussed. The first model of LIGHT, a linac-based hadron-therapy system that operates at 100 Hz with an energy sweep, is going to be installed at Harley Street, London. The present status of the Ion Rapid Cycling Medical Synchrotron (iRCMS), which was developed by a collaboration between BNL and Best Medical (Springfield, VA), was presented. The Energy Sweep Compact Rapid Cycling Therapy (ESCORT) proposed by a collaboration between KEK, SAMEER in India, and Nuclear Malaysia was also discussed.

These are just a few highlights of the event, which also saw presentations of therapy involving multi-beam irradiation and full-body PET cameras, which would be essential for monitoring tumour shape and position and dose image in real time.

- *Ken Takayama, KEK.*

OBITUARIES

Alberto Benvenuti 1940–2018

Alberto Benvenuti was a key figure in the construction of the CMS muon system.

J P Palayo

It was with great sadness that we learnt that Alberto Benvenuti, who was one of the main contributors to the construction of the CMS muon system, passed away in April.

Alberto graduated from the University of Florence, Italy, in 1964 and then moved to the US, where he did his PhD at the University of Minnesota. It was there that he met and married his lifelong companion, Rita. In 1969, he moved to the University of Wisconsin and joined the E1A experiment at Fermilab to measure high-energy neutrino–antineutrino interactions. Key results from the experiment were the first evidence for weak neutral currents and the observation of final states with multiple muons.

In 1978, Alberto moved to CERN and joined the NA4 experiment at the Super Proton Synchrotron (SPS) as a research staff member. At CERN, his principle contributions were: the measurement of the F2 structure function of the proton and its evolution – a key result still used in many global fits today; finding evidence for interference between photons and Z bosons in mu+ and mu– deep-inelastic interactions; and the study of nuclear effects in different target materials.

After three years as a CERN staff member, he became a researcher at INFN Bologna, but also continued his work at CERN. In 1985 he joined the SLD collaboration at SLAC National Accelerator Laboratory in the US and worked on the construction, commissioning and operation of the SLD muon detector.

Returning to CERN in 1991, Alberto joined the DELPHI collaboration at the LEP collider, contributing to the design and construction of DELPHI's second-generation luminosity monitor and to Bhabha-scattering studies. He joined the CMS collaboration at the LHC in 1992, and became one of the key figures in the development of the drift-tube chambers for the CMS detector. He guided the production of the 250 chambers in Russia and Bologna, coordinated their testing at CERN before installation, and led their installation and commissioning. The chambers were one of the main components of the CMS detector, playing a key role in the discovery of the Higgs boson. After his retirement in 2015 to Minneapolis, Albert continued to participate actively in the life of CMS, advising students at the University of Minnesota and serving as co-chair of the annual detector review of CMS's replacement calorimeter for the high-luminosity LHC upgrade.

All through his career, in both analysis and hardware, Alberto made experiments work often with innovative solutions. He was admired by his colleagues for his sense of purpose, his honesty and his humour. He was a great example to those who worked with him, passing on skills learnt over a long career to the next generation of young physicists. He was always striving for excellence and had little tolerance for mistakes. He would say "do it with passion or don't do it at all…" Upon news of his passing, there was an outpouring of memories and thoughts of gratitude from many of his colleagues, from CMS and from around the world. He leaves behind his wife Rita and a little bit of himself in each one of us.

- *His friends and colleagues.*

Ishfaq Ahmad 1930–2018

Ishfaq Ahmad brought Pakistan and CERN together.

The architect of Pakistan–CERN collaboration and former chairman of the Pakistan Atomic Energy Commission (PAEC), Ishfaq Ahmad, passed away on 15 January in Islamabad aged 87. He remained associated with PAEC for more than 40 years. After joining the organisation in 1960 on completion of his PhD at the University of Montreal in Canada, and post-doc positions at University of Ottawa and Sorbonne (Université de Paris), he played a crucial role in the development of civil and military nuclear technology in Pakistan.

Ishfaq's doctoral work was based on the use of fine-grained nuclear emulsions, pioneered by his thesis supervisor, Pierre Demers. He also worked at the Niels Bohr Institute in Copenhagen between 1961 and 1962, where he had opportunities to interact with Bohr himself. It was during his stay there that his experimental work on nuclear reactions brought him to CERN, where nuclear emulsions were exposed for subsequent analyses at different laboratories. Years later, he recalled that his fascination with CERN and the work being done there never faded, resulting in the establishment of close ties between CERN and PAEC.

The first formal scientific and technical agreement between CERN and Pakistan, which formed the basis of future Pakistan–CERN cooperation, was signed on 11 January 1994 by Ishfaq on behalf of Pakistan and the then CERN Director-General Chris Llewellyn-Smith, on behalf of CERN. Thereafter, a series of protocols, addendums and extensions of protocols, MoUs and Letters-of-Intent were signed by CERN DGs and PAEC chairmen, many concerning specific projects related to the construction of the Large Hadron Collider and components of the CMS and ATLAS detectors. The most conspicuous of these projects was the supply of eight steel supports for the CMS yoke, which were fabricated in PAEC laboratories in Islamabad. Concurrently, the participation of the National Centre for Physics (NCP) in the CMS collaboration resulted in scientific exchanges and data simulations. A node for grid computing was also established at NCP. Another institution in Pakistan that joined the CERN collaboration was the COMSATS Institute of Information Technology, which was granted membership of the ALICE collaboration. Eventually, Pakistan gained Associate Membership of CERN on 31 July 2015.

While overseeing the increasingly deeper ties between Pakistan and CERN, Ishfaq remained actively engaged with other international fora, such as the International Atomic Energy Agency (IAEA), the International Centre for Theoretical Physics (ICTP) and the International Institute for Applied Systems Analysis (IIASA). As member of the board of governors of IAEA, he was able to convince the then director-general of IAEA, Hans Blix, to establish an advisory group that strengthened the agency's role as a facilitator of civilian nuclear technology through improved technical cooperation programmes, especially for developing countries.

His avid support for ICTP was also based on his strong belief in science as a vehicle of peace and development. It is not surprising that he was the one who wrote to the then UN secretary-general Ban Ki Moon to launch World Science Day for Peace and Development, which was duly approved by the Security Council and has been organised internationally by UNESCO since 2001. He regularly participated in PUGWASH meetings following the 1974 Indian nuclear tests and strongly advocated for a nuclear-free South Asia. He was a strong supporter of nuclear power as a significant component of the energy mix in Pakistan, but kept open mind about alternative energy sources. He lobbied and successfully achieved Pakistan's membership of IIASA, and remained on its board from 2007 to 2012. His broader vision of national economic interests led to the creation of institutions such as the Global Climate Change Impact Study Centre and the Centre for Earthquake Studies in Pakistan.

In 1998 the government of Pakistan bestowed upon Ishfaq the highest civil award, "Nishan-i-Imtiaz", besides several other honours and awards in preceding years, and entrusted him with prestigious positions such as advisor to the prime minister of Pakistan and other senior roles. He held government posts until 2012, when he decided to restrict his activities to the work of NCP as the chairman of its board of governors. He was buried with state honours in Islamabad on 16 January.

- *Imtinan Qureshi, Islamabad.*

Bookshelf

Compiled by Virginia Greco, CERN

Welcome to the Universe

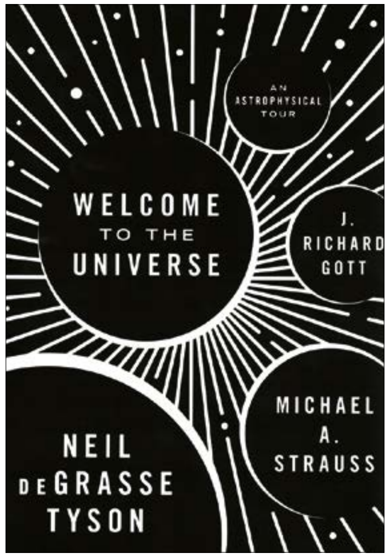
by Neil deGrasse Tyson, Michael A Strauss and J Richard Gott

Princeton University Press

It is commonly believed that popular-science books should abstain as much as possible from using equations, apart from the most iconic ones, such as $E=mc^2$. The three authors of *Welcome to the Universe* boldly defy this stereotype in a book that is intended to guide readers with no previous scientific education from the very basics (the first chapters explain the scientific notation, how to round-up numbers and some trigonometry) to cutting-edge research in astrophysics and cosmology.

This book reflects the content of a course that the authors gave for a decade to non-science majors at Princeton University. They are a small dream team of teachers and authors: Tyson is a star of astrophysics outreach, Strauss a renowned observational astronomer and Gott a theoretical cosmologist with other successful popular-science books to his name. The authors split the content of the book into three equal parts (stars and planets, galaxies, relativity and cosmology), making no attempt at stylistic uniformity. Apparently this was the intention, as they keep their distinct voices and refer frequently to their own research experiences to engage the reader. Despite this, the logical flow remains coherent, with a smooth progression in complexity.

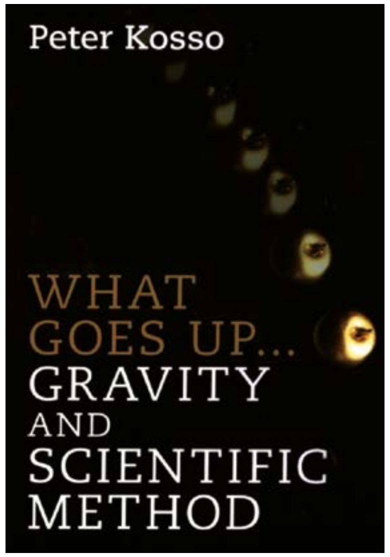
Welcome to the Universe promises and delivers a lot. Non-scientist readers will get a rare opportunity to be taken from a basic understanding of the subject to highly advanced content, not only giving them the "wow factor" (although the authors do appeal to this a lot) but also approaching the same level of depth as a masters course in physics. A representative example is the lengthy derivation of $E=mc^2$, the popular formula that everyone is familiar with but few know how to explain. And while that particular example is probably demanding to the layperson, most chapters are very pleasant to read, with a good balance of narration and analysis. The authors also make a point of explaining why recognised geniuses such as Einstein and Hawking got their fame in the first place. Scientifically-educated readers will find many insights in this volume too.



While I generally praise this book, it does have a few weak points. Some of the explanations are non-rigorous and confusing at the same time (an example of this is the sentence: "the formula has a constant h that quantises energy"). In addition, an entire chapter boasts of the role of one of the authors in the debate on whether Pluto has the status of a planet or not, which I found a bit out of place. But these issues are more irritating than harmful, and overall this book achieves an excellent balance between clarity and accuracy. The authors introduce several original analogies and provide an excellent non-technical explanation of the counterintuitive behaviour of the outer parts of a dying star, which expand while the inner parts contract.

I also appreciated the general emphasis on how measurements are done in practice, including an interesting digression on how Cavendish measured Newton's constant more than two centuries ago. However, there are places where one feels the absence of such an explanation, for example, the practical limitations of measuring the temperatures of distant bodies are glossed over with a somewhat patronising "all kinds of technical reasons".

This text comes with a problem book that is a real treasure trove. The exercises proposed are very diverse, reflecting the variety of audiences that the authors clearly target with their book. Some are meant to practice basic competences about units, orders of magnitude and rounding. Others demand readers to think outside of the box (e.g. by playing with geodesics in flatland, we see how to construct an object that is larger inside than outside, and have to estimate its mass using only trigonometry). For some of the quantitative exercises, the solution is provided twice: once in a lengthy way and then in a clever way. People more versed in literature than mathematics will find an exercise that demands you write a scientifically accurate, short science-fiction story (guidelines for grading are offered to the teachers) and one that simply asks, "If you could travel in time, which epoch would you visit and why?"



The book ends with a long and inspiring digression on the role of humans in the universe, and Gott's suggestion of using the Copernican principle to predict the longevity of civilisations – and of pretty much everything – is definitely food for thought.

- *Andrea Giammanco, UCLouvain, Louvain-la-Neuve, Belgium*

What goes up… Gravity and Scientific Method

By Peter Kosso

Cambridge University Press

Peter Kosso states that his book is "about the science of gravity and the scientific method"; I would say that it is about how scientific knowledge develops over time, using the historical evolution of our understanding of gravity as a guiding thread. The author has been a professor of philosophy and physics, with expert knowledge on how the scientific method works, and this book was born out of his classes. The topic is presented in a clear way, with certain subjects explored more than once as if to ensure that the student gets the point. The text was probably repeatedly revised to remove any wrinkles in its surface and provide smooth reading, setting out a few basic concepts along the way. The downside of this "textbook style" is that it is unexpectedly dry for a book aimed at a broad audience.

As the author explains, a scientific observation must refer to formal terms with universally-agreed meaning, ideally quantifiable in a precise and systematic way, to facilitate the testing of hypotheses. Thinking in the context of a certain theory will specify the important questions and guide the collection of data, while irrelevant factors are to be ignored (Newton's famous apple could just as well have been an orange, for example). But theoretical guidance comes with the risk that the answers might too easily conform to the expectation and, indeed, the nontrivial give-and-take between theory and observation is a critical part of scientific practice. In particular, the author insists that it is naïve to think that a theory is abandoned or significantly revised as soon as an experimental observation disagrees with the corresponding prediction.

Considering that the scientific method is the central topic of this book, it is surprising to notice that no reference is made to Karl Popper and many other relevant thinkers; this absence is even more remarkable since, on the contrary, Thomas Kuhn is mentioned a few times. One might expect such a book to reflect a basic enlightenment principle more faithfully: the price of acquiring knowledge is that it will be distorted by the conditions of its acquisition, so that keeping a critical mind is a mandatory part of the learning process. For instance, when the reader is told that the advancement of science benefits from the authority of established science (the structural adhesive of Kuhn's paradigm), it would have been appropriate to also mention the "genetic fallacy" committed when we infer the validity and credibility of an idea from our knowledge of its source. The author could then have pointed the interested reader to suitable literature, one option (among many) being *Kuhn vs. Popper; the struggle for the soul of science* by Steve Fuller.

What goes up… is certainly an excellent guide to the science of gravity and its historical evolution, from the standpoint of a 21st-century expert. It is interesting, for instance, to compare the "theories of principle" of Aristotle and Einstein with the "constructive theory" of Newton. While Newton started from a wealth of observations and looked for a universal description, unifying the falling apple with the orbiting Moon, Einstein gave more importance to the beauty of the concepts at the heart of relativity than to its empirical success. I enjoyed reading about the discovery of Neptune from the comparison between the precise observations of the orbit of Uranus and the Newtonian prediction, and about the corresponding (unsuccessful) search for the planet Vulcan, supposedly responsible for Mercury's anomalous orbit until general relativity provided the correct explanation. And it is fascinating to read about the "direct observation" of dark matter in the context of the searches for Neptune and Vulcan.

I enjoyed reading about the search for the planet Vulcan, supposedly responsible for Mercury's anomalous orbit.

It is important (but surely not easy) to ensure "that a theory is accurate in the conditions for which it is being used to interpret the evidence", and that it is "both well-tested and independent of any hypothesis for which the observations are used as evidence".

The text is well written and accessible. My teenage children learned about non-Euclidean geometry from figures in the book and were intrigued by the thought that gravity is not a force field but rather a metric field, which determines the straightest possible lines (geodesics) between two points in space–time. I think, however, that progress in humankind's understanding of gravity and related topics could be narrated in a more captivating way. People who prefer more vivid and passionate accounts of the lives and achievements of Copernicus, Brahe, Kepler, Galileo, Newton and many others would more likely enjoy *The Sleepwalkers* by Arthur Koestler or *From the Closed World to the Infinite Universe* by Alexandre Koyré. I also vehemently recommend chapter one of *Only the Longest Threads* by Tasneem Zehra Husain, a delightful account of Newton's breakthrough from the perspective of someone living in the early 18th century.

● *Carlos Lourenço, CERN*

Books received

Gravitational Lensing

By Scott Dodelson

Cambridge University Press

Based on university lectures given by the author, this book provides an overview of gravitational lensing, which has emerged as a powerful tool in astronomy with numerous applications, ranging from the quest for extrasolar planets to the study of the cosmic mass distribution.

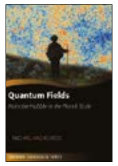
Gravitational lensing is a consequence of general relativity (GR): the gravitational field of a massive object causes light rays passing close to it to bend and refocus somewhere else. As a consequence, any treatment of this topic has to make reference to GR theory; nevertheless, as the author highlights, not much formalism is required to learn how to apply lensing to specific problems. Thus, using very little GR and not too complex mathematics, this text presents the basics of gravitational lensing, focusing on the equations needed to understand the phenomenon. It then dives into a number of applications, including multiple images, time delays, exoplanets, microlensing, cluster masses, galaxy shape measurements, cosmic shear and lensing of the cosmic microwave background.

Written with a pedagogical approach, this book is meant as a textbook for one-semester undergraduate or graduate courses. But it can also be used for independent study by researchers interested in entering this fascinating and fast-evolving field.

Quantum Fields: From the Hubble to the Planck Scale

By Michael Kachelriess

Oxford University Press



This book treats two fields of physics that are usually taught separately – quantum field theory (QFT) on one side and cosmology and gravitation on the other – in a more unified manner. Kachelriess uses this unusual approach because he is convinced that, besides studying a subject in depth, what is often difficult is to put the pieces into a general picture. Thus, he makes an effort to introduce QFT together with its most important applications to cosmology and astroparticle physics in a coherent framework.

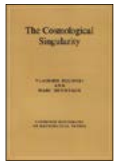
The path-integral approach is employed from the start and the use of tools such as Green's functions in quantum mechanics and in scalar field-theory is illustrated. Massless spin-1 and spin-2 fields are introduced on an equal footing, and gravity is presented as a gauge theory in analogy with the Yang–Mills case. The book also deals with various concepts relevant to modern research, such as helicity methods and effective theories, as well as applications to advanced research topics.

This volume can serve as a textbook for courses in QFT, astroparticle physics and cosmology, and students interested in working at the interface between these fields can certainly appreciate the uncommon approach used. It was also the intention of the author to make the book suitable for self study, so all explanations and derivations are given in detail. Nevertheless, a solid knowledge of calculus, classical and quantum mechanics, electrodynamics and special relativity is required.

The Cosmological Singularity

By Vladimir Belinski and Marc Henneaux

Cambridge University Press



This monograph discusses at length the structure of the general solution of the Einstein equations with a cosmological singularity in Einstein-matter systems in four and higher space–time dimensions, starting from the fundamental work of Belinski (the book's lead author), Khalatnikov and Lifshitz (BKL) – published in 1969.

The text is organised in two parts. The first, comprising chapters one to four, is dedicated to an exhaustive presentation of the BKL analysis. The authors begin deriving the oscillatory, chaotic behaviour of the general solution for pure Einstein gravity in four space–time dimensions by following the original approach of BKL. In chapters two and three, homogeneous cosmological models and the nature of the chaotic behaviour near the cosmological singularity are discussed. In these three chapters, the properties of the general solution of the Einstein equation are studied in the case of empty space in four space–time dimensions. The fourth chapter instead deals with different systems: perfect fluids in four space–time dimensions; gauge fields of the Yang–Mills and electromagnetic types and scalar fields, also in four space–time dimensions; and pure gravity in higher dimensions.

The second part of the book (chapters five to seven) is devoted to a model in which the chaotic oscillations discovered by BKL can be described in terms of a "cosmological billiard" system. In chapter five, the billiard description is provided for pure Einstein gravity in four dimensions, without any simplifying symmetry assumption, while the following chapter extends this analysis to arbitrary higher space–time dimensions and to general systems containing gravity coupled to matter fields. Finally, chapter seven covers the intriguing connection between the BKL asymptotic regime and Coxeter groups of reflections in hyperbolic space. Four appendices complete the treatment.

Quite technical and advanced, this book is meant for theoretical and mathematical physicists working on general relativity, supergravity and cosmology.

Recruitment

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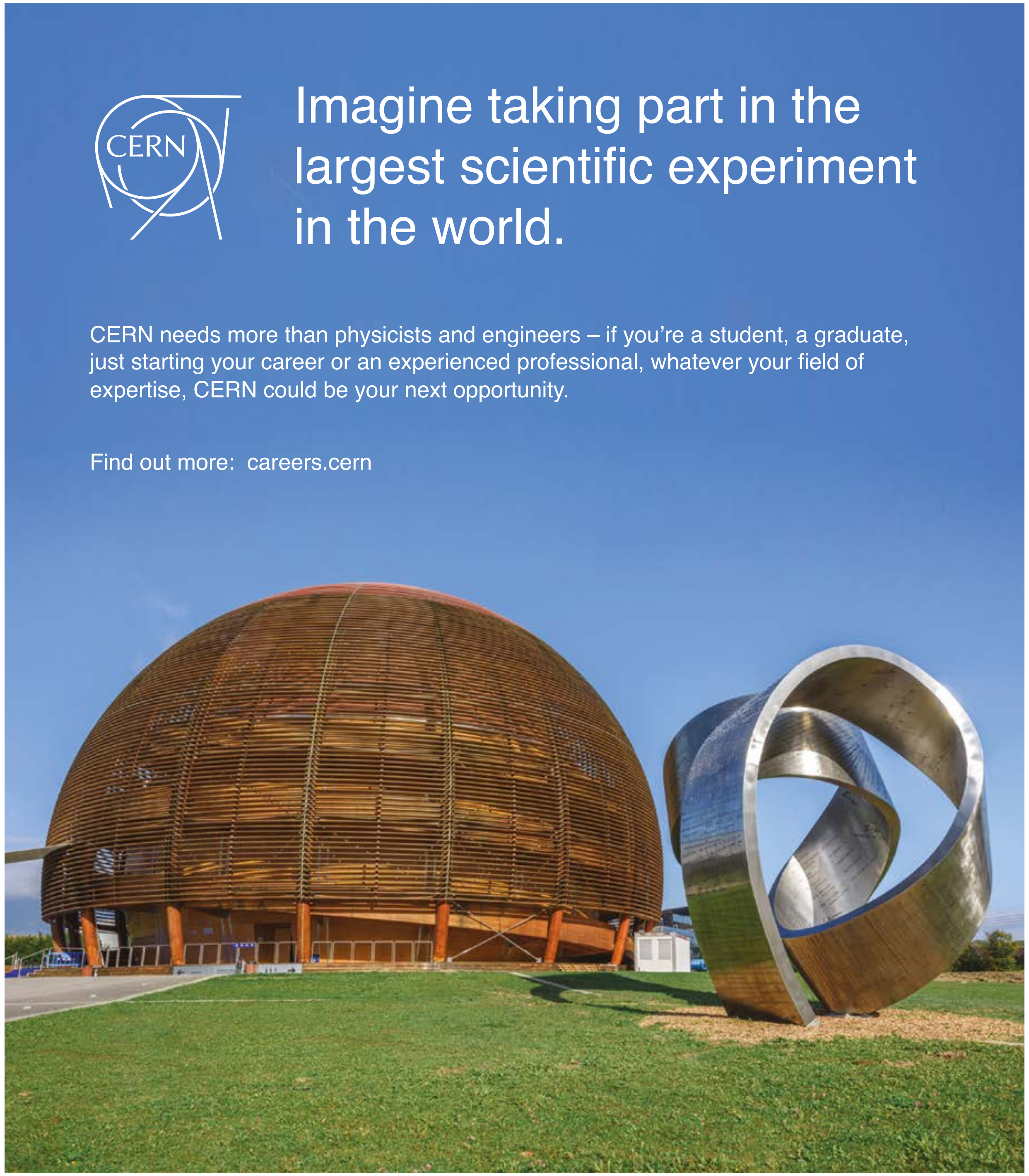

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- Develop research program closely linked to the major research themes of the center, namely, photonics (including integrated/quantum optics, ultrafast photonics and laser-matter interaction), materials for specific applications and sustainable energy systems. The candidate's research plan should be at the forefront of advanced materials, nanotechnology, photonics or electrochemical devices for energy conversion and storage, ideally linking conceptually at least two of these sectors. The ability for the candidate to integrate his/her research program with these research themes is an important element in the evaluation.
- Secure external funding from a variety of funding agencies, both provincial and federal, also involving various partners from the public and private sectors whenever needed/pertinent.
- Participate in teaching and training at the graduate level (both M.Sc. and Ph.D. students), as well as supervising post-doctoral fellows and research personnel.

REQUIREMENTS

- Doctorate in theoretical physics, chemistry, materials science or related fields;
- Relevant postdoctoral research experience would be an asset;
- Strong scientific publishing record illustrating leadership and innovation;
- Ability to work in multidisciplinary teams and networks as well as in collaboration with representatives of various agencies;
- Aptitude for basic and applied research, as well as multidisciplinary teaching and mentoring at the masters and doctorate levels;
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WORKING LANGUAGE

- French is the working language of the Institute. Fluency in English is required.

Candidates whose native language is not French are encouraged to apply. The Centre will provide them with all the resources necessary to facilitate their learning of the French language.

WORKPLACE

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Centre Énergie Matériaux Télécommunications
1650, boulevard Lionel-Boulet, Varennes (Québec) J3X 1S2 CANADA
Varennes is located on the South Shore of Montreal.

SALARY

In accordance with the collective agreement in effect at INRS.

HOW TO APPLY

Interested applicants should send their application including a complete curriculum vitæ, a copy of their three most significant publications, a two to three page summary of their research interests, a statement of teaching experience and philosophy, and the names and contact information of three referees, before **September 1st, 2018** indicating the position number AP 18-04 to:

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

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

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eli | beamlines

Institute of Physics ASCR, v. v. i., Na Slovance 2, 182 21 Praha 8
info@eli-beams.eu | www.eli-beams.eu

ELI- Beamlines (Extreme Light Infrastructure) will be the home of the world's highest energy femtosecond laser (1.5 kJ, 150 fs) and the highest repetition rate (1 PW, 10 Hz, 30fs) Petawatt laser facility. The beam transport system which connects the high power Femtosecond lasers with the experimental areas is currently designed and built in Dolní Břežany (on the southern border of Prague).

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The position requires the capability of interfacing with an international team of engineers, technicians and target scientists through all the stages of the development, production and installation.

Requirements:

- University degree in technical field or natural sciences (laser or optics preferable) followed by desirable five years of progressive work experience in job
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- Experience to work in an international multidisciplinary and multicultural team is a significant plus
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I agree that, according to the decree 101/2000 coll. (Czech Republic), my personal details sent to FZU AV CR, v. v .i., Na Slovance 2, 18221 Praha 8, Czech Republic can be used for the purpose of obtaining employment and management of database of employment candidates. This permission is given for the period of one year and can be at any time withdrawn by giving a notice in writing.

TEST BEAM.

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DESY
DESY is one of the world's leading research centres for photon science, particle and astroparticle physics as well as accelerator physics.

DESY operates the DESY II Test Beam Facility (testbeam.desy.de) to provide electron beams for detector tests for a growing international user community. In the next three years, it is foreseen to further improve and extend the facility. In the upcoming years, DESY will host the international Beam Line for Schools competition organized by CERN, which allows high school students to conduct experiments at one of the beam lines.

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- Support and extend the DESY II Test Beam Facility including user support, maintenance and improvements of the beam line instrumentation
- Participate in additional outreach activities at DESY and at the DESY II Test Beam Facility in particular

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For further information please contact Marcel Stanitzki (marcel.stanitzki@desy.de).

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CERN Courier Archive: 1975

A look back to CERN Courier vol. 15, July/August 1975, compiled by Peggie Rimmer

CERN NEWS

Extended collaboration with Soviet scientists

CERN 124.7.75

Signature of the Protocol between CERN and high-energy physics centres in the Soviet Union. On the left Deputy Chairman I G Morozov signs for the USSR State Committee for the Utilization of Atomic Energy. On the right Director General W K Jentschke signs for CERN.

On 10 July a Protocol was signed by Director General W K Jentschke, representing CERN, and Deputy Chairman I G Morozov, representing the USSR State Committee for the Utilization of Atomic Energy, extending the collaboration already existing between CERN and high-energy physics centres in the Soviet Union. The Protocol opens up, for Soviet scientists, access to the CERN Intersecting Storage Rings and the 400 GeV proton synchrotron. It is a further stage of the collaboration that gives Western European scientists access to the 76 GeV proton synchrotron at Serpukhov, for several years the highest energy accelerator in the world.

The Protocol has now become the formal mechanism of co-operation between CERN and the Institutes of the State Committee and Academy of Sciences – such as Serpukhov, Yerevan, Gatchina, Novosibirsk and ITEP Moscow. Relations with the international Laboratory at Dubna will continue under a separate system, as in the past.

- Compiled from text on p220.

PEOPLE

CERN 50.7.75

On 30 June Ch Peyrou received yet another tribute to his achievements during his years as head of track chambers at CERN. The photograph shows D C Colley, Chairman of the Track Chamber Committee, presenting Professor Peyrou with a first edition copy of the collected works of the 18th century physicist J Bernoulli.

CERN 346.6.75

On 27 June Dr H Firnberg, the Austrian Minister of Science and Technology, visited CERN. She is pictured here in conversation with W Schnell, Director of the ISR Department, during a tour of the Intersecting Storage Rings.

- Compiled from text on p221.

Inauguration of the SC II machine

CERN 13.7.75

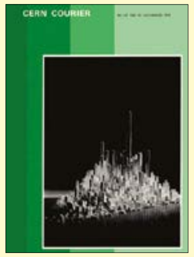
Dr E G Michaelis, head of the Synchrocyclotron Division (second from left), escorts distinguished attendees at the inauguration of SC II on a tour of the improved machine.

On 1 July, the improved 600 MeV synchrocyclotron was officially inaugurated. The Director General of CERN Laboratory I, Professor W K Jentschke, gave the Inaugural Address, E G Michaelis, Head of the SC Division, described the improvement programme and Sir Denys Wilkinson spoke about the physics the machine can now tackle.

The accelerator has been modified so that its internal beam current can increase from 1.3 to 10 μA and its ejection efficiency from 1% to 70%. This has involved the installation of a new type of ion source, a rotating condenser in the r.f. accelerating system, a magnetic beam extraction channel and a variety of other modifications needed to cope with higher intensities. With a performance at these levels, the CERN synchrocyclotron provides facilities competitive with the new meson factories at LAMPF, SIN and TRIUMF.

- Compiled from text on p222.

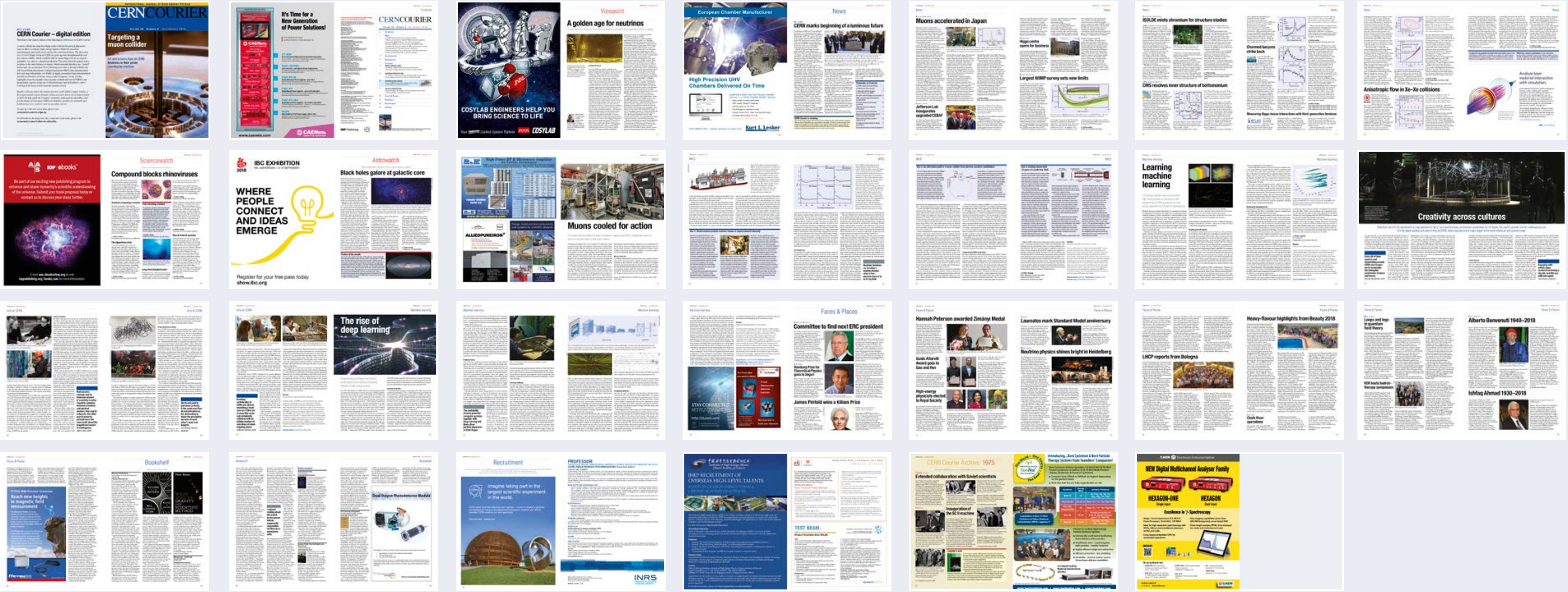
Compiler's note



In 1971 a quasi-separate CERN Laboratory II had been set up to build the Super Proton Synchrotron (SPS), coupled to machines in the existing laboratory. By 1975 the SPS was nearing completion and in June the CERN Council voted for a major reorganisation.

In 1976 the two laboratories were united under two Directors-General (DG), with L van Hove as research DG and J B Adams as executive DG. Laboratory II became the SPS Division and in ex-Laboratory I, the Synchrocyclotron Division [leader Ernst Michaelis, image above] was amalgamated with the Proton Synchrotron Division.

With the increasing overlap of experimental approaches using electronic techniques and bubble chambers, the Nuclear Physics Division and Track Chambers Division [leader Charles Peyrou, image above] were regrouped into an Experimental Physics Division, housing the experimental research physicists, and an Experimental Physics Facilities Division, housing staff working on large shared facilities such as bubble chambers and spectrometers.



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