WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the July/August 2021 issue of *CERN Courier*.

Since the early 1980s, successive generations of silicon trackers have driven numerous discoveries (p39). The LHC detectors represent the state of the art in particle-tracking applications, delivering high-granularity data at speed under the most extreme operating conditions imaginable. Containing some 12.5 Gpixels, the recently installed upgraded inner tracker for the ALICE detector, pictured on this issue's cover, is the largest pixel detector ever built and the first at the LHC to use monolithic active pixel sensors (p29). Next year, LHCb will also be equipped with an entirely new pixel tracker, the VELO, while ATLAS and CMS are developing advanced pixel trackers to be installed for future high-luminosity LHC operations (p36).

Silicon-pixel detectors developed for particle physics have also had a major impact on medical imaging, in particular via the CERN-led Medipix and Timepix collaborations (p23). Sticking with societal impact, this issue's Viewpoint argues for an exascale computing facility based on the organisation of CERN (p49).

Elsewhere in our summer issue: collider neutrinos on the horizon (p7); particle accelerators meet gravitational waves (p18); reducing greenhouse gases in detectors (p20); exploring the Hubble tension (p51); reviews (p55); careers (p59); and much more.

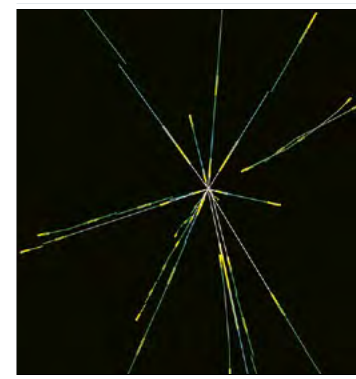
To sign up to the new-issue alert, please visit:
http://comms.iop.org/k/iop/cerncourier

To subscribe to the magazine, please visit:
https://cerncourier.com/p/about-cern-courier

EDITOR: MATTHEW CHALMERS, CERN
DIGITAL EDITION CREATED BY IOP PUBLISHING

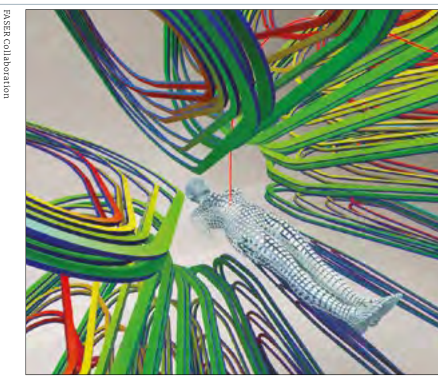
IN THIS ISSUE

Volume 61 Number 4 July/August 2021



FASER Collaboration

New frontier *Collider neutrinos on the horizon at FASERν and SND@LHC.* **7**



Clinical dimensions *CERN's growing impact on medical technologies.* **23**

F Camallonga

Expanding views *Cosmologist Licia Verde on the Hubble tension.* **51**

FROM THE EDITOR

Marvels of engineering and collaboration

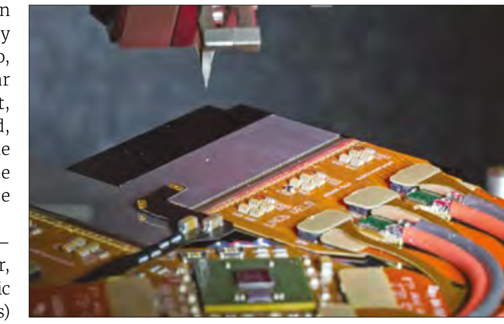
Matthew Chalmers
Editor

The story of silicon pixel detectors is like that of an art form, describes our in-depth take on their history (p39): with well-defined beginnings half a century ago, the technology has morphed into a vast array of spectacular creations. One, packing 10 million pixels into your pocket, is the smartphone camera; another is the newly installed, upgraded inner tracker for the ALICE detector adorning the cover of this issue. Containing some 12.5 Gpixels, it is the largest pixel detector ever built and the first at the LHC to use monolithic active pixel sensors, or MAPS (p29).

As well as disrupting photography, the silicon pixel detector – in parallel with its close sibling the silicon-microstrip detector, which will be explored in a future issue – revolutionised scientific imaging in the 1980s and 1990s. Charge-coupled devices (CCDs) tend to be the preferred option for astronomical applications, most recently the 3.2 Gpixel optical camera for the Vera Rubin Observatory, while MAPS tend to be used for ultrafast imaging such as studies of protein dynamics at X-ray free-electron lasers. It took a few years to move away from gaseous drift chambers for the highest precision tracking, but particle physicists adopted silicon detectors for these applications in the early 1980s and never looked back. Successive generations of trackers based on CCDs, MAPS and hybrid-pixel detectors have driven numerous discoveries. With the consumer electronics industry continuing to push chips to new levels of sophistication there are also no signs that advances are slowing down.

Silicon-pixel detectors developed for particle physics have also had a major impact on medical imaging

The LHC detectors represent the state-of-the-art in particle-tracking applications, delivering high-granularity data at speed under the most extreme operating conditions imaginable. The chips themselves are only one part of the story. They need to be integrated into modules with minimal material budget and installed with great precision in confined spaces, cooled, cabled and read-out (p36). From R&D to construction, this complex task, like that for the other LHC-experiment upgrades, is shared between international collaborating laboratories and institutes, with teams at CERN and across the world currently working hard under challenging global circumstances to prepare their detectors for Run 3 and beyond.



Nikhef

On point *A LHCb VELO pixel module being assembled at Nikhef.*

Beyond tracking

Silicon-pixel detectors developed for particle physics have also had a major impact on medical imaging, for example via the CERN-led Medipix and Timepix collaborations (p23). Medipix chips recently enabled the first 3D colour X-rays and, via CERN spin-out ADVACAM, are soon to be sent to the lunar surface to assess radiation levels ahead of NASA's first crewed flight to the Moon in 50 years. A spin-out from the Paul Scherrer Institute called DECTRIS, meanwhile, has pioneered the development of hybrid-pixel X-ray detectors for use in light sources, medicine and industry.

Sticking with the societal-impact theme, this issue's Viewpoint by two leading climate scientists (p49) argues for a "CERN for climate change" – an exascale computing facility based on the organisation of CERN that would allow better quantification of climate models. Elsewhere in our summer issue: learn about the fascinating potential for particle accelerators to detect gravitational waves (p18), the detection of the first collider-neutrino candidates (p7), the latest attempts to address the Hubble tension (p51), efforts to reduce greenhouse gases in particle detectors (p20), reviews (p55), careers (p59) and much more.

Reporting on international high-energy physics

CERN Courier is distributed to governments, institutes and laboratories affiliated with CERN, and to individual subscribers. It is published six times per year. The views expressed are not necessarily those of the CERN management.

IOP Publishing

Editor Matthew Chalmers
Associate editor Mark Rayner
Editorial assistant Craig Edwards
Astrowatch contributor Merlin Kole
E-mail cern.courier@cern.ch

Advisory board Peter Jenni, Christine Sutton, Claude Amsler, Philippe Bloch, Roger Forty, Mike Lamont, Joachim Kopp

Laboratory correspondents
Argonne National Laboratory Tom LeCompte
Brookhaven National Laboratory Achim Franz
Cornell University D G Cassel
DESY Laboratory Till Mundzeck
Fermilab Kurt Riesselmann
Forschungszentrum Jülich Markus Buescher
GSI Darmstadt I Peter
IHEP, Beijing Lijun Guo
IHEP, Serpukhov Yu Ryabov
INFN Antonella Varaschin
Jefferson Laboratory Kandice Carter
JINR Dubna B Starchenko
KEK National Laboratory Hajime Hikino
Lawrence Berkeley Laboratory Spencer Klein
Los Alamos National Lab Rajan Gupta
NCSL Ken Kingery
Nikhef Robert Fleischer
Novosibirsk Institute S Eidelman
Orsay Laboratory Anne-Marie Lutz
PSI Laboratory P-R Kettle
Saclay Laboratory Elisabeth Locci
UK STFC Jane Binks
SLAC National Accelerator Laboratory Melinda Baker
SNOLAB Samantha Kuula
TRIUMF Laboratory Marcello Pavan

Produced for CERN by IOP Publishing Ltd Temple Circus, Temple Way, Bristol BS1 6HG, UK Tel +44 (0)117 929 7481

Head of Media Jo Allen
Head of Media Business Development Ed Jost
Content and production manager Ruth Leopold
Technical illustrator Alison Tovey
Advertising sales Tom Houlden
Recruitment sales Chris Thomas
Advertisement production Katie Graham
Marketing and circulation Laura Gillham, Jessica Pratten

Advertising Tel +44 (0)117 930 1026 (for UK/Europe display advertising) or +44 (0)117 930 1164 (for recruitment advertising); e-mail sales@cerncourier.com

General distribution Courrier Adressage, CERN, 1211 Geneva 23, Switzerland; e-mail courrier-adressage@cern.ch

Published by CERN, 1211 Geneva 23, Switzerland Tel +41 (0) 22 767 61 11

Printed by Warners (Midlands) plc, Bourne, Lincolnshire, UK

ISSN 0304-288X

NEWS ANALYSIS

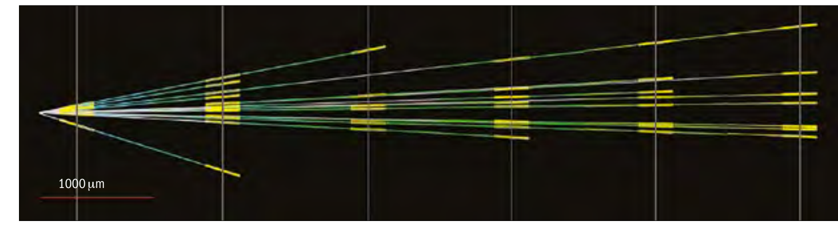
Neutrinos

Collider neutrinos on the horizon

Think "neutrino detector" and images of giant installations come to mind, necessary to compensate for the vanishingly small interaction probability of neutrinos with matter. The extreme luminosity of proton–proton collisions at the LHC, however, produces a large neutrino flux in the forward direction, with energies leading to cross-sections high enough for neutrinos to be detected using a much more compact apparatus.

In March the CERN research board approved the Scattering and Neutrino Detector (SND@LHC) for installation in an unused tunnel that links the LHC to the SPS, 480 m downstream from the ATLAS experiment. Designed to detect neutrinos produced in a hitherto unexplored pseudorapidity range ($7.2 < \eta < 8.6$), the experiment will complement and extend the physics reach of the other LHC experiments – in particular FASERν, which was approved last year. Construction of FASERν, which is located in an unused service tunnel on the opposite side of ATLAS along the LHC beamline (covering $|\eta| > 9.1$), was completed in March, while installation of SND@LHC is about to begin.

Both experiments will be able to detect neutrinos of all types, with SND@LHC positioned off the beamline to detect neutrinos produced at slightly larger angles. Expected to commence data-taking during LHC Run 3 in spring 2022, these latest additions to the LHC-experiment family are poised to make the first observation of collider neutrinos while opening new searches for feebly interacting particles and other new physics.



New territory *A candidate collider-neutrino event from the FASERν pilot detector in the plane transverse to the beam direction, showing charged-particle tracks originating from the neutrino interaction point.*

Neutrinos galore

SND@LHC will comprise 800 kg of tungsten plates interleaved with emulsion films and electronic tracker planes based on scintillating fibres. The emulsion acts as a vertex detector with micron resolution while the tracker provides a time stamp, the two subdetectors acting as a sampling electromagnetic calorimeter. The target volume will be immediately followed by planes of scintillating bars interleaved with iron blocks serving as a hadron calorimeter, followed downstream by a muon-identification system.

During its first phase of operation, SND@LHC is expected to collect an integrated luminosity of 150 fb^{-1}, corresponding to more than 1000 high-energy neutrino interactions. Since electron neutrinos and antineutrinos are predominantly produced by charmed-hadron decays in the pseudorapidity range explored, the experiment will enable the gluon parton-density function to be constrained in an unexplored region of very small x. With projected statistical and systematic uncertainties of 30% and 22% in the ratio between ν_e and ν_τ, and about 10% for both uncertainties in the ratio between ν_e and ν_τ at high energies, the Run-3 data will also provide unique tests of lepton flavour universality with neutrinos, and have sensitivity in the search for feebly interacting particles via scattering signatures in the detector target.

"The angular range that SND@LHC will cover is currently unexplored," says SND@LHC spokesperson Giovanni De Lellis. "And because a large fraction of the neutrinos produced in this range come from the decays of particles made of heavy quarks, these neutrinos can be used to study heavy-quark particle production in an angular range that the other LHC experiments can't access. These measurements are relevant for the prediction of very-high-energy neutrinos produced in cosmic-ray interactions, so the experiment is also acting as a bridge between accelerator and astroparticle physics."

FASERν is an addition to the Forward Search Experiment (FASER), which was approved in March 2019 to search for light and weakly interacting long-lived particles at solid angles beyond the reach of conventional collider detectors. Comprising a small and inexpensive stack of emulsion films and tungsten plates measuring $0.25 \times 0.25 \times 1.35$ m and weighing 1.2 tonnes, FASERν is already undergoing tests. The detector is positioned on the beam-collision axis to maximise the neutrino flux, and should detect a total of around 20,000 muon neutrinos, 1300 electron neutrinos and 20 tau neutrinos in an unexplored energy regime at the TeV scale. This will allow measurements of the interaction cross-sections of all neutrino flavours, provide constraints on non-standard neutrino interactions, and improve measurements of proton parton-density functions in certain phase-space regions.

A FASER first

In May, based on an analysis of pilot emulsion data taken in 2018 using a target mass of just 10 kg, the FASERν team reported the detection of the first neutrino-interaction candidates, based on a measured 2.7σ excess of a neutrino-like signal above muon-induced backgrounds. The result paves the way for high-energy neutrino measurements at the LHC and future colliders, explains FASER co-spokesperson Jamie Boyd: "The final detector should do much better – it will be a hundred times bigger, be exposed to much more luminosity, have muon identification capability, and be able to link observed neutrino interactions in the FASER spectrometer. It is quite impressive that such a small and simple detector can detect neutrinos given that usual neutrino detectors have masses measured in kilotons."

Further reading

FASER Collab. 2021 arXiv:2105.06197.
SHiP Collab. 2020 arXiv:2002.08722.

Searches for new physics

'X' boson feels the squeeze at NA64

Recent measurements bolstering the longstanding tension between the experimental and theoretical values of the muon's anomalous magnetic moment generated a buzz in the community (*CERN Courier* May/June 2021 p5). Though with a much lower significance, a similar puzzle may also be emerging for the anomalous magnetic moment of the electron, a_e.

Depending on which of two recent independent measurements of the fine-structure constant is used in the theoretical calculation of a_e – one obtained at Berkeley in 2018 or the other at Kastler–Brossel Laboratory in Paris in 2020 – the Standard Model prediction stands 2.4σ higher or 1.6σ lower than the best experimental value, respectively. Motivated by this inconsistency, the NA64 collaboration at CERN set out to investigate whether new physics – in the form of a lightweight "X boson" – might be influencing the electron's behaviour.

CERN-PHOTO-201611-278-3

Exploration *The NA64 set up is being used to search for new particles that might account for the electron g–2 and ATOMKI anomalies.*

The generic X boson could be a sub-GeV scalar, pseudoscalar, vector or axial-vector particle. Given experimental constraints on its decay modes involving Standard Model particles, it is presumed to decay predominantly invisibly, for example into dark-sector particles. NA64 searches for X bosons by directing 100 GeV electrons generated by the SPS onto a target, and looking for missing energy in the detector via electron–nuclei scattering $e^-Z \rightarrow e^-ZX$.

Analysing data collected in 2016, 2017 and 2018, corresponding to about 3×10^{11} electrons-on-target, the NA64 team found no evidence for such events. The result sets new bounds on the e–X interaction strength and, as a result, on the contributions of X bosons to a_e: X bosons with a mass below 1 GeV could contribute at most between one part in 10^{15} and one part in 10^{13}, depending on the X-boson type and mass. These contributions are too small to explain the current anomaly in the electron's anomalous magnetic moment, says NA64 spokesperson Sergei Gninenko. "But the fact that NA64 reached an experimental sensitivity that is better than the current accuracy of the direct measurements of a_e, and of recent high-precision measurements of the fine-structure constant, is amazing."

In a separate analysis, the NA64 team carried out a model-independent search for a particular pseudoscalar X boson with a mass of around 17 MeV. Coupling to electrons and decaying into e^+e^- pairs, the so-called "X17" has been proposed to explain an excess of e^+e^- pairs created during nuclear transitions of excited ^{8}Be and ^{4}He nuclei reported by the "ATOMKI" experiment in Hungary since 2015 (*CERN Courier* January/February 2020 p7).

The e–X17 coupling strength is constrained by data: too large and the X17 would contribute too much to a_e; too small and the X17 would decay too rarely and too far away from the ATOMKI target. In 2019, the NA64 team excluded a large range of couplings, although at large values, for a vector-like X17. More recently, they searched for a pseudoscalar X17, which has a lifetime about half that of the vector version for the same coupling strength. Re-analysing a sample of approximately 8.4×10^{10} electrons-on-target collected in 2017 and 2018 with 100 and 150 GeV electrons, respectively, the collaboration has now excluded couplings in the range $2.1–3.2 \times 10^{-4}$ for a 17 MeV X-boson.

"We plan to further improve the sensitivity to vector and pseudoscalar X17's after long shutdown 2, and also try to reconstruct the mass of X17, to be sure that if we see the signal it is the ATOMKI boson," says Gninenko.

Further reading

NA64 Collab. 2021 *Phys. Rev. Lett.* **126** 211802.
NA64 Collab. 2021 arXiv:2104.13342.
NA64 Collab. 2020 *Eur. Phys. J. C* **80** 1159.

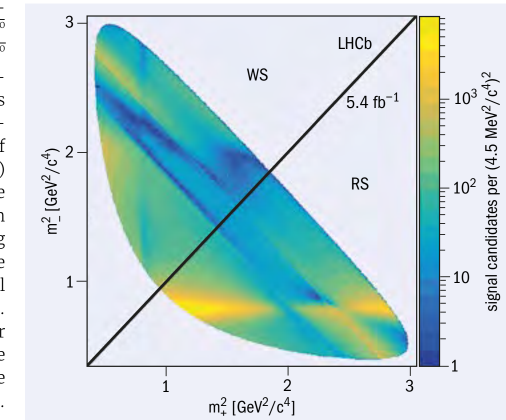
Flavour physics

Charmed matter–antimatter flips clocked by LHCb

The ability of certain neutral mesons to oscillate between their matter and antimatter states at distinctly unworldly rates is a spectacular feature of quantum mechanics. The phenomenon arises when the states are orthogonal combinations of narrowly split mass eigenstates that gain a relative phase as the wavefunction evolves, allowing quarks and antiquarks to be interchanged at a rate that depends on the mass difference. Forbidden at tree level, proceeding instead via loops, such flavour-changing neutral-current processes offer a powerful test of the Standard Model and a sensitive probe of physics beyond it.

Only four meson systems can oscillate

Predicted by Gell-Mann and Pais in the 1950s, only four known meson systems (those containing quarks from different generations) can oscillate. $K^0–\overline{K^0}$ oscillations were observed in 1955, $B^0–\overline{B^0}$ oscillations in 1986 at the ARGUS experiment at DESY, and $B^0_s–\overline{B^0_s}$ oscillations in 2006 by the CDF experiment at Fermilab. Following the first evidence of charmed-meson oscillations ($D^0–\overline{D^0}$) at Belle and BaBar in 2007, LHCb made the first single-experiment observation confirming the process in 2012. Being relatively slow (more than 100 times the average lifetime of a D^0 meson), the full oscillation period cannot be observed. Instead, the collaboration looked for small changes in the flavour mixture of the D^0 mesons as a function of the time at which they decay via the Kπ final state.



Bin flips *LHCb used a Dalitz plot-based "bin-flip method" analysis of $D^0 \rightarrow K^0_S\pi^+\pi^-$ decays to infer the $D^0 - \overline{D^0}$ mass difference, where the axes of the plot are the squares of the invariant masses of two pairs of the decay products.*

On 4 June, during the 10th International Workshop on CHARM Physics, the LHCb collaboration reported the first observation of the mass difference between the $D^0–\overline{D^0}$ states, precisely determining the frequency of the oscillations. The value represents one of the smallest ever mass differences between two particles: 6.4×10^{-6} eV, corresponding to an oscillation rate of around 1.5×10^9 per second. Until now, the measured value of the mass-difference between the underlying D^0 and $\overline{D^0}$ eigenstates was marginally compatible with zero. By establishing a non-zero value with high significance, the LHCb team was able to show that the data are consistent with the Standard Model, while significantly improving limits on mixing-induced CP violation in the charm sector.

"In the future we hope to discover time-dependent CP violation in the charm system, and the precision and luminosity expected from LHCb upgrades I and II may make this possible," explains Nathan Jurik, a CERN fellow who worked on the analysis.

The latest measurements of neutral charm–meson oscillations follow hot on the heels of an updated LHCb measurement of the $B^0_s–\overline{B^0_s}$ oscillation frequency announced in April, based on the heavy and light strange-beauty-meson mass difference. The very high precision of the $B^0_s–\overline{B^0_s}$ measurement provides one of the strongest constraints on physics beyond the Standard Model. Using a large sample of $B^0_s \rightarrow D^-_s\pi^+$ decays, the new measurement improves upon the previous precision of the oscillation frequency by a factor of two: $\Delta m_s = 17.7683 \pm 0.0051$ (stat) ± 0.0032 (sys) ps^{-1} which, when combined with previous LHCb measurements, gives a value of 17.7656 ± 0.0057 ps^{-1}. This corresponds to an oscillation rate of around 3×10^{12} per second, the highest of all four meson systems.

Further reading

LHCb Collab. 2021 arXiv:2106.03744.
LHCb Collab. 2021 arXiv:2104.04421.

Neutron lifetime

KEK tackles neutron-lifetime puzzle

More than a century after its discovery, the proton remains a source of intrigue, its charge-radius and spin posing puzzles that are the focus of intense study (*CERN Courier* May/June 2019 p38). But what of its mortal sibling, the neutron? In recent years, discrepancies between measurements of the neutron lifetime using different methods constitute a puzzle with potential implications for cosmology and particle physics. The neutron lifetime determines the ratio of protons to neutrons at the beginning of big-bang nucleosynthesis and thus affects the yields of light elements, and it is also used to determine the CKM matrix-element V_{ud} in the Standard Model.


KEK

Way to go *The apparatus in which neutrons from J-PARC were clocked.*

The neutron-lifetime puzzle stems from measurements using two techniques. The "bottle" method counts the number of surviving ultra-cold neutrons contained in a trap after a certain period, while the "beam" method uses the decay probability of the neutron obtained from the ratio of the decay rate to an incident neutron flux. Back in the 1990s, the methods were too imprecise to worry about differences between the results. Today, however, the average neutron lifetime measured using the bottle and beam methods, 879.4 ± 0.4 s and 888.0 ± 2.0 s, respectively, stand 8.5 s (or 4σ) apart.

In an attempt to shed light on the issue, a team at Japan's KEK laboratory in collaboration with Japanese universities has developed a new experimental setup. Similar to the beam method, it compares the decay rate to the reaction rate of neutrons in a pulsed beam from the Japan Proton Accelerator Research Complex (J-PARC). The decay rate and the reaction rate are determined by simultaneously detecting electrons from the neutron decay and protons from the reaction ^{3}He → ^{3}H in a 1 m-long time-projection chamber containing diluted ^{3}He, removing some of the systematic uncertainties that affect previous beam methods. The experiment is still in its early stages, and while the first results have been released – $\tau_n = 898 \pm 10(\text{stat})^{+15}_{-18}$ (sys) s – the uncertainty is currently too large to draw conclusions.

"In the current situation, it is important to verify the puzzle by experiments in which different systematic errors dominate," says Kenji Mishima of KEK, adding that further improvements in the statistical and systematic uncertainties are underway. "We think it will take two years to obtain a competitive result from our experiment."

Several new-physics scenarios have been proposed as solutions of the neutron lifetime puzzle. These include exotic decay modes involving undetectable particles with a branching ratio of about 1%, such as "mirror neutrons" or dark-sector particles.

Further reading

K Hirota *et al.* 2020 *Prog. Theor. Exp. Phys.* 123C02.

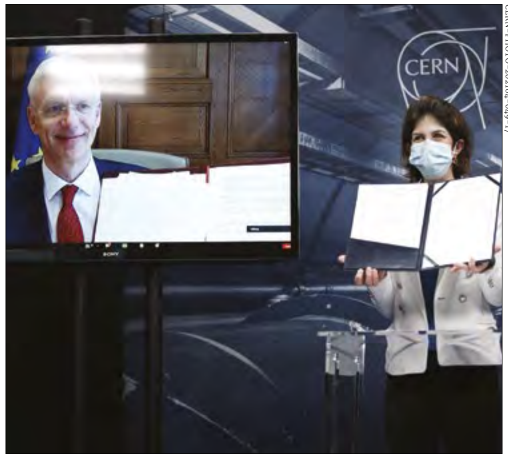
CERN

Latvia to become Associate Member of CERN

On 14 April, representatives of CERN and the Republic of Latvia gathered in a virtual ceremony to sign an agreement admitting Latvia as an Associate Member State.

Latvia, which is the third of the Baltic States to join CERN in recent years after Lithuania and Estonia, first became involved with CERN activities in the early 1990s. Latvian researchers have since participated in many CERN projects, including contributions to the CMS hadron calorimeter and, more recently, participation in the Future Circular Collider study.

"As we become CERN's newest Associate Member State, we look forward to enhancing our contribution to the Organization's major scientific endeavours, as well as to investing the unparalleled scientific and technological excellence gained by this membership in further building the economy and well-being of our societies," said Latvian prime minister Krišjānis Kariņš.



CERN-PHOTO-202104-049-17

Strengthening ties *Lativan prime minister Krišjānis Kariņš and CERN Director-General Fabiola Gianotti on the occasion of the remote signature of the agreement.*

As an Associate Member State, Latvia will be entitled to appoint representatives to attend meetings of the CERN Council and Finance Committee. Its nationals will be eligible for staff positions, fellowships and studentships, and its industries will be entitled to bid for CERN contracts, increasing opportunities for collaboration in advanced technologies.

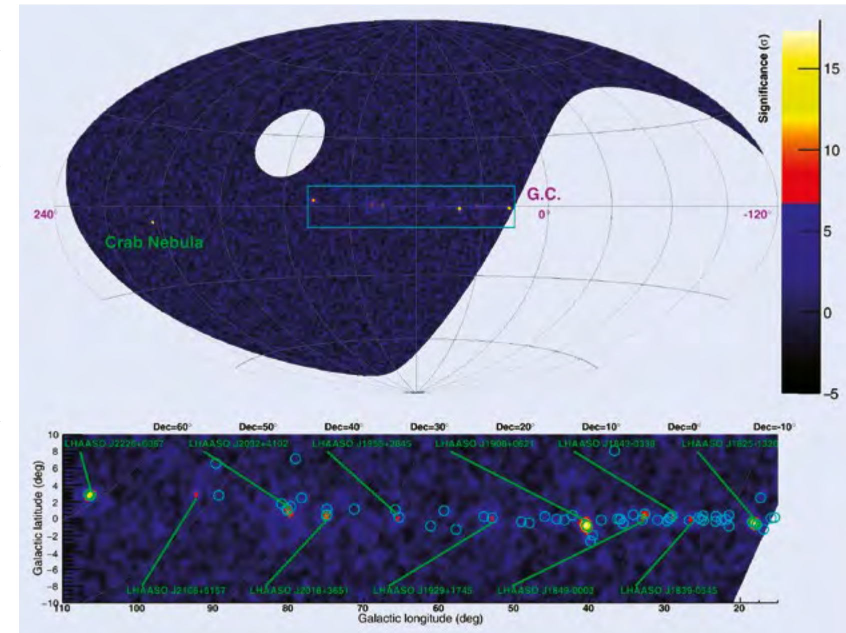
"We are delighted to welcome Latvia as a new Associate Member State," said CERN Director-General Fabiola Gianotti. "The present agreement contributes to strengthening the ties between CERN and Latvia, thereby offering opportunities for the further growth of particle physics in Latvia through partnership in research, technological development and education."

Astrowatch

Mountain observatory nets PeV gamma rays

Recent years have seen rapid growth in high-energy gamma-ray astronomy, with the first measurement of TeV photons from gamma-ray bursts by the MAGIC telescope (*CERN Courier* January/February 2020 p10) and the first detection of gamma rays with energies above 100 TeV by the HAWC observatory (*CERN Courier* July/August 2020 p12).

Now, the Large High Altitude Air Shower Observatory (LHAASO) in China has increased the energy scale at which the universe has been observed by a further order of magnitude. The recent LHAASO detection provides the first clear evidence of the presence of galactic "pevatrons": sources in the Milky Way capable of accelerating protons and electrons to PeV energies. Although PeV cosmic rays are known to exist, magnetic fields pervading the universe perturb their direction and therefore do not allow their origin to be traced. The gamma rays produced by such cosmic-rays, on the other hand, point directly to their source.



Nature

High-energy vista *The universe seen using photons with energies exceeding 100 TeV by LHAASO. A total of 12 sources, including the Crab nebula, can be observed along the galactic plane, indicating that all lie within the Milky Way.*

Wide field of view

LHAASO is located in the mountains of the Sichuan province of China and offers a wide field of view to study both high-energy cosmic and gamma rays. Once completed, the observatory will contain a water Cherenkov detector with a total area of about 78,000 m^2, 18 wide-field-of-view Cherenkov telescopes and a 1 km^2 array of more than 5000 scintillator-based electromagnetic detectors (EDs). Finally, more than 1000 underground water Cherenkov tanks (the MDs) are placed over the grid to detect muons.

The latter two detectors, of which only half were finished during data-taking for this study, are used to directly detect the showers produced when high-energy particles interact with the Earth's atmosphere. The EDs detect the shower profile and incoming angle, using charge and timing information of the detector array, while the MDs are used to distinguish hadronic showers from the electromagnetic showers produced by high-energy gamma rays. Thanks to both its large size and the MDs, LHAASO will ultimately be two orders of magnitude more sensitive at 100 TeV than the HAWC facility in Mexico, the previous most sensitive detector of this type.

The measurements reported by the Chinese-led international LHAASO collaboration reveal a total of 12 sources located across the galactic plane (see image above). This distribution is expected, since gamma rays at such energies have a high cross-section for pair production with the cosmic microwave background and therefore the universe starts to become opaque at energies exceeding tens to hundreds of TeV, leaving only sources within our galaxy visible. Of the 12 presented sources, only the Crab nebula can be directly confirmed. This substantiates the pulsar-wind nebulae as a source in which electrons are accelerated beyond PeV energies, which in turn are responsible for the gamma rays through inverse Compton scattering.

Of specific interest is the source responsible for the photon with the highest energy, 1.4 PeV

The origin of the other photons remains unknown as the observed emission regions contain several possible sources within them. The sizes of the emission regions exceed the angular resolution of LHAASO, however, indicating that emission takes place over large scales. Of specific interest is the source responsible for the photon with the highest energy, 1.4 PeV. This came from a region containing both a supernova remnant as well as a star-forming cluster, both of which are prime theoretical candidates for hadronic pevatrons.

Tip of the iceberg

More detailed spectrometry as well as morphological measurements, in which the differences in emission intensity throughout the sources are measured, could allow the sources of > 100 TeV gamma rays to be identified in the next one or two years, say the authors. Furthermore, as the current 12 sources were visible using only one year of data from half the detector, it is clear that LHAASO is only seeing the tip of iceberg when it comes to high-energy gamma rays.

Further reading

Z Cao *et al.* 2021 *Nature* **594** 33.

NEWS DIGEST

LUX/DESY

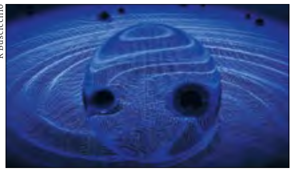
An electron bunch (centre) surfs on a plasma wave of electrons (white) driven by a laser pulse (red).

Optimal wakefield acceleration
In a step towards the continuous operation necessary for applications, physicists at DESY and the University of Hamburg have narrowed the energy distribution of electron bunches emerging from a plasma-wakefield accelerator. Plasma accelerators can have gradients 1000 times higher than conventional radio-frequency cavities, but have thus far only been operated on a shot-by-shot basis. Using the LUX test facility at Hamburg, the team employed a new type of hydrogen cell, with nitrogen added to a 10 mm region where the bunch is formed. Artificial-intelligence techniques were then used to optimise the concentration and density of the gases and the energy and focus of the laser that drives the plasma wave on which the bunch surfs (see figure above). As a result of this "optimal beam loading", the electrons reach the same energy regardless of their position along the wave (*Phys. Rev. Lett.* **126** 104801 and 174801).

Wash-in leptogenesis
Early attempts to explain the origin of the baryon asymmetry of the universe using CP-violating decays of massive GUT particles were spoiled by electroweak "sphaleron" processes that non-perturbatively wash out baryon-plus-lepton number. This prompted an alternative explanation called leptogenesis, during which the CP-violating decays of hypothesised right-handed neutrinos (RHNs) create a lepton asymmetry that is then converted by Standard Model interactions (including sphalerons) into a baryon asymmetry. By generalising standard "freeze-out" leptogenesis, such that all conserved charges at the time of leptogenesis are allowed to take arbitrary values, CERN's Valerie Domcke, Kyohei Mukaida, Kai Schmitz and colleagues have recently made an important contribution to the theory that lowers the possible mass range of the RHNs down to a few 100 TeV, actively "washing in" the observed baryon asymmetry (arXiv:2011.09347).

Looking for GW lensing
LIGO and Virgo have published the first search for the gravitational lensing of gravitational waves (GWs). Just as light bends around massive astronomical objects such as stars, black holes and galaxies, causing magnification, multiple images and "Einstein rings", GWs can also be lensed by intervening objects. Possible signals include an overall amplification of the waves, making binary-merger signals appear to come from closer and higher-mass sources than they really do; "repeated" events separated by minutes, months or years; or a beating pattern caused by tiny time delays ("microlensing"). As expected, given current sensitivities, no evidence for lensing was found. In the future, however, the effect could help locate merging black holes, estimate the population of primordial and intermediate-mass black holes, measure the speed of GWs, and test general relativity (arXiv:2105.06384).

R Buscicchio



Artist's impression of lensed gravitational waves.

Leptoquarks and $H \to \mu\mu$
Andreas Crivellin (CERN), Dario Müller (PSI) and Francesco Saturnino (Bern) have shown that leptoquarks (LQs) are not only well motivated by hints of lepton-flavour-universality violation (*CERN Courier* May/June 2021 p17) but that there may also be a LQ link between the muon g–2 anomaly and ongoing measurements of the decay of the Higgs boson to a pair of muons (arXiv:2008.02643, accepted in *Phys. Rev. Lett.*). Should LQs prove to be the true explanation of the 4.2σ tension in the muon g–2 reported by Fermilab in April (*CERN Courier* May/June 2021 p7), the effect of LQs should also be observable in future precision measurements of $H \to \mu^+\mu^-$. The first evidence for this decay was reported by CMS and ATLAS in August last year, with signal strengths with respect to the Standard Model of 1.2 ± 0.4 and 1.2 ± 0.6, respectively (*CERN Courier* September/October 2020 p7).

France and Japan launch ILANCE
On 1 April, the University of Tokyo and France's Centre National de la Recherche Scientifique (CNRS) established the International Laboratory for Astrophysics, Neutrino and Cosmology Experiments (ILANCE) in Kashiwa, Greater Tokyo. CNRS's seventh international research lab in Japan, ILANCE will participate in the Super- and Hyper-Kamiokande neutrino experiments, the LiteBIRD cosmic-microwave-background experiment, the KAGRA gravitational-wave detector, the ATLAS experiment and studies for the International Linear Collider. The lab will be directed by Michel Gonin and Nobel-laureate Takaaki Kajita.

Sicilian neutrino upgrade
During a week-long campaign in April, the KM3NeT neutrino observatory upgraded its seabed infrastructure near Sicily. A hub for power distribution and data transmission was installed and connected to five new detection units of the ARCA telescope. Once complete, the detector will form an array of more than 200 detection units – each 700 m tall and comprising 18 sensor modules to register the faint flashes of light generated by neutrino interactions in the pitch-black abyss of the Mediterranean Sea. Together with its sister detector, ORCA, located offshore from Toulon, France, the KM3NeT telescopes will identify astrophysical sources of high-energy cosmic neutrinos and study neutrino oscillations. With a total of six ARCA detection units now joining six ORCA units in taking data, KM3NeT now has comparable sensitivity to itspredecessor telescope in the northern hemisphere, ANTARES.

M Brice/CERN

Sergio Arguedas Cuendis adjusts the RADES detector.

RADES reports results
The Relic Axion Dark-Matter Exploratory Setup (RADES) haloscope at CERN has reported the results of its first search for axions (arXiv:2104.13798). The detector was installed inside one of the CAST experiment's dipole magnet bores in 2018. While CAST seeks to use the inverse Primakoff effect to convert solar axions into X-rays, RADES seeks to observe electric-field oscillations in a resonant cavity – evidence, potentially, for the presence of axions in the dark-matter halo of the Milky Way (*CERN Courier* March/April 2021 p25). The detector pushes this technique to search for axions with a relatively high axion mass of 34.67 μeV by subdividing its cavity into several cells, thereby offsetting the lower detection probability of the smaller cavities needed to probe higher masses. The team found no evidence for axions in 100 hours of data.

CERNCOURIER
VOLUME 61 NUMBER 4 JULY/AUGUST 2021
IOP Publishing

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

Four top quarks seen at once

The production of four top quarks is an extremely rare event at the LHC, with an expected cross section five orders of magnitude below the production of a top-quark pair. With the heaviest elementary particle in the Standard Model produced four times in the final state, it is also one of the most spectacular processes accessible at the LHC. By combining two analyses, the ATLAS collaboration has uncovered the first strong evidence to support the existence of this unique event topology with sensitivity to theories beyond the Standard Model (BSM).

As a result of its large mass, the top quark plays a special role in numerous BSM theories, and many of these theories predict an increase in the four-top-quark production cross section. In particular, four-top-quark production is the only process that could probe potentially anomalous effective four-heavy-fermion operators. The cross section is also sensitive to the value of the top-quark Yukawa coupling, as a result of contributions mediated by Higgs bosons. However, until now, four-top-quark production has not been observed, in part because of its tiny production rate, and in part because the experimental signature of this process is very complex, requiring up to 12 particles to be reconstructed from the top-quark decays. The search is also affected by background sources in kinematic regions that are at the limit of the domain of validity of the simulations.

Despite these challenges, the ATLAS collaboration has recently released two studies of four-top-quark production using its full Run-2 data sample. The first study searches for events with two leptons (electrons or muons) with the same electric charge or with three leptons. This selection corresponds to only 13% of all possible four-top-quark final states, but is contaminated by only a small background, mainly from the production of a top-quark pair with a W, Z or Higgs boson and additional jets, or from events with one lepton with misidentified electric charge or a "fake" lepton that doesn't correspond to a W or Z boson decay. Background processes were primarily simulated using the best available theoretical predictions; the rates of the most difficult ones were measured using control samples with similar properties to the signal events. The second study searches for events with one lepton or two oppositely-charged leptons. This selection retains 57% of the possible four-top-quark final states, but suffers from a large background from top-quark pairs produced in association with many jets, some of which are consistent with originating from b-quarks (b-jets). This background is difficult to model and was determined using data control samples. To better isolate the signal from the background, multivariate discriminants were trained in both analyses using distinct features of the signal, such as the number of b-jets and the kinematic properties of the reconstructed particles (see figure 1).

Results from the two studies were combined, leading to a four-top-quark cross-section measurement at 13 TeV of 25^{+7}_{-6} fb, which is consistent with the Standard Model prediction of 12.0 ± 2.4 fb within 2.0σ (see figure 2). The statistical significance of the signal corresponds to 4.7σ, providing strong evidence for this process, close to the observation threshold of 5σ. LHC Run-3 data, possibly at a higher centre-of-mass energy, will allow ATLAS to verify whether the larger measured cross section relative to the prediction is confirmed or not.

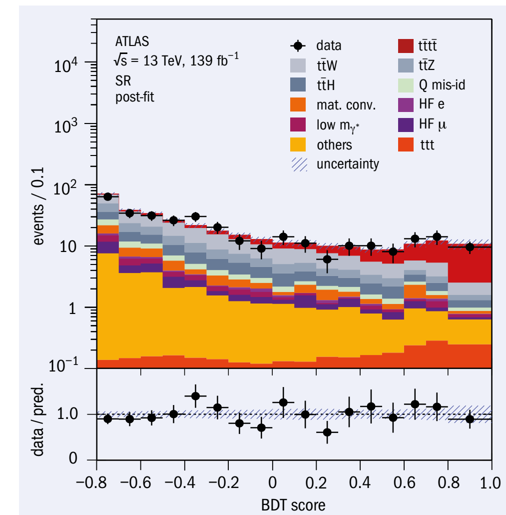


Fig. 1. *Distribution of the multivariate discriminant score for data events (black dots) together with the background and signal prediction (stacked histograms) for the analysis using events with two leptons with the same electric charge or three leptons. The lower panel shows the ratio of the data to the total prediction, where the band represents the total uncertainty.*

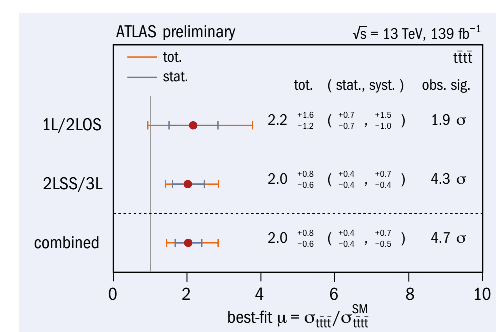
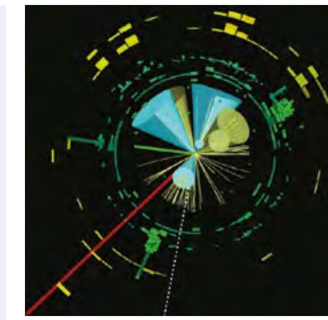


Fig. 2. *Measurements of the four-top-quark cross section over its Standard Model prediction (μ) at 13 TeV, for the analysis using events with only one lepton or two oppositely-charged leptons (1L/2LOS), for the analysis with two leptons with the same electric charge or three leptons (2LSS/3L), and for the combination.*



ATLAS

Four-top candidate *One top quark decays to a muon (red), one to an electron (green) and two decay hadronically. Missing transverse momentum is indicated by a dotted line and the blue cones are b-jets.*

Further reading
ATLAS Collab. 2020 *Eur. Phys. J. C* **80** 1085.
ATLAS Collab. 2021 ATLAS-CONF-2021-013.

CERNCOURIER
VOLUME 61 NUMBER 4 JULY/AUGUST 2021
IOP Publishing
CERN

CMS

Gauge–boson polarisation observed in WZ production

At the collision energies of the LHC, diboson processes have relatively high production cross sections and often produce relatively clean final states with two or more charged leptons. Consequently, multilepton final states resulting from diboson processes are powerful signatures to study the properties of the electroweak sector of the Standard Model. In particular, WZ production is sensitive to the strength of the triple gauge coupling that characterises the WWZ vertex, which derives from the non-Abelian nature of the electroweak sector. Additionally, as the Higgs mechanism is responsible for the appearance of longitudinally polarised gauge bosons, studying W and Z boson polarisation indirectly probes the validity of the Higgs mechanism.

A recent result from the CMS collaboration uses the full power of the data taken during Run 2 of the LHC to learn as much as possible from WZ production in the decay channels involving three charged leptons (electrons or muons). The results include the first observation at any experiment of longitudinally polarised W bosons in diboson production.

Reconstruction and event selection were optimised to reduce contributions from processes with "non-isolated" electrons and muons produced in hadron decays – traditionally one of the primary sources of experimental uncertainty in such measurements. The total production cross section for WZ production was measured with a simultaneous fit to the signal-enriched region and three different control regions. This elaborate fitting scheme paid off, as the final result has a relative uncertainty of 4%, down from the 6% obtained in past iterations of the measurement. The results are all consistent with state-of-the-art theoretical predictions (figure 1, left).

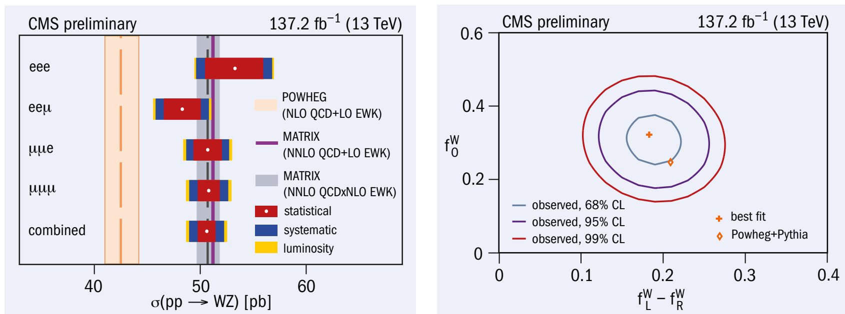


Fig. 1. *Left: the measured WZ production cross section in various final states compared to predictions at different orders in perturbative QCD and electroweak theory (EWK). Right: measured polarisation fractions for the W boson in WZ production, compared with the Standard Model expectation (◊).*

The results include the first observation of longitudinally polarised W bosons in diboson production

A highlight of the analysis is the study of the polarisation of both the W and the Z bosons in the helicity frame, using missing transverse energy as a proxy for the transverse momentum of the neutrino in the W decay. This choice, coupled with the precisely measured four-momenta of the three leptons and the requirement that W boson be on-shell, allows both the W and Z momenta to be fully reconstructed. The angle between the W (Z) boson and the (negatively) charged lepton originating from its decay is then computed. The resulting distributions are fitted to extract the polarisation fractions f_R, f_L, and f_0, which correspond to the proportion of bosons in the left, right and longitudinally polarised states in WZ production.

The measured polarisation fractions are consistent within 1σ with the Standard Model predictions (figure 1, right), in accordance with our knowledge of the electroweak spontaneous symmetry breaking mechanism. The significance for the presence of longitudinally polarised vector bosons is measured to be 5.6σ for the W boson and well beyond 5σ for Z-boson production. These new studies pave the way for future measurements of doubly polarised diboson cross sections, including the challenging doubly longitudinal polarisation mode in WW, WZ or ZZ production.

Further reading

CMS Collab. 2021 CMS-PAS-SMP-20-014.

ALICE

Hadron formation differs outside of jets

The production of different types of hadrons provides insights into one of the most fundamental transitions in nature – the "hadronisation" of highly energetic partons into hadrons with confined colour charge. To understand how this transition takes place we have to rely on measurements, and measurement-driven modelling. This is because the strong interaction processes that govern hadronisation are characterised by a scale given by the typical size of hadrons – about 1 fm – and cannot be calculated with perturbative techniques. The ALICE collaboration has recently performed a novel study of hadronisation by comparing the production of strange neutral baryons and mesons inside and outside of charged-particle jets.

One of the ways to contrast baryon and meson production is to analyse the ratio of their momentum distributions. This has been done in most of the collision systems, but the comparison is particularly interesting in heavy-ion collisions, where a large baryon-to-meson enhancement is often referred to as the "baryon anomaly". A characteristic maximum at intermediate transverse momenta (1–5 GeV) is found in all systems, but in Pb–Pb collisions the ratio is strongly increased, to the extent that it exceeds unity, implying the production of more baryons than mesons. The rise of the ratio has been associated with either hadron formation from the recombination of two or three quarks, or the migration of the heavier baryons to higher momenta by the strong all-particle "radial" flow associated with the production and expansion of a quark-gluon plasma.

A recent result adds an extra twist to the study of strange baryons and mesons

The ALICE collaboration has studied baryon-to-meson ratios extensively. A recent result adds an extra twist to the study of strange baryons and mesons by studying the ratios in two parts of the events separately – inside jets and ▷ in the event portion perpendicular to a jet cone. This allows physicists to look "under the peak" to reveal more about its origin. The latest study focuses on the neutral and weakly decaying Λ baryon and K^0_S meson – particles often known collectively as V^0 due to their decay particles forming a "V" within a detector. The ALICE detector can reconstruct these decaying particles reliably even at high momenta via invariant-mass analysis using the charged-particle tracks seen in the detectors.

The particles associated with the jets show the typical ratio known from the high momentum tail of the inclusive baryon-to-meson distribution – essentially no enhancement – and similar values were found in both pp and p–Pb collisions, consistent with simulations of hard pp collisions using PYTHIA 8 (see figure 1). By contrast, the particles found away from jets do indeed show a baryon-to-meson enhancement that qualitatively resembles the observations in Pb–Pb collisions. The new study clarifies that the high rise of the ratio is associated with the soft part of the events (regions where no jet with more than p_T = 10 GeV is produced) and brings the first quantitative guidance for modelling the baryon-to-meson enhancement with an additional important constraint – the absence of the jet. Moreover, finding that the "within-jet" ratio is similar in pp and p–Pb collisions, while the "out-of-jet" ratio shows larger values in p–Pb than in pp collisions, gives even more to ponder about the possible origin of the effect in relation to an expanding strongly interacting system. Future measurements involving multi-strange baryons may shed further light on this question.

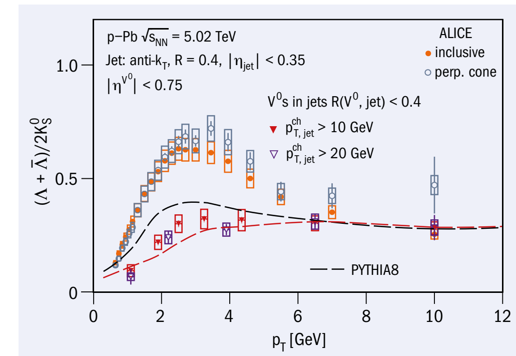


Fig. 1. *The enhancement in the production of Λ baryons with respect to K^0_S mesons at intermediate transverse momenta (orange circles) is largely due to V^0-particle decays found outside charged-particle jets (open circles), and is not seen for the V^0-particle decays found inside them (red and open triangles). The dashed curves represent PYTHIA 8 simulations of pp collisions outside (black) and inside jets (red).*

Further reading

ALICE Collab. 2021 arXiv:2105.04890.

LHCb

New charmed-baryon lifetime hierarchy cast in stone

Which charmed baryon decays first? The LHCb collaboration recently challenged the received wisdom of fixed-target experiments by almost quadrupling the measured lifetime of the doubly strange Ω^0_c (*CERN Courier* July/August 2018 p11). Now, a follow-up measurement by the collaboration confirms the revised hierarchy, offering valuable input to theoretical models of the decays.

Ground-state baryons containing a charm quark (c), such as Λ^+_c (udc), Ξ^+_c (usc), Ξ^0_c (dsc) and Ω^0_c (ssc), decay via the weak interaction. The ordering of their lifetimes has long been thought to be $\tau(\Xi^+_c) > \tau(\Lambda^+_c) > \tau(\Xi^0_c) > \tau(\Omega^0_c)$, based on measurements from fixed-target experiments nearly 20 years ago. However, the situation changed dramatically in 2018 when LHCb joined the game using a sample of Ω^0_c baryons obtained from bottom-baryon semileptonic decays. That LHCb study measured the Ω^0_c lifetime to be nearly four times larger than previously measured, transforming the hierarchy into $\tau(\Xi^+_c) > \tau(\Omega^0_c) > \tau(\Lambda^+_c) > \tau(\Xi^0_c)$. One year later, LHCb significantly improved the precisions of the lifetimes of the other three charmed baryons using the same method, also finding the lifetime of the Ξ^0_c baryon to be larger than the world-average value by about 3σ (figure 1).

The corresponding theoretical calculations are challenging. In the charm sector, an effective theory of heavy-quark expansion is taken to calculate lifetimes of charmed baryons through an expansion in powers of $1/m_c$, where m_c is the constituent charm-quark mass. Calculations up to order $1/m_c^3$ imply a lifetime hierarchy consistent with the original fixed-target measurements, though only qualitatively. Attempts at higher-order calculations up to order $1/m_c^4$, however, cannot accommodate the old hierarchy, but can explain the new one if a suppression factor to the constructive Pauli-interference and semileptonic terms is written in. The origin of the suppression factor is still unknown, but probably due to even higher order effects. An independent measurement was therefore needed to confirm the experimental situation.

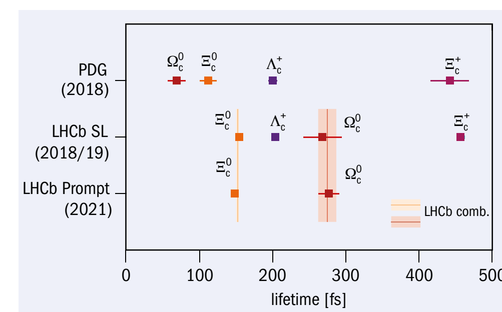


Fig. 1. *Measurements of charmed-baryon lifetimes from fixed-target experiments (PDG 2018) and from the LHCb experiment using charmed baryons produced from semileptonic b-decays (LHCb SL) and now from proton–proton collisions directly (LHCb Prompt), showing the progression in our understanding.*

The charmed-baryon lifetime puzzle has now been resolved by a new measurement from LHCb using a much larger sample of Ω^0_c and Ξ^0_c baryons produced directly in proton–proton collisions. Both particles are detected in the final state $pK^-K^-\pi^+$. The measurement is made relative to the lifetime distribution of the charmed meson D^0 via $D^0 \to K^+K^-\pi^+\pi^-$ decays, in order to control systematic uncertainties. Taking advantage of the performance and detailed understanding of the LHCb detector, the lifetimes of the Ω^0_c and Ξ^0_c baryons are found to be $\tau(\Omega^0_c) = 276.5 \pm 13.4\,(stat) \pm 4.5\,(syst)$ fs and $\tau(\Xi^0_c) = 148.0 \pm 2.3\,(stat) \pm 2.2\,(syst)$ fs, respectively, where the precision of the Ω^0_c lifetime is improved by a factor of two compared to the semileptonic measurement. The new results are consistent with the previous LHCb measurements, and hence establish the new lifetime hierarchy. Combining this measurement with the previous LHCb results gives $\tau(\Omega^0_c) = 274.5 \pm 12.4$ fs and $\tau(\Xi^0_c) = 152.0 \pm 2.0$ fs, the most precise charm-baryon lifetimes to date. The newly confirmed lifetime hierarchy will help improve our knowledge of QCD dynamics in charm hadrons, and provides a crucial input to calibrate theoretical calculations.

Further reading

LHCb Collab. 2021 LHCb-PAPER-2021-021.
LHCb Collab. 2019 LHCb-PAPER-2019-008.
LHCb Collab. 2018 LHCb-PAPER-2018-028.

CERNCOURIER
VOLUME 61 NUMBER 4 JULY/AUGUST 2021
IOP Publishing

FIELD NOTES

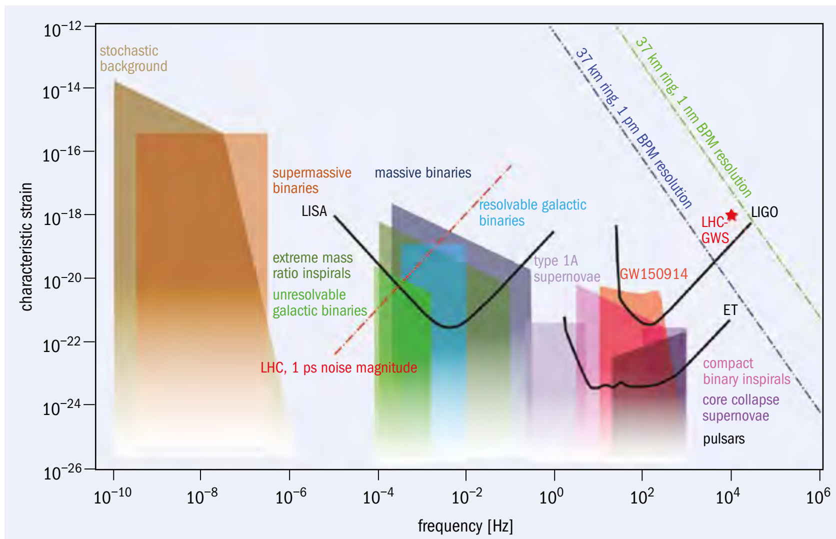
Reports from events, conferences and meetings

TOPICAL WORKSHOP ON STORAGE RINGS AND GRAVITATIONAL WAVES

Accelerators meet gravitational waves

Gravitational waves (GWs) crease and stretch the fabric of space–time as they ripple out across the universe. As they pass through regions where beams circulate in storage rings, they should therefore cause charged-particle orbits to seem to contract, as they climb new peaks and plumb new troughs, with potentially observable effects.

Proposals in this direction have appeared intermittently over the past 50 years, including during and after the construction of LEP and the LHC. Now that the existence of GWs has been established by the LIGO and VIRGO detectors, and as new, even larger storage rings are being proposed in Europe and China, this question has renewed relevance. We are on the cusp of the era of GW astronomy – a young and dynamic domain of research with much to discover, in which particle accelerators could conceivably play a major role.



gwplotter.com/S Rao et al./K Oide, G Franchetti & F Zimmermann/P Chen

Sources and sensitivities *Gravitational-wave sources (shaded) and detector sensitivities (lines), including those for the space-based interferometer LISA and the ground-based interferometers LIGO and the Einstein Telescope. Accelerator-based detection methods and sources are superimposed based on optimistic assumptions that require future confirmation.*

From 2 February to 31 March this year, a topical virtual workshop titled "Storage Rings and Gravitational Waves" (SRGW2021) shone light on this tantalising possibility. Organised within the European Union's Horizon 2020 ARIES project, the meeting brought together more than 100 accelerator experts, particle physicists and members of the gravitational-physics community to explore several intriguing proposals.

Theoretically subtle

GWs are extremely feebly interacting. The cooling and expanding universe should have become "transparent" to them early in its history, long before the timescales probed through other known phenomena. Detecting cosmological backgrounds of GWs would, therefore, provide us with a picture of the universe at earlier times that we can currently access, prior to photon decoupling and Big-Bang nucleosynthesis. It could also shed light on high-energy phenomena, such as high-temperature phase transitions, inflation and new heavy particles that cannot be directly produced in the laboratory.

In the opening session of the workshop, Jorge Cervantes (ININ Mexico) presented a vivid account of the history of GWs, revealing how subtle they are theoretically. It took about 40 years and a number of conflicting papers to definitively establish their existence. Bangalore S Sathyaprakash (Penn State and Cardiff) reviewed the main expected sources of GWs: the gravitational collapse of binaries of compact objects such as black holes, neutron stars and white dwarfs; supernovae and other transient phenomena; spinning neutron stars; and stochastic backgrounds with either astrophysical or cosmological origins. The GW frequency range of interest extends from 0.1 nHz to 1 MHz (see "Sources and sensitivities" figure).

Raffaele Flaminio (LAPP Annecy) reviewed the mindboggling precision of VIRGO and LIGO, which can measure motion 10,000 times smaller than the width of an atomic nucleus. Jörg Wenninger (CERN) reported the similarly impressive sensitivity of LEP and the LHC to small effects, such as tides and earthquakes on the other side of the planet. Famously, LEP's beam-energy resolution was so precise that it detected a diurnal distortion of the 27 km ring at an amplitude of a single millimetre, and the LHC beam-position-monitor system can achieve measurement resolutions on the average circumference approaching the micrometre scale over time intervals of one hour. While impressive, given that these machines are designed with completely different goals in mind, it is still far from the precision achieved by LIGO and VIRGO. However, one can strongly enhance the sensitivity to GWs by exploiting resonant effects and the long distances travelled by the particles over their storage times. In one hour, protons at the LHC travel through the ring about 40 million times. In principle, the precision of modern accelerator optics could allow storage rings and accelerator technologies to cover a portion of the enormous GW frequency range of interest. ▷

We are on the cusp of the era of gravitational-wave astronomy

Resonant responses

Since the invention of the synchrotron, storage rings have been afflicted by difficult-to-control resonance effects that degrade beam quality. When a new ring is commissioned, accelerator physicists work diligently to "tune" the machine's parameters to avoid such effects. But could accelerator physicists turn the tables and seek to enhance these effects and observe resonances caused by the passage of GWs?

In accelerators and storage rings, charged particles are steered and focused in the two directions transverse to their motion by dipole, quadrupole and higher-order magnets – the "betatron motion" of the beam. The beam is also kept bunched in the longitudinal plane as a result of an energy-dependent path length and oscillating electric fields in radio-frequency (RF) cavities – the "synchrotron motion" of the beam. A gravitational wave can resonantly interact with either the transverse betatron motion of a stored beam, at a frequency of several kHz, or with the longitudinal synchrotron motion at a frequency of tens of hertz.

Katsunobu Oide (KEK and CERN) discussed the transverse betatron resonances that a gravitational wave can excite for a beam circulating in a storage ring. Typical betatron frequencies for the LHC are a few kHz, potentially offering sensitivity to GWs with frequencies of a similar order of magnitude. Starting from a standard 30 km ring, Oide-san proposed special beam-optical insertions with a large beta function, which would serve as "GW antennas" to enhance the resonance strength, resulting in 37.5 km-long optics. Among several parameters, the sensitivity to GWs should depend on the size of the ring.

Suvrat Rao (Hamburg University) presented an analysis of the longitudinal beam response of the LHC. An impinging GW affects the revolution period, in a similar way to the static gravitational gradient effect due to the presence of Mont Blanc (which alters the revolution time at the level of 10^{-16} s) and the diurnal effect of the changing locations of the Sun and Moon (10^{-18} s) – the latter effect being about six orders of magnitude smaller than the tidal effect on the ring circumference.

The longitudinal beam response to a GW should be enhanced for perturbations close to the synchrotron frequency, which, for the LHC, would be in the range 10 to 60 Hz. Raffaele D'Agnolo (IPhT) estimated the sensitivity to the gravitational strain, h, at the synchrotron frequency, without any backgrounds, as $h \sim 10^{-13}$, and listed three possible paths to further improve the sensitivity by several orders of magnitude. Rao also highlighted that storage-ring GW detection potentially allows for an Earth-based GW observatory sensitive to millihertz GWs, which could complement space-based laser interferometers such as LISA, which is planned to be launched in 2034. This would improve the sky-localisation of the GW source, which is useful for electromagnetic follow-up studies with astronomical telescopes.

Extraordinarily, storage rings could act not only as GW detectors, but also as observable sources of GWs

ARIES SRGW2021 workshop

Out of the ordinary

More exotic accelerators were also mooted. A "coasting-beam" experiment might have zero restoring voltage and no synchrotron oscillations. Cold "crystalline" beams of stable ordered 1D, 2D or 3D structures of ions (*CERN Courier* November 2001 p8) could open up a whole new frequency spectrum, as the phonon spectrum that could be excited by a GW could easily extend up to the MHz range. Witek Krasny (LPNHE) suggested storing beams consisting of "atomic clocks" in the LHC: decay times and transition rates could be modified by an incident GW. The stored particles could, for example, include the excited partially stripped heavy ions that are the basis of a "gamma factory" (*CERN Courier* November 2017 p7).

Finally on the storage-ring front, Andrey Ivanov (TU Vienna) and coworkers discussed the possibly shrinking circumference of a storage ring, such as the 1.4 km light source SPring-8 in Japan, under the influence of the relic GW background.

Delegates at SRGW2021 also proposed completely different ways of using accelerator technology to detect GWs. Sebastian Ellis (IPhT) explained how an SRF cavity might act as a resonant bar or serve as a Gertsenshtein converter, in both cases converting a graviton into a photon in the presence of a strong background magnetic field and yielding a direct electromagnetic signal – similar to axion searches. Related attempts at GW detection using cavities were pioneered in the 1970s by teams in the Soviet Union and Italy, but RF technology has made big strides in quality factors, cooling and insulation since then, and a new series of experiments appears to be well justified.

Another promising approach for GW detection is atomic-beam interferometry. Instead of light interference, as in LIGO and VIRGO, an incident GW would cause interference between carefully prepared beams of cold atoms. This approach is being pursued by the recently approved AION experiment using ultra-cold-strontium atomic clocks over increasingly large path lengths, including the possible use of an LHC access shaft to house a 100 m device targeting the 0.01 to 1 Hz range (*CERN Courier* March/April 2021 p10). Meanwhile, a space-based version, AEDGE, could be realised with a pair of satellites in medium Earth orbit separated by 4.4×10^{7} m (*CERN Courier* September/October 2019 p23).

Storage rings as sources

Extraordinarily, storage rings could act not only as GW detectors, but also as observable sources of GWs. Pisin Chen (NTU Taiwan) discussed how relativistic charged particles executing circular orbital motion can emit GWs in two channels: "gravitational synchrotron radiation" (GSR) emitted directly by the massive particle, and "resonant conversion" in which, via the Gertsenshtein effect, electromagnetic synchrotron radiation (EMSR) is converted into GWs.

John Jowett (GSI, retired from CERN) and Fritz Caspers (also retired from CERN) recalled that GSR from beams at the SPS and other colliders had been discussed at CERN as early as the 1980s. It was realised that these beams would be among the most powerful terrestrial sources of gravitational radiation, although the total radiated power would still be many orders of magnitude lower than from regular synchrotron radiation. The dominant frequency of direct GSR is the revolution frequency, ~10 kHz, while the dominant frequency of resonant EMSR-GSR conversion is a factor γ^3 higher, around 10 THz at the LHC, conceivably allowing the observation of gravitons. If all particles and bunches of a beam excited the GW coherently, the space-time metric perturbation has been estimated to ▷

CERNCOURIER
VOLUME 61 NUMBER 4 JULY/AUGUST 2021
IOP Publishing

be as large as $h_{GSR} \sim 10^{-18}$. Gravitons could also be emitted via "gravitational beam-strahlung" during the collision with an opposing beam, perhaps producing the most prominent GW signal at future proposed lepton colliders. At the LHC, argued Caspers, such signals could be detected by a torsion-balance experiment with a very sensitive, resonant mechanical pickup installed close to the beam in one of the arcs. In a phase-lock mode of operation, an effective resolution bandwidth of millihertz or below could be possible, opening the exciting prospect of detecting synthetic sources of GWs.

The concluding workshop discussion, moderated by John Ellis (King's College London), focused on the GW-detection proposals considered closest to implementations: resonant betatron oscillations near 10 kHz; changes in the revolution period using "low-energy" coasting ion-beams without a longitudinally focusing RF system; "heterodyne" detection using SRF cavities up to 10 MHz; beam-generated GWs at the LHC; and atomic interferometry. These potential components of a future R&D plan cover significant regions of the enormous GW frequency space.

New horizons

Apart from an informal meeting at CERN in the 1990s, SRGW2021 was the first workshop to link accelerators and GWs, and bring together the implicated scientific communities. Lively discussions in this emerging field attest to the promise of employing accelerators in a completely different way to either detect or generate GWs. The subtleties of the particle dynamics when embedded in an oscillating fabric of space and time, and the inherent sensitivity problems in detecting GWs, pose exceptional challenges. The great interest prompted by SRGW2021, and the tantalising preliminary findings from this workshop, call for more thorough investigations into harnessing future storage rings and accelerator technologies for GW physics.

Gravitons could be emitted via gravitational beamstrahlung

Raffaele Tito D'Agnolo *IPhT,*
Giuliano Franchetti *GSI and*
Frank Zimmermann *CERN.*

MINI-WORKSHOP ON GAS TRANSPORT PARAMETERS

Greening gaseous detectors


B Regnery

Trigger and track *In ATLAS and CMS (pictured), gaseous detectors form the backbone of the experiments' muon systems.*

Thanks to their large volumes and cost effectiveness, particle-physics experiments rely heavily on gaseous detectors. Unfortunately, environmentally harmful hydrofluorocarbons known as freons play an important role in traditional gas mixtures. To address this issue, more than 200 gas-detector experts participated in a workshop hosted online by CERN on 22 April to study the operational behaviour of novel gases and alternative gas mixtures.

Freon-based gases are essential to many detectors currently used at CERN, especially for tracking and triggering. Examples run from muon systems, ring-imaging Cherenkov (RICH) detectors and time-projection chambers (TPCs) to wire chambers, resistive-plate chambers (RPCs) and micro-pattern gas detectors (MPGDs). While the primary gas in the mixture is typically a noble gas, adding a "quencher" gas helps achieve a stable gas gain, well separated from the noise of the electronics. Large gas molecules such as freons absorb energy in relevant vibrational and rotational modes of excitation, thereby preventing secondary effects such as photon feedback and field emission. Extensive R&D is needed to reach the stringent performance required of each gas mixture.

CERN has developed several strategies to reduce greenhouse-gas emissions from particle detectors. As demonstrated by the ALICE experiment's TPC, gas-recirculation systems can reduce emissions by almost 100%. When it is not possible to recirculate all of the gas mixture, gas recuperation is an option – for example, the recuperation of CF_4 by the CMS experiment's cathode-strip-chamber (CSC) muon detector and the LHCb experiment's RICH-2 detector. A complex gas-recuperation system for the $C_2H_2F_4$ (R134a) in RPC detectors is also under study, and physicists are exploring the use of commonplace gases. In the future, new silicon photomultipliers could reduce chromatic error and increase photon yield, potentially allowing CF_4 to be replaced with CO_2. Meanwhile, in LHCb's RICH-1 detector, C_4F_{10} could possibly be replaced with hydrocarbons like C_4H_{10} if the flammability risk is addressed.

Finally, alternative "eco-gases" are the subject of intense R&D. Eco-gases have a low global-warming potential because of their very limited stability in the atmosphere as they react with water or decompose in ultraviolet light. Unfortunately, these conditions are also present in gaseous detectors, potentially leading to detector aging. In addition to their stability, there is also the challenge of adapting current LHC detectors, given that access is difficult and many components cannot be replaced.

Roberto Guida (CERN), Davide Piccolo (Frascati), Rob Veenhof (Uludağ University) and Piet Verwilligen (Bari) convened workshop sessions at the April event. Groups from Turin, Frascati, Rome, CERN and GSI presented results based on the new hydro-fluoro-olefin (HFO) mixture with the addition of neutral gases such as helium and CO_2 as a way of lowering the high working-point voltage. Despite challenges related to the larger signal charge and streamer probability, encouraging results have been obtained in test beams in the presence of LHC-like background gamma rays. CMS's CSC ▷

detector is an interesting example where HFO could replace CF_4. In this case, its decomposition could even be a positive factor, however more studies are needed.

We now need to create a compendium of simulations and measurements for "green" gases in a similar way to the concerted effort in the 1990s and 2000s that proved indispensable to the design of the LHC detectors. To this end, the INRS-hosted LXCAT database enables the sharing and evaluation of data to model non-equilibrium low-temperature plasmas. Users can upload data on electron- and ion-scattering cross sections and compare "swarm" parameters. The ETH Zürich, Aachen and HZDR (Dresden) groups illustrated measurements of transport parameters, opening possibilities of collaboration, while the Bari group sought feedback and collaboration on a proposal to precisely measure transport parameters for green gases in MPGDs using electron and laser beams.

Future challenges will be significant. The volumes of detector systems for the High-Luminosity LHC and the proposed Future Circular Collider, for example, range from 10 to 100 m^3, posing a significant environmental threat in the case of leaks. Furthermore, since 2014 an EU "F-gas" regulation has come into force, with the aim of reducing sales to one-fifth by 2030. Given the environmental impact and the uncertain availability and price of freon-based gases, preparing a mitigation plan for future experiments is of fundamental importance to the high-energy-physics community, and the next generation of detectors must be completely designed around eco-mixtures. Although obtaining funding for this work can be difficult, for example due to a lack of expected technological breakthroughs in low-energy plasma physics, the workshop showed that a vibrant cadre of physicists is committed to taking the field forward. The next workshop will take place in 2022.

We now need to create a compendium of simulations and measurements for "green" gases

Archana Sharma *CERN.*

EUROPEAN CONSORTIUM FOR ASTROPARTICLE THEORY ANNUAL SYMPOSIUM

Astroparticle theory in rude health

The European Consortium for Astroparticle theory (EuCAPT) held its first annual symposium from 5 to 7 May. Hundreds of theoretical physicists from Europe and beyond met online to discuss the present and future of astroparticle physics and cosmology, in a dense and exciting meeting that featured 29 invited presentations, 42 lightning talks by young researchers, and two community-wide brainstorming sessions.

Participants discussed a wide array of topics at the interface between particle physics, astrophysics and cosmology, with particular emphasis on the challenges and opportunities for these fields in the next decade. Rather than focusing on experimental activities and the discoveries they might enable, the sessions were structured around thematic areas and explored the interdisciplinary multi-messenger aspects of each.


N Sarcevic/R Nenad/M Rayner

Unleashing potential *A visualisation of the "EuCAPT census" of theoretical astroparticle physicists and cosmologists who are affiliated to a research institution in a European country.*

Two sessions were dedicated to cosmology, exploring the early and late universe. As stressed by Geraldine Servant (Hamburg), several unresolved puzzles of particle physics – such as the origin of dark matter, the baryon asymmetry, and inflation – are directly linked to the early universe, and new observational probes may soon shed new light on them. Julien Lesgourgues (Aachen) showed how the very same puzzles are also linked to the late universe, and cautiously elaborated on a series of possible inconsistencies between physical quantities inferred from early- and late-universe probes, for example the Hubble constant. Those inconsistencies represent both a challenge and an extraordinary opportunity for cosmology, as they might "break" the standard Lambda-cold-dark-matter model of cosmology, and allow us to gain insights into the physics of dark matter, dark energy and gravity.

New strategies to go beyond the standard models of particle physics and cosmology were also discussed by Marco Cirelli (LPTHE) and Manfred Lindner (Heidelberg), in the framework of dark-matter searches and neutrino physics, respectively. Progress in both fields is currently not limited by a lack of ideas – we are actually witnessing a proliferation of theoretically well-motivated models – but by the difficulty of identifying experimental strategies to conclusively validate or rule them out. Much of the discussion here concerned prospects for detecting new physics with dedicated ex s and multi-messenger observations.

Gravitational waves have added a new observational probe in astroparticle physics and cosmology. Alessandra Buonanno (Max Planck Institute for Gravitational Physics) illustrated the exciting prospects for this new field of research, whose potential for discovering new physics is attracting enormous interest from particle and astroparticle theorists. The connection between cosmic rays, gamma rays and high-energy neutrinos was explored in the final outlook by Elena Amato (Arcetri Astrophysical Observatory), who highlighted how progress in theory and observations is leading the community to reconsider some long-held beliefs – such as the idea that supernova remnants are the acceleration sites of cosmic rays up to the so-called "knee" – and stimulating new ideas.

In line with EuCAPT's mission, the local organisers and the consortium's steering committee organised a series of community-building activities. Participants stressed the importance of supporting diversity and inclusivity, a continuing high priority for EuCAPT, while a second brainstorming session was devoted to the discussion of the EuCAPT white paper currently being written, which should be published by September. Last but not least, Hannah Banks (Cambridge), Francesca Capel (TU Munich) and Charles Dalang (University of Geneva) received prizes for the best lightning talks, and Niko Sarcevic (Newcastle) was awarded an "outstanding contributor" prize for the help and support she provides for the analysis of the EuCAPT census (pictured).

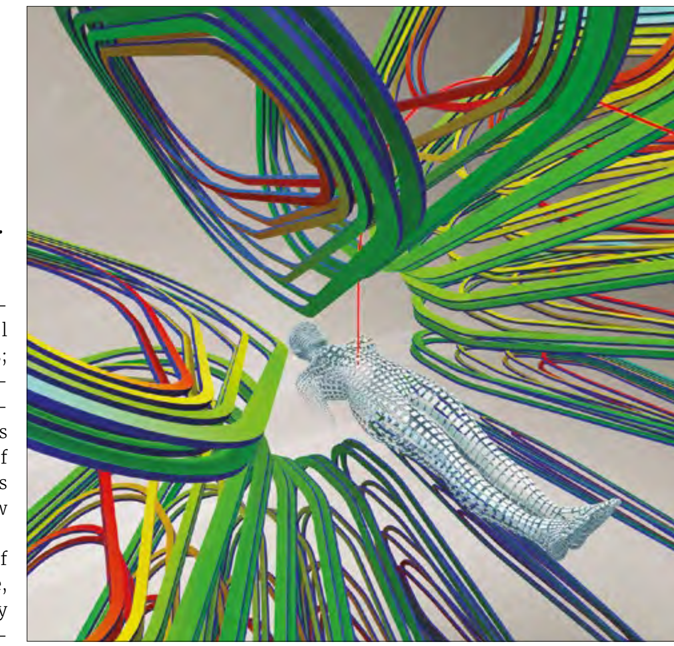
The next symposium will take place in 2022, hopefully in person, at CERN.

Gianfranco Bertone *EuCAPT director.*

CERNCOURIER
VOLUME 61 NUMBER 4 JULY/AUGUST 2021
IOP Publishing

CERN'S IMPACT ON MEDICAL TECHNOLOGY

Frontier instruments like the LHC and its detectors not only push back the boundaries of our knowledge, but also catalyse innovative technology for medical applications, writes Manuela Cirilli.



GaToroid *Innovative gantry designs reduce the size, weight and complexity of the massive magnetic structures that allow a hadron-therapy beam (red) to reach the patient from different angles.*

Today, the tools of experimental particle physics are ubiquitous in hospitals and biomedical research. Particle beams damage cancer cells; high-performance computing infrastructures accelerate drug discoveries; computer simulations of how particles interact with matter are used to model the effects of radiation on biological tissues; and a diverse range of particle-physics-inspired detectors, from wire chambers to scintillating crystals to pixel detectors, all find new vocations imaging the human body.

CERN has actively pursued medical applications of its technologies as far back as the 1970s. At that time, knowledge transfer happened – mostly serendipitously – through the initiative of individual researchers. An eminent example is Georges Charpak, a detector physicist of outstanding creativity who invented the Nobel-prize-winning multiwire proportional chamber (MWPC) at CERN in 1968.The MWPC's ability to record millions of particle tracks per second opened a new era for particle physics (*CERN Courier* December 1992 p1). But Charpak strived to ensure that the technology could also be used outside the field – for example in medical imaging, where its sensitivity promised to reduce radiation doses during imaging procedures – and in 1989 he founded a company that developed an imaging technology for radiography which is currently deployed as an orthopaedic application. Following his example, CERN has continued to build a culture of entrepreneurship ever since.

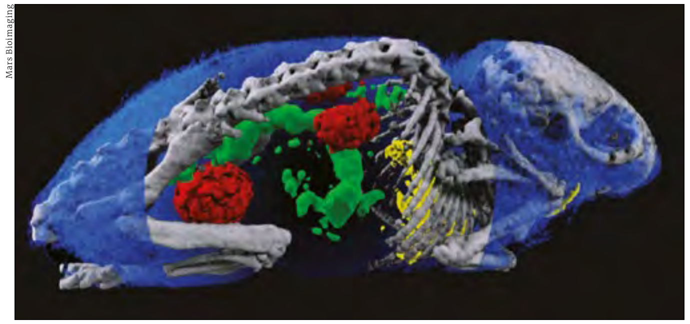
Triangulating tumours

Since as far back as the 1950s, a stand-out application for particle-physics detector technology has been positron-emission tomography (PET) – a "functional" technique that images changes in the metabolic process rather than anatomy. The patient is injected with a compound carrying a positron-emitting isotope, which accumulates in areas of the body with high metabolic activity (the uptake of glucose, for example, could be used to identify a malignant tumour). Pairs of back-to-back 511 keV photons are detected when a positron annihilates with an electron in the surrounding matter, allowing the tumour to be triangulated.

Pioneering developments in PET instrumentation took place in the 1970s. While most scanners were based on scintillating crystals, the work done with wire chambers at the University of California at Berkeley inspired CERN physicists David Townsend and Alan Jeavons to use high-density avalanche chambers (HIDACs) – Charpak's detector plus a photon-conversion layer (*CERN Courier* June 2005 p23). In 1977, with the participation of CERN radiobiologist Marilena Streit-Bianchi, this technology was used to create some of the first PET images, most famously of a mouse. The HIDAC detector later contributed significantly to 3D PET image reconstruction, while a prototype partial-ring tomograph developed at CERN was a forerunner for combined PET and computed tomography

THE AUTHOR
Manuela Cirilli
CERN.

CERNCOURIER
Volume 61 Number 4 July/August 2021
IOP Publishing

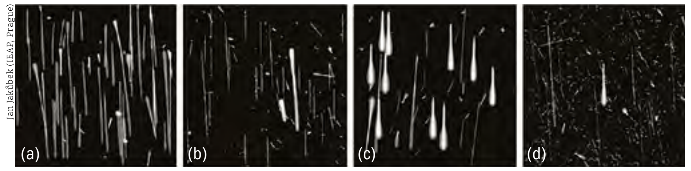


Mars Bioimaging

Colour X-ray *Spectroscopic techniques using CERN's Medipix chips may be used to partly cut away water (blue), to reveal bone and organs in this colour X-ray of a mouse.*

M Brice/CERN-PHOTO-201803-081-2

Radioisotopes *In the MEDICIS project, non-conventional isotopes are collected by mass separation.*



Jan Jakůbek (IEAP, Prague)

Hadron therapy *In these images, Timepix chips were combined with a silicon detector to visualise energy deposition from (a) 48 MeV protons, (b) 221 MeV protons, (c) 89 MeV/u carbon ions and (d) 430 MeV/u carbon ions. In each case, secondary particles are present only at the higher energy.*

(CT) scanners. Townsend went on to work at the Cantonal Hospital in Geneva and then in the US, where his group helped develop the first PET/CT scanner, which combines functional and anatomic imaging.

Crystal clear

In the onion-like configuration of a collider detector, an electromagnetic calorimeter often surrounds a descendant of Charpak's wire chambers, causing photons and electrons to cascade and measuring their energy. In 1991, to tackle the challenges posed by future detectors at the LHC, the Crystal Clear collaboration was formed to study innovative scintillating crystals suitable for electromagnetic calorimetry (*CERN Courier* November 2016 p17). Since its early years, Crystal Clear also sought to apply the technology to other fields, including healthcare. Several breast, pancreas, prostate and animal-dedicated PET scanner prototypes have since been developed, and the collaboration continues to push the limits of coincidence-time resolution for time-of-flight (TOF) PET.

In TOF-PET, the difference between the arrival times of the two back-to-back photons is recorded, allowing the location of the annihilation along the axis connecting the detection points to be pinned down. Better time resolution therefore improves image quality and reduces the acquisition time and radiation dose to the patient. Crystal Clear continues this work to this day through the development of innovative scintillating-detector concepts, including at a state-of-the-art laboratory at CERN.

The dual aims of the collaboration have led to cross-fertilisation, whereby the work done for high-energy physics spills over to medical imaging, and vice versa. For example, the avalanche photodiodes developed for the CMS electromagnetic calorimeter were adapted for the ClearPEM breast-imaging prototype, and technology developed for detecting pancreatic and prostate cancer (EndoTOFPET-US) inspired the "barrel timing layer" of crystals that will instrument the central portion of the CMS detector during LHC Run 3.

Pixel perfect

In the same 30-year period, the family of Medipix and Timepix read-out chips has arguably made an even bigger impact on med-tech and other application fields, becoming one of CERN's most successful technology-transfer cases. Developed with the support of four successive Medipix collaborations, involving a total of 37 research institutes, the technology is inspired by the high-resolution hybrid pixel detectors initially developed to address the challenges of particle tracking in the innermost layers of the LHC experiments. In hybrid detectors, the sensor array and the read-out chip are manufactured independently and later coupled by a bump-bonding process. This means that a variety of sensors can be connected to the Medipix and Timepix chips, according to the needs of the end user.

The first Medipix chip produced in the 1990s by the Medipix1 collaboration was based on the front-end architecture of the Omega3 chip used by the half-million-pixel tracker of the WA97 experiment, which studied strangeness production in lead-ion collisions. The upgraded Medipix1 chip also included a counter per pixel. This demonstrated that the chips could work like a digital camera, providing high-resolution, high-contrast and noise-hit-free images, making them uniquely suitable for medical applications. Medipix2 improved spatial resolution and produced a modified version called Timepix that offers time or amplitude measurements in addition to hit counting. Medipix3 and Timepix3 then allowed the energy of each individual photon to be measured – Medipix3 allocates incoming hits to energy bins in each pixel, providing colour X-ray images, while Timepix3 times hits with a precision of 1.6 ns, and sends the full hit data – coordinate, amplitude and time – off chip. Most recently, the Medipix4 collaboration, which was launched in 2016, is designing chips that can seamlessly cover large areas, and is developing new read-out architectures, thanks to the possibility of

tiling the chips on all four sides.

Medipix and Timepix chips find applications in widely varied fields, from medical imaging to cultural heritage, space dosimetry, materials analysis and education. The industrial partners and licence holders commercialising the technology range from established enterprises to start-up companies. In the medical field, the technology has been applied to X-ray CT prototype systems for digital mammography, CT imagers for mammography, and beta- and gamma-autoradiography of biological samples. In 2018 the first 3D colour X-ray images of human extremities were taken by a scanner developed by MARS Bioimaging Ltd, using the Medipix3 technology. By analysing the spectrum recorded in each pixel, the scanner can distinguish multiple materials in a single scan, opening up a new dimension in medical X-ray imaging: with this chip, images are no longer black and white, but in colour (see "Colour X-ray" image).

Although the primary aim of the Timepix3 chip was applications outside of particle physics, its development also led directly to new solutions in high-energy physics, such as the VELOpix chip for the ongoing LHCb upgrade, which permits data-driven trigger-free operation for the first time in a pixel vertex detector in a high-rate experiment.

Dosimetry

CERN teams are also exploring the potential uses of Medipix technology in dosimetry. In 2019, for example, Timepix3 was employed to determine the exposure of medical personnel to ionising radiation in an interventional radiology theatre at Christchurch Hospital in New Zealand. The chip was able to map the radiation fluence and energy spectrum of the scattered photon field that reaches the practitioners, and can also provide information about which parts of the body are most exposed to radiation.

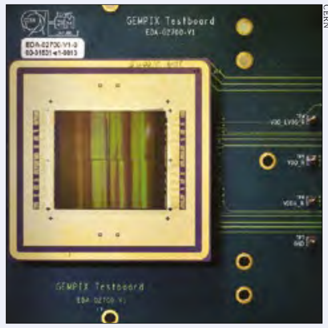
Meanwhile, "GEMPix" detectors are being evaluated for use in quality assurance in hadron therapy. GEMPix couples gas electron multipliers (GEMs) – a type of gaseous ionisation detector developed at CERN – with the Medipix integrated circuit as readout to provide a hybrid device capable of detecting all types of radiation with a high spatial resolution. Following initial results from tests on a carbon-ion beam performed at the National Centre for Oncological Hadrontherapy (CNAO) in Pavia, Italy, a large-area GEMPix detector with an innovative optical read-out is now being developed at CERN in collaboration with the Holst Centre in the Netherlands. A version of the GEMPix called GEMTEQ is also currently under development at CERN for use in "microdosimetry", which studies the temporal and spatial distributions of absorbed energy in biological matter to improve the safety and effectiveness of cancer treatments.

Two further dosimetry applications illustrate how technologies developed for CERN's needs have expanded into commercial medical applications. The B-RAD, a hand-held radiation survey meter designed to operate in strong magnetic fields, was developed by CERN in collaboration with the Polytechnic of Milan and is now available off-the-shelf from an Italian company. Originally conceived for radiation surveys around the LHC experiments and inside ATLAS with the magnetic field on, it has found applications in several other tasks, such as radiation measurements on permanent magnets, radiation surveys at PET-MRI scanners and at MRI-guided radiation therapy linacs. Meanwhile, the radon dose monitor (RaDoM) tackles exposure to radon, a natural radioactive gas that is the second leading cause of lung cancer after smoking. The RaDoM device directly estimates the dose by reproducing the energy deposition inside the lung instead of deriving the dose from a measurement of radon concentration in air; CERN also developed a cloud-based service to collect and analyse the data, to control the measurements and to drive mitigation measures based on real time data. The technology is licensed to the CERN spin-off BAQ.

Knowledge transfer at CERN

As a publicly funded laboratory, CERN has a remit, in addition to its core mission to perform fundamental research in particle physics, to expand the opportunities for its technology and expertise to deliver tangible benefits to society. The CERN Knowledge Transfer group strives to maximise the impact of CERN technologies and know-how on society in many ways, including through the establishment of partnerships with clinical, industrial and academic actors, support to budding entrepreneurs and seed funding to CERN personnel.

Supporting the knowledge-transfer process from particle physics to medical research and the med-tech industry is a promising avenue to boost healthcare innovation and provide solutions to present and future health challenges. CERN has provided a framework for the application of its technologies to the medical domain through a dedicated strategy document approved by its Council in June 2017 (*CERN Courier* January/February 2018 p5) . CERN will continue its efforts to maximise the impact of the laboratory's know-how and technologies on the medical sector.



CERN

Tangible benefits *GEMPix detectors are being evaluated for use in quality assurance in hadron therapy.*

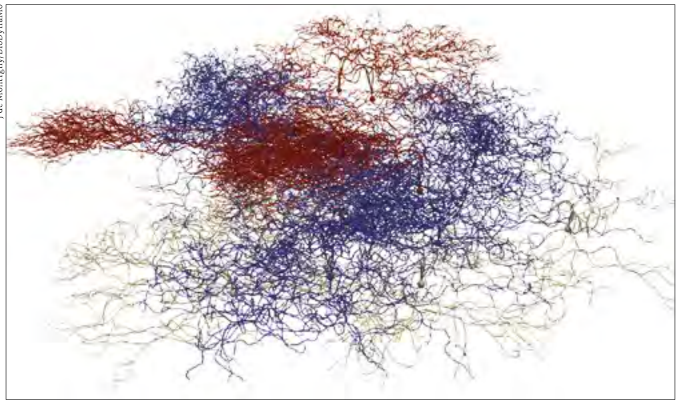
Cancer treatments

Having surveyed the medical applications of particle detectors, we turn to the technology driving the beams themselves. Radiotherapy is a mainstay of cancer treatment, using ionising radiation to damage the DNA of cancer cells. In most cases, a particle accelerator is used to generate a therapeutic beam. Conventional radiation therapy uses X-rays generated by a linac, and is widely available at relatively low cost.

Radiotherapy with protons was first proposed by Fermilab's founding director Robert Wilson in 1946 while he was at Berkeley, and interest in the use of heavier ions such as carbon arose soon after. While X-rays lose energy roughly exponentially as they penetrate tissue, protons and other ions deposit almost all of their energy in a sharp "Bragg" peak at the very end of their path, enabling the dose to be delivered on the tumour target, while sparing

Medipix and Timepix read-out chips have become one of CERN's most successful technology-transfer cases

CERNCOURIER
Volume 61 Number 4 July/August 2021
IOP Publishing



J de Montigny/BioDynaMo

Computational neuroscience *BioDynaMo simulation of a dendritic arbour.*

the surrounding healthy tissues. Carbon ions have the additional advantage of a higher radiobiological effectiveness, and can control tumours that are radio-resistant to X-rays and protons. Widespread adoption of hadron therapy is, however, limited by the cost and complexity of the required infrastructures, and by the need for more pre-clinical and clinical studies.

PIMMS and NIMMS

Between 1996 and 2000, under the impulsion of Ugo Amaldi, Meinhard Regler and Phil Bryant, CERN hosted the Proton-Ion Medical Machine Study (PIMMS). PIMMS produced and made publicly available an optimised design for a cancer-therapy synchrotron capable of using both protons and carbon ions. After further enhancement by Amaldi's TERA foundation, and with seminal contributions from Italian research organisation INFN, the PIMMS concept evolved into the accelerator at the heart of the CNAO hadron therapy centre in Pavia. The MedAustron centre in Wiener Neustadt, Austria, was then based on the CNAO design. CERN continues to collaborate with CNAO and MedAustron by sharing its expertise in accelerator and magnet technologies (*CERN Courier* January/February 2018 p25).

In the 2010s, CERN teams put to use the experience gained in the construction of Linac 4, which became the source of proton beams for the LHC in 2020, and developed an extremely compact high-frequency radio-frequency quadrupole (RFQ) to be used as injector for a new generation of high-frequency, compact linear accelerators for proton therapy. The RFQ accelerates the proton beam to 5 MeV after only 2 m, and operates at 750 MHz – almost double the frequency of conventional RFQs. A major advantage of using linacs for proton therapy is the possibility of changing the energy of the beam, and hence the depth of treatment in the body, from pulse to pulse by switching off some of the accelerating units. The RFQ technology was licensed to the CERN spin-off ADAM, now part of AVO (Advanced Oncotherapy), and is being used as an injector for a breakthrough linear proton therapy machine at the company's UK assembly and testing centre at STFC's Daresbury Laboratory.

In 2019 CERN launched the Next Ion Medical Machine Study (NIMMS) to develop cutting-edge accelerator technologies for a new generation of compact and cost-effective ion-therapy facilities. The goal is to propel the use of ion therapy, given that proton installations are already commercially available and that only four ion centres exist in Europe, all based on bespoke solutions.

NIMMS is organised along four different lines of activities. The first aims to reduce the footprint of facilities by developing new superconducting magnet designs with large apertures and curvatures, and for pulsed operation. The second is the design of a compact linear accelerator optimised for installation in hospitals, which includes an RFQ based on the design of the proton therapy RFQ, and a novel source for fully-stripped carbon ions. The third concerns two innovative gantry designs, with the aim of reducing the size, weight and complexity of the massive magnetic structures that allow the beam to reach the patient from different angles: the SIGRUM lightweight rotational gantry originally proposed by TERA, and the GaToroid gantry invented at CERN which eliminates the need to mechanically rotate the structure by using a toroidal magnet (see figure "GaToroid"). Finally, new high-current synchrotron designs will be developed to reduce the cost and footprint of facilities while reducing the treatment time compared to present European ion-therapy centres: these will include a superconducting and a room-temperature option, and advanced features such as multi-turn injection for 10^{10} particles per pulse, fast and slow extraction, and multiple ion operation. Through NIMMS, CERN is contributing to the efforts of a flourishing European community, and a number of collaborations have been already established.

Another recent example of frontier radiotherapy techniques is the collaboration with Switzerland's Lausanne University Hospital (CHUV) to build a new cancer therapy facility that would deliver high doses of radiation from very-high-energy electrons (VHEE) in milliseconds instead of minutes. The goal here is to exploit the so-called FLASH effect, wherein radiation doses administered over short time periods appear to damage tumours more than healthy tissue, potentially minimising harmful side-effects. This pioneering installation will be based on the high-gradient accelerator technology developed for the proposed CLIC electron–positron collider. Various research teams have been performing their biomedical research related to VHEE and FLASH at the CERN Linear Electron Accelerator for Research (CLEAR), one of the few facilities available for characterising VHEE beams.

Radioisotopes

CERN's accelerator technology is also deployed in a completely different way to produce innovative radioisotopes for medical research. In nuclear medicine, radioisotopes are used both for internal radiotherapy and for diagnosis of cancer and other diseases, and progress has always been connected to the availability of novel radioisotopes. Here, CERN has capitalised on the experience of its ISOLDE facility, which during the past 30 years has the proton beam from the CERN PS Booster to produce 1300 different isotopes from 73 chemical elements for research ranging from nuclear physics to the life sciences. A new facility, called ISOLDE-MEDICIS, is entirely dedicated to the production of unconventional radioisotopes with the right properties to enhance the precision of both patient

imaging and treatment. In operation since late 2017, MEDICIS will expand the range of radioisotopes available for medical research – some of which can be produced only at CERN – and send them to partner hospitals and research centres for further studies. During its 2019 and 2020 harvesting campaigns, for example, MEDICIS demonstrated the capability of purifying isotopes such as ^{169}Er or ^{153}Sm to new purity grades, making them suitable for innovative treatments such as targeted radioimmunotherapy.

Data handling and simulations

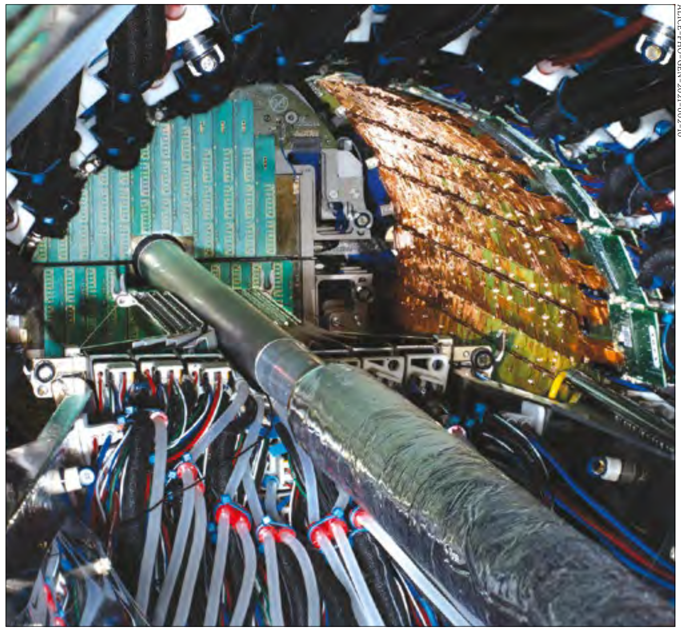
The expertise of particle physicists in data handling and simulation tools are also increasingly finding applications in the biomedical field. The FLUKA and Geant4 simulation toolkits, for example, are being used in several applications, from detector modelling to treatment planning. Recently, CERN contributed its know-how in large-scale computing to the BioDynaMo collaboration, initiated by CERN openlab together with Newcastle University, which initially aimed to provide a standardised, high-performance and open-source platform to support complex biological simulations (see figure "Computational neuroscience"). By hiding its computational complexity, BioDynaMo allows researchers to easily create, run and visualise 3D agent-based simulations. It is already used by academia and industry to simulate cancer growth, accelerate drug discoveries and simulate how the SARS-CoV-2 virus spreads through the population, among other applications, and is now being extended beyond biological simulations to visualise the collective behaviour of groups in society.

Many more projects related to medical applications are in their initial phases. The breadth of knowledge and skills available at CERN was also evident during the COVID-19 pandemic when the laboratory contributed to the efforts of the particle-physics community in fields ranging from innovative ventilators to masks and shields, from data management tools to open-data repositories, and from a platform to model the concentration of viruses in enclosed spaces to epidemiologic studies and proximity-sensing devices, such as those developed by Terabee.

Fundamental research has a priceless goal: knowledge for the sake of knowledge. The theories of relativity and quantum mechanics were considered abstract and esoteric when they were developed; a century later, we owe to them the remarkable precision of GPS systems and the transistors that are the foundation of the electronics-based world we live in. Particle-physics research acts as a trailblazer for disruptive technologies in the fields of accelerators, detectors and computing. Even though their impact is often difficult to track as it is indirect and diffused over time, these technologies have already greatly contributed to the advances of modern medicine and will continue to do so. ●

The expertise of particle physicists in data handling and simulation tools are increasingly finding applications in the biomedical field

ALICE TRACKS NEW TERRITORY



All in *Half of the three-layer inner barrel (surrounding the beampipe) and the first layer of the outer barrel (gold) of ALICE's "ITS2", along with the new muon forward tracker (green panel).*

The recently installed, upgraded ALICE inner tracking system is the largest pixel detector ever built and the first at the LHC to use monolithic active pixel sensors, describe Luciano Musa and Stefania Beolé.

In the coming decade, the study of nucleus–nucleus, proton–nucleus and proton–proton collisions at the LHC will offer rich opportunities for a deeper exploration of the quark–gluon plasma (QGP). An expected 10-fold increase in the number of lead–lead (Pb–Pb) collisions should both increase the precision of measurements of known probes of the QGP medium as well as give access to new ones. By focusing on rare probes down to very low transverse momentum, such as heavy-flavour particles, quarkonium states, real and virtual photons, as well as the study of jet quenching and exotic heavy nuclear states, very large data samples will be required.

To seize these opportunities, the ALICE collaboration has undertaken a major upgrade of its detectors to increase the event readout, online data processing and recording capabilities by nearly two orders of magnitude (*CERN Courier* January/February 2019 p25). This will allow Pb–Pb minimum-bias events to be recorded at rates in excess of 50 kHz, which is the expected Pb–Pb interaction rate at the LHC in Run 3, as well as proton–lead (p–Pb) and proton–proton (pp) collisions at rates of about 500 kHz and 1 MHz, respectively. In addition, the upgrade will improve the ability of the ALICE detector to distinguish secondary vertices of particle decays from the interaction vertex and to track very low transverse-momentum particles. This will allow measurements of heavy-flavour hadrons and low-mass dileptons with unprecedented precision and down to zero transverse momentum.

These ambitious physics goals have motivated the development of an entirely new inner tracking system, ITS2. Starting from LHC Run 3 next year, the ITS2 will allow pp and Pb–Pb collisions to be read out 100 and 1000 times more quickly than was possible in previous runs, offering superior ability to measure particles at low transverse momenta (see "High impact" figure). Moreover, the inner three layers of the ITS2 feature a material budget three times lower than the original detector, which is also important for improving the tracking performance at low transverse momentum.

With its $10\,m^2$ of active silicon area and nearly 13 billion pixels, the ITS2 is the largest pixel detector ever built. It is also the first detector at the LHC to use monolithic active pixel sensors (MAPS), instead of the more conventional and well-established hybrid pixels and silicon microstrips.

Change of scale

The particle sensors and the associated readout electronics used for vertexing and tracking detection systems in particle-physics experiments have very demanding requirements in terms of granularity, material thickness, readout speed and radiation hardness. The development of sensors based on silicon-semiconductor technology and readout integrated circuits based on CMOS technology revolutionised the implementation of such detection systems. The development of silicon microstrips and hybrid pixel detectors, already successfully used at the Large Electron–Positron (LEP) collider, enabled the construction of tracking and vertexing detectors that meet the extreme requirements – in terms of particle rates and radiation hardness – set by the LHC. As a result, silicon microstrip and pixel sensors are at the heart of the particle-tracking systems in most particle-physics

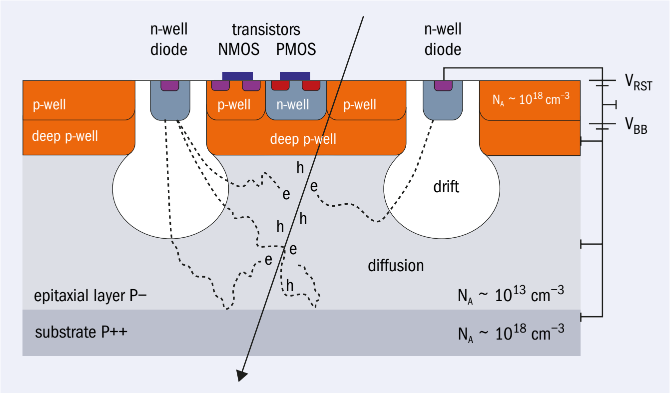
THE AUTHORS

Luciano Musa *CERN and* **Stefania Beolé** *University of Torino and INFN.*

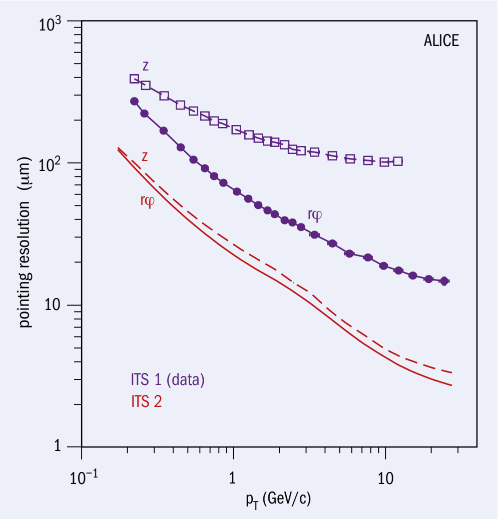
CERNCOURIER

Volume 61 Number 4 July/August 2021

IOP Publishing



ALPIDE journeys *A schematic cross-section of the ALPIDE chip. When a charged particle traverses the silicon sensor's active volume, it liberates charge carriers (electron and holes) in the semiconductor material. The released charge is then collected by electrodes (reversed-biased junction diodes) that reveal not only the presence of a particle but also, due to the fine segmentation, its impinging point onto the sensor. The nature and quantitative behaviour of the charge collection mechanism are functions of the material properties (doping concentration N_A and profile) and geometry (thickness of sensitive material, pixel pitch, electrode shape) as well as the electric field configuration (electrode potential and geometry) of the sensor.*



High impact *The pointing resolution as a function of the transverse momentum for the original ALICE tracker, ITS1, (experimental data) and the upgraded ITS2 (simulated) along the z-axis and in the transverse (rφ) plane.*

experiments today (see p39).

Nevertheless, compromises exist in the implementation of this technology. Perhaps the most significant is the interface between the sensor and the readout electronics, which are typically separate components. To go beyond these limitations and construct detection systems with higher granularity and less material thickness requires the development of new technology. The optimal way to achieve this is to integrate both sensor and readout electronics to create a single detection device. This is the approach taken with CMOS active pixel sensors (APSs). Over the past 20 years, extensive R&D has been carried out on CMOS APSs, making this a viable option for vertexing and tracking detection systems in particle and nuclear physics, although their performance in terms of radiation hardness is not yet at the level of hybrid pixel detectors.

The first large-scale application of CMOS APS technology in a collider experiment was the STAR PXL detector at Brookhaven's Relativistic Heavy-Ion Collider in 2014 (*CERN Courier* October 2015 p6). The ALICE ITS2 has benefitted from significant R&D since then, in particular concerning the development of a more advanced CMOS imaging sensor, named ALPIDE, with a minimum feature size of 180 nm. This has led to a significant improvement in the field of MAPS for single-particle detection, reaching unprecedented performance in terms of signal/noise ratio, spatial resolution, material budget and readout speed.

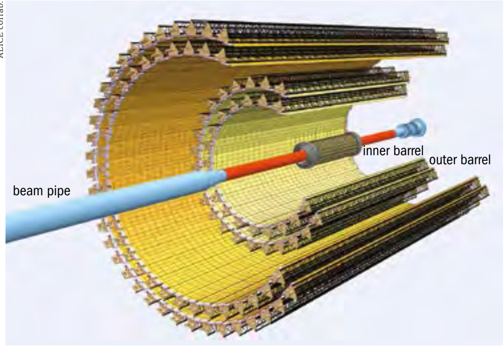
ALPIDE, which is the result of an intensive R&D effort, is the building block of the ITS2

ALPIDE sensors

ALPIDE, which is the result of an intensive R&D effort carried out by ALICE over the past eight years, is the building block of the ITS2. The chip is 15 × 30 mm² in area and contains more than half a million pixels organised in 1024 columns and 512 rows. Its very low power consumption (< 40 mW/cm²) and excellent spatial resolution (~5 µm) are perfect for the inner tracker of ALICE.

In ALPIDE the sensitive volume is a 25 µm-thick layer of high-resistivity p-type silicon (> 1 kΩ cm) grown epitaxially on top of a standard (low-resistivity) CMOS wafer (see "ALPIDE journeys" figure). The electric charge generated by particles traversing the sensitive volume is collected by an array of n–p diodes reverse-biased with a positive potential (~1 V) applied on the n-well electrode and a negative potential (down to a minimum of –6 V) applied to the substrate (backside). The possibility of varying the reverse-bias voltage in the range 1 to 7 V allows control over the size of the depleted volume (the fraction of the sensitive volume where the charge is collected by drift due to the presence of an electric field) and, correspondingly, the charge-collection time. Measurements carried out on sensors with characteristics identical to ALPIDE have shown an average charge-collection time consistently below 15 ns for a typical reverse-bias voltage of 4 V. Applying reverse substrate bias to the ALPIDE sensor also increases the tolerance to non-ionising energy loss to well beyond 10^{13} 1 MeV n_{eq}/cm², which is largely sufficient to meet ALICE's requirements.

Another important feature of ALPIDE is the use of a p-well to shield the full CMOS circuitry from the epitaxial layer. Only the n-well collection electrode is not shielded. The deep p-well prevents all other n-wells – which contain circuitry – from collecting signal charge from the epitaxial layer, and therefore allows the use of full CMOS and consequently more complex readout circuitry in the pixel. ALICE is the first experiment where this has been used to implement a MAPS with a pixel front-end (amplifier and discriminator) and a sparsified readout within the pixel matrix similar to hybrid sensors. The low capacitance of the small collection electrode (about 2 × 2 µm²), combined with a circuit that performs sparsified readout within the matrix without a free-running clock, keeps the power consumption as low as 40 nW per pixel.



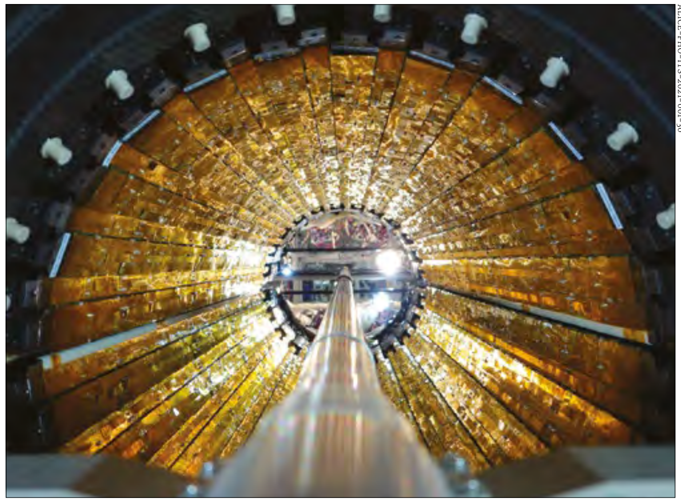
Cylindrical structure *Layout of the ITS2 detector showing the inner barrel surrounding the beam pipe and the outer barrel.*

ITS2 structure

The ITS2 consists of seven layers covering a radial extension from 22 to 430 mm with respect to the beamline (see "Cylindrical structure" figure). The innermost three layers form the inner barrel (IB), while the middle two and the outermost two layers form the outer barrel (OB). The radial position of each layer was optimised to achieve the best combined performance in terms of pointing resolution, momentum resolution and tracking efficiency in the expected high track-density environment of a Pb–Pb collision. It covers a pseudo-rapidity range |η| < 1.22 for 90% of the most luminous beam interaction region, extending over a total surface of 10 m² and containing about 12.5 Gpixels with binary readout, and is operated at room temperature using water cooling.

Given the small size of the ALPIDE (4.5 cm²), sensors are tiled-up to form the basic detector unit, which is called a stave. It consists of a "space-frame" (a carbon-fibre mechanical support), a "cold plate" (a carbon ply embedding two cooling pipes) and a hybrid integrated circuit (HIC) assembly in which the ALPIDE chips are glued and electrically connected to a flexible printed circuit. An IB HIC and an OB HIC include one row of nine chips and two rows of seven chips, respectively. The HICs are glued to the mechanical support: 1 HIC for the IB and 8 or 14 HICs for the two innermost and two outermost layers of the OB, respectively (see "State of the art" figure).

Zero-suppressed hit data are transmitted from the staves to a system of about 200 readout boards located 7 m away from the detector. Data is transmitted serially with a bit-rate up to 1.2 Gb/s over more than 3800 twin-axial cables reaching an aggregate bandwidth of about 2 Tb/s. The readout boards aggregate data and re-transmit it over 768 optical-fibre links to the first-level processors of the combined online/offline (O2) computing farm. The data are then sequenced in frames, each containing the hit information of the collisions occurring in contiguous time intervals of constant duration, typically 22 µs.



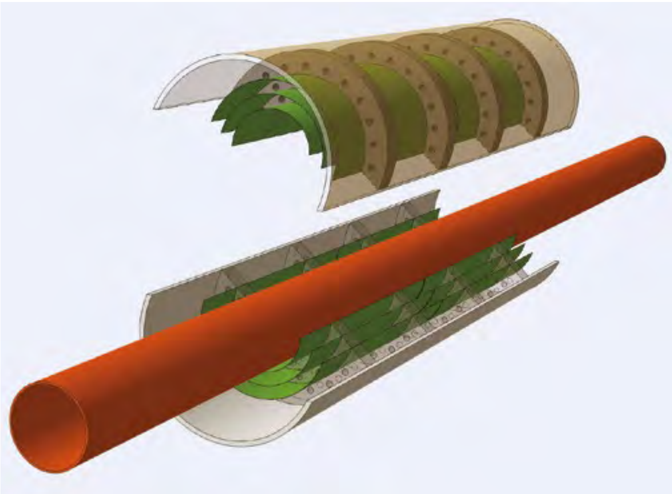
State of the art *Top: the bottom half of the ITS2 inner barrel ready for insertion, where the staves of the innermost layer are clearly visible. Bottom: integration test for the ITS2 outer barrel, which proved that the alignment is adequate to avoid interference between the top and bottom halves.*

The process and procedures to build the HICs and staves are rather complex and time-intensive. More than 10 construction sites distributed worldwide worked together to develop the assembly procedure and to build the components. More than 120 IB and 2500 OB HICs were built using a custom-made automatic module-assembly machine, implementing electrical testing, dimension measurement, integrity inspection and alignment for assembly. A total of 96 IB staves, enough to build two copies of the three IB layers, and a total of 160 OB staves, including 20% spares, have been assembled.

A large cleanroom was built at CERN for the full detector assembly and commissioning activities. Here the same backend system that will be used in the experiment was installed, including the powering system, cooling system,

CERNCOURIER
Volume 61 Number 4 July/August 2021
IOP Publishing

ALICE Collab.



Into the future *Conceptual design of the ITS3, where all silicon layers (green) surround the beam pipe (orange) supported by carbon-foam support rings (grey).*

full readout and trigger chains. Staves were installed on the mechanical support structures to form layers, and the layers are assembled in half-barrels, IB (layers 0, 1 and 2) top and bottom and OB (layers 3, 4, 5 and 6) top and bottom. Each stave is then connected to power-supply and readout systems. The commissioning campaign started in May 2019 to fully characterise and calibrate all the detector components, and installations of both the OB and IB were completed in May this year.

Physics ahead

After nearly 10 years of R&D, the upgrade of the ALICE experimental apparatus – which includes an upgraded time projection chamber, a new muon forward tracker, a new fast-interaction trigger detector, forward diffraction detector, new readout electronics and an integrated online–offline computing system – is close to completion. Most of the new or upgraded detectors, including the ITS2, have already been installed in the experimental area and the global commissioning of the whole apparatus will be completed this year, well before the start of Run 3, which is scheduled for the spring of 2022.

The significant enhancements to the performance of the ALICE detector will enable detailed, quantitative characterisation of the high-density, high-temperature phase of strongly interacting matter, together with the exploration of new phenomena. The ITS2 is at the core of this programme. With improved pointing resolution and tracking efficiency at low transverse momentum, it will enable the determination of the total production cross-section of the charm quark. This is fundamental for understanding the interplay between the production of charm quarks in the initial hard scattering, their energy loss in the QGP and possible in-medium thermal production. Moreover, the ITS2 will also make it possible to measure a larger number of different charmed and beauty hadrons, including baryons, opening the possibility for determining the heavy-flavour transport coefficients. A third area where the new ITS will have a major impact is the measurement of electron–positron pairs emitted as thermal radiation during all stages of the heavy-ion collision, which offer an insight into the bulk properties and space–time evolution of the QGP.

The significant enhancements to the performance of the ALICE detector will enable the exploration of new phenomena

More in store

The full potential of the ALPIDE chip underpinning the ITS2 is yet to be fully exploited. For example, a variant of ALPIDE explored by ALICE based on an additional low-dose deep n-type implant to realise a planar junction in the epitaxial layer below the wells containing the CMOS circuitry results in a much faster charge collection and significantly improved radiation hardness, paving the way for sensors that are much more resistant to radiation.

Further improvements to MAPS for high-energy physics detectors could come by exploiting the rapid progress in imaging for consumer applications. One of the features offered recently by CMOS imaging sensor technologies, called stitching, will enable a new generation of MAPS with an area up to the full wafer size. Moreover, the reduction in the sensor thickness to about 30–40 μm opens the door to large-area curved sensors, making it possible to build a cylindrical layer of silicon-only detectors with a further significant reduction in the material thickness. The ALICE collaboration is already preparing a new detector based on these concepts, which consists of three cylindrical layers based on curved wafer-scale stitched sensors (see "Into the future" figure). This new vertex detector will be installed during Long Shutdown 3 towards the middle of the decade, replacing the three innermost layers of the ITS2. With the first detection layer closer to the interaction point (from 23 to 18 mm) and a reduction in the material budget close to the interaction point by a factor of six, the new vertex detector will further improve the tracking precision and efficiency at low transverse momentum.

The technologies developed by ALICE for the ITS2 detector are now being used or considered for several other applications in high-energy physics, including the vertex detector of the sPHENIX experiment at RHIC, and the inner tracking system for the NICA MPD experiment at JINR. The technology is also being applied to areas outside of the field, including in medical and space applications. The Bergen pCT collaboration and INFN Padova's iMPACT project, for example, are developing novel ALPIDE-based devices for clinical particle therapy to reconstruct 3D human body images. The HEPD02 detector for the Chinese–Italian CSES-02 mission, meanwhile, includes a charged-particle tracker made of three layers of ALPIDE sensors that represents a pioneering test for next-generation space missions. Driven by a desire to learn more about the fundamental laws of nature, it is clear that advanced silicon-tracker technology continues to make an impact on wider society, too. ●

Further reading

B Abelev *et al.* 2014 *J. Phys. G* **41** 087002.
G Aglieri *et al.* 2013 *JINST* **8** C12041.
G Aglieri *et al.* 2021 *Nucl. Instrum. Meth. A* **988** 164859.
W Snoeys *et al.* 2017 *Nucl. Instrum. Meth. A* **871** 90.

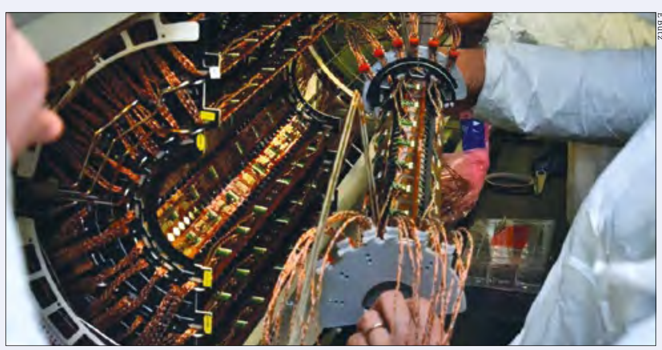
STATE-OF-THE-ART TRACKING FOR HIGH LUMINOSITIES

Each at different stages of development depending on their implementation schedules and operating conditions, the tracking systems of the ATLAS, LHCb and CMS experiments, like that for ALICE, are undergoing complete replacements to prepare for the extreme operating conditions of future LHC runs, explains Matthew Chalmers.

Towards the CMS phase-2 pixel detector

The original silicon pixel detector for CMS – comprising three barrel layers and two endcap disks – was designed for a maximum instantaneous luminosity of $10^{34}\,\mathrm{cm^{-2}s^{-1}}$ and a maximum average pile-up of 25. Following LHC upgrades in 2013–2014, it was replaced with an upgraded system (the CMS Phase-1 pixel detector) in 2017 to cope with higher instantaneous luminosities. With a lower mass and an additional barrel layer and endcap disk, it was an evolutionary upgrade maintaining the well-tested key features of the original detector while enabling higher-rate capability, improved radiation tolerance and more robust tracking. During Long Shutdown 2, maintenance work on the Phase-1 device included the installation of a new innermost layer (see image, below) to enable the delivery of high-quality data until the end of LHC Run 3.

During the next long shutdown, scheduled for 2025, the entire tracker detector will be replaced in preparation for the High-Luminosity LHC (HL-LHC). This Phase-2 pixel detector will need to cope with a pile-up and hit rate eight times higher than before, and with a trigger rate and radiation dose 7.5 and 10 times higher, respectively. To meet these extreme requirements, the CMS collaboration, in partnership with ATLAS via the RD53 collaboration, is developing a next-generation hybrid-pixel chip utilising 65 nm CMOS technology. The overall system is much bigger than the Phase-1 device (~5 m^2 compared to 1.75 m^2) with vastly more read-out channels (~2 billion compared to 120 million). With six-times smaller pixels, increased detection coverage, reduced material budget, a new readout chip to enable a lower detection threshold, and a design that continues to allow easy installation and removal, the state-of-the-art Phase-2 pixel detector will serve CMS well into the HL-LHC era.



Present and future *Top: the new innermost layer of the CMS tracker being installed in January 2021. Left: how the CMS Phase-2 pixel detector, called "Inner Tracker", will look.*

LHCb's all-new VELO takes shape

LHCb's Vertex Locator (VELO) has played a pivotal role in the experiment's flavour-physics programme. Contributing to triggering, tracking and vertexing, and with a geometry optimised for particles traveling close to the beam direction, its 46 orthogonal silicon-strip half-disks have enabled the collaboration to pursue major results. These include the 2019 discovery of CP violation in charm using the world's largest reconstructed samples of charm decays, a host of matter-antimatter asymmetry measurements and rare-decay searches, and the recent hints of lepton non-universality in B decays.

Placing the sensors as close as possible to the primary proton-proton interactions requires the whole VELO system to sit inside the LHC vacuum pipe (separated from the primary vacuum by a 1.1 m-long thin-walled "RF foil"), and a mechanical system to move the disks out of harm's way during the injection and stabilisation of the beams. After more than a decade of service witnessing the passage of some 10^{26} protons, the original VELO is now being replaced with a new one to prepare for a factor-five increase in luminosity for LHCb in LHC Run 3.

The entirety of the new VELO will be read out at a rate of 40 MHz, requiring a huge data bandwidth: up to 20 Gbits/s for the hottest ASICs, and 3 Tbit/s in total. Cooling using the minimum of material is another major challenge. The upgraded VELO will be kept at –20° via the novel technique of evaporative CO_2 circulating in $120 \times 200\,\mu m$ channels within a silicon substrate (see "Fine structure", left). The harsh radiation environment also demands a special ASIC, the VeloPix, which has been developed with the CERN Medipix group and will allow the detector to operate a much more efficient trigger. To cope with increased occupancies at higher luminosity, the original silicon strips have been replaced with pixels. The new sensors (in the form of rectangles rather than disks) will be located even closer to the interaction point (5.1 mm versus the previous 8.2 mm for the first measured point), which requires the RF foil to sit just 3.5 mm from the beam and 0.9 mm from the sensors. The production of the foil was a huge technical achievement. It was machined from a solid-forged aluminium block with 98% of the material removed and the final shape machined to a thickness of 250 μm, with further chemical etching taking it to just 100 μm (see "Fine structure", right).

Around half of the VELO-module production is complete, with the work shared between labs in the UK and the Netherlands (see "In production"). Assembly of the 52 modules into the "hood", which provides cooling, services and vacuum, is now under way, with installation in LHCb scheduled to start in August. The VELO Upgrade I is expected to serve LHCb throughout Run 3 and Run 4. Looking further to the future, the next upgrade will require the detector to operate with a huge jump in luminosity, where vertexing will pose a significant challenge. Proposals under consideration include a new "4D" pixel detector with time-stamp information per hit, which could conceivably be achieved by moving to a smaller CMOS node. At this stage, however, the collaboration is actively investigating all options, with detailed technical design reports expected towards the middle of the decade.

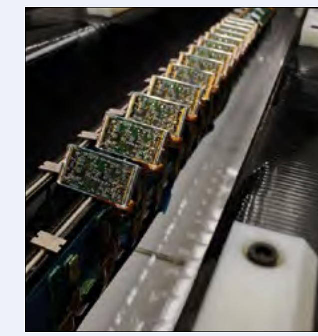
In production *Wouter Hulsbergen and Krista De Roo assemble VELO modules at Nikhef (left), while Stefano De Capua is shown undertaking parallel work at the University of Manchester (right).*

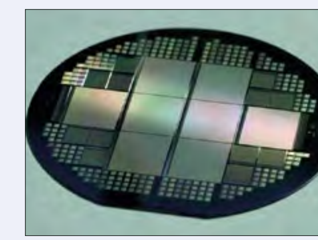
Fine structure *Left: a silicon wafer containing "race track" microchannels (overlaid for illustration only), in which evaporative CO_2 circulates to cool the detector. Right: inspecting the thickness of the upgraded RF foil that will enclose the new VELO within the LHC vacuum.*

ATLAS ITk pixel detector on track

The ATLAS collaboration upgraded its original pixel detector in 2014, adding an innermost layer to create a four-layer device. The new layer contained a much smaller pitch, 3D sensors at large angles and CO_2 cooling, and the pixel tracker will continue to serve ATLAS throughout LHC Run 3. Like CMS, the collaboration has long been working towards the replacement of the full inner tracker during the next long shutdown expected in 2025, in preparation for HL-LHC operations. The innermost layers of this state-of-the-art all-silicon tracker, called the ITk, will be built from pixel detectors with an area almost 10 times larger than that of the current device. With 13 m^2 of active silicon across five barrel layers and two end caps, the pixel detector will contribute to precision tracking up to a pseudorapidity $|\eta| = 4$, with the innermost two layers expected to be replaced a few years into the HL-LHC era, and the outermost layers designed to last the lifetime of the project. Most of the detector will use planar silicon sensors, with 3D sensors (which are more radiation-hard and less power-hungry) in the innermost layer. Like the CMS Phase-2 pixel upgrade, the sensors will be read out by new chips being developed by the RD53 collaboration, with support structures made of low-mass carbon materials and cooling provided by evaporative CO_2 flowing in thin-walled pipes. The device will have a total of 5.1 Gpixels (55 times more than the current one), and the very high expected HL-LHC data rates, especially in the innermost layers, will require the development of new technologies for high-bandwidth transmission and handling. The ITk pixel detector is now in the final stages of R&D and moving into production. After that, the final stages of integrating the subdetectors assembled in ATLAS institutes worldwide will take place on the surface at CERN before final installation underground.

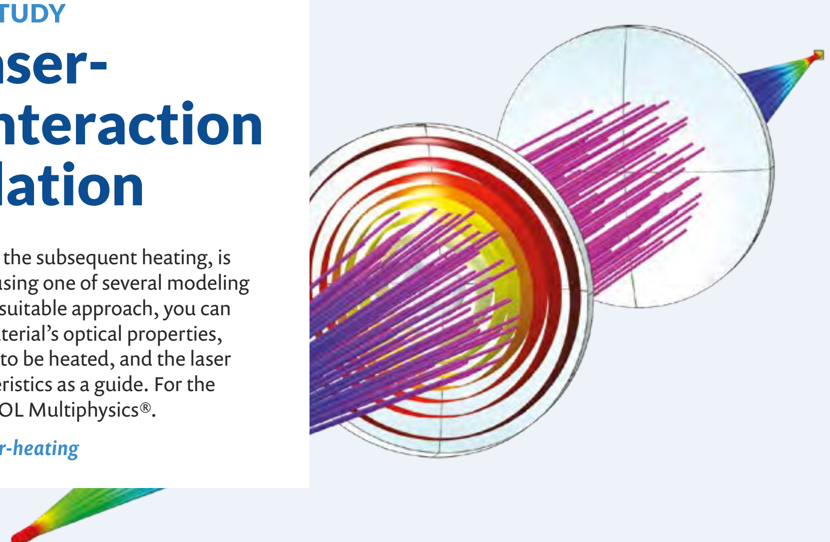
The device will have a total of 5.1 Gpixels – 55 times more than the current one

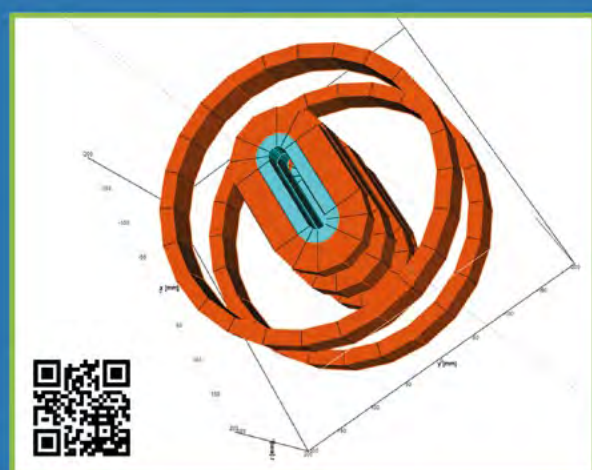




ATLAS pixels *Top: a prototype of the ATLAS ITk pixel detector, showing sensors tilted with respect to the beam axis to improve tracking performance while reducing the total silicon area. Bottom: a 3D silicon sensor developed for the pixel region of the ATLAS inner detector.*

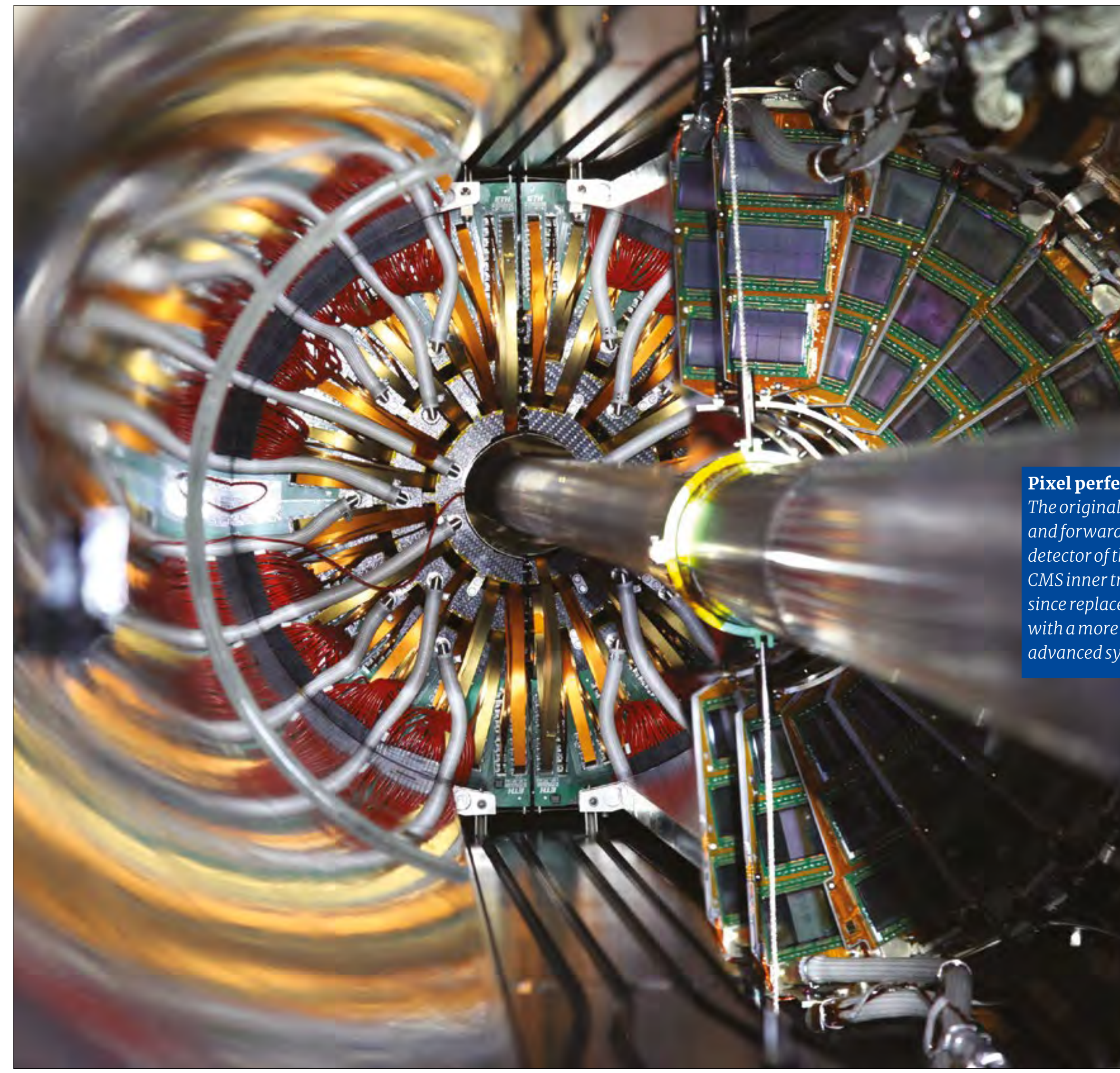
CERNCOURIER
VOLUME 61 NUMBER 4 JULY/AUGUST 2021
IOP Publishing





TRACKING THE RISE OF PIXEL DETECTORS

From their beginnings at CERN half a century ago, writes Chris Damerell, silicon pixel detectors for particle tracking have blossomed into a vast array of beautiful creations that have driven numerous discoveries, with no signs of the advances slowing down.



Pixel perfect *The original central and forward pixel detector of the CMS inner tracker, since replaced with a more advanced system.*

CERNCOURIER

VOLUME 61 NUMBER 4 JULY/AUGUST 2021

IOP Publishing

CERN

THE AUTHOR
Chris Damerell *Rutherford Appleton Laboratory (RAL).*

Pixel detectors have their roots in photography. Up until 50 years ago, every camera contained a roll of film on which images were photochemically recorded with each exposure, after which the completed roll was sent to be "developed" to finally produce eagerly awaited prints a week or so later. For decades, film also played a big part in particle tracking, with nuclear emulsions, cloud chambers and bubble chambers. The silicon chip, first unveiled to the world in 1961, was to change this picture forever.

By the 1970s, new designs of silicon chips were invented that consisted of a 2D array of charge-collection sites or "picture elements" (pixels) below the surface of the silicon. During the exposure time, an image focused on the surface generated electron–hole pairs via the photoelectric effect in the underlying silicon, with the electrons collected as signal information in the pixels. These chips came in two forms: the charge-coupled device (CCD) and the monolithic active pixel sensor (MAPS) – more commonly known commercially as the CMOS image sensor (CIS). Willard Boyle and George Smith of Bell Labs in the US were awarded the Nobel Prize for Physics in 2009 for inventing the CCD.

In a CCD, the charge signals are sequentially transferred to a single on-chip output circuit by applying voltage pulses to the overlying electrode array that defines the pixel structure. At the output circuit the charge is converted to a voltage signal to enable the chip to interface with external circuitry. In the case of the MAPS, each pixel has its own charge-integrating detection circuitry and a voltage signal is again sequentially read out from each by on-chip switching or "scanning" circuitry. Both architectures followed rapid development paths, and within a couple of decades had completely displaced photographic film in cameras.

During the past 40 years, silicon sensors have transformed particle tracking in high-energy physics experiments

For the consumer camera market, CCDs had the initial lead, which passed to MAPS by about 1995. For scientific imaging, CCDs are preferred for most astronomical applications (most recently the 3.2 Gpixel optical camera for the Vera Rubin Observatory), while MAPS are the preferred option for fast imaging such as super-resolution microscopy, cryoelectron microscopy and pioneering studies of protein dynamics at X-ray free-electron lasers. Recent CMOS imagers with very small, low-capacitance pixels achieve sufficiently low noise to detect single electrons. A third member of the family is the hybrid pixel detector, which is MAPS-like in that the signals are read out by scanning circuitry, but in which the charges are generated in a separate silicon layer that is connected, pixel by pixel, to a readout integrated circuit (ROIC).

During the past 40 years, these devices (along with their silicon-microstrip counterparts, to be described in a later issue) have transformed particle tracking in high-energy physics experiments. The evolution of these device types is intertwined to such an extent that any attempt at historical accuracy, or who really invented what, would be beyond the capacity of this author, for which I humbly apologise. Space constraints have also led to a focus on the detectors themselves, while ignoring the exciting work in ROIC development, cooling systems, mechanical supports, not to mention the advanced software for device simulation, the simulation of physics performance, and so forth.

CCD design inspiration

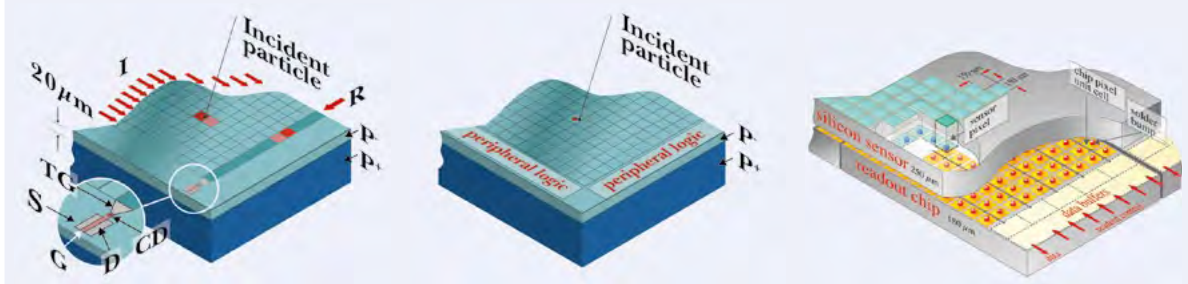
The early developments in CCD detectors were disregarded by the particle-detector community. This is because gaseous drift chambers, with a precision of around 100 μm, were thought to be adequate for all tracking applications. However, the 1974 prediction by Gaillard, Lee and Rosner that particles containing charm quarks "might have lifetimes measurable in emulsions", followed by the discovery of charm in 1975, set the world of particle-physics instrumentation ablaze. Many groups with large budgets tried to develop or upgrade existing types of detectors to meet the challenge: bubble chambers became holographic; drift chambers and streamer chambers were pressurised; silicon microstrips became finer-pitched, etc.

The ACCMOR Collaboration (Amsterdam, CERN, Cracow, Munich, Oxford, RAL) had built a powerful multi-particle spectrometer, operating at CERN's Super Proton Synchrotron, to search for hadronic production of the recently-discovered charm particles, and make the first measurements of their lifetimes. We in the RAL group picked up the idea of CCDs from astronomers at the University of Cambridge, who were beginning to see deeper into space than was possible with photographic film (see left figure in "Pixel architectures" panel). The brilliant CCD developers in David Burt's team at the EEV Company in Chelmsford (now Teledyne e2v) suggested designs that we could try for particle detection, notably to use epitaxial silicon wafers with an active-layer thickness of about 20 μm. At a collaboration meeting in Cracow in 1978, we demonstrated via simulations that just two postage-stamp-sized CCDs, placed 1 and 2 cm beyond a thin target, could cover the whole spectrometer aperture and might be able to deliver high-quality topological reconstruction of the decays of charm particles with expected lifetimes of around 10^{-13} s.

We still had to demonstrate that these detectors could be made efficient for particle detection. With a small telescope comprising three CCDs in the T6 beam from CERN's Proton Synchrotron we established a hit efficiency of more than 99%, a track measurement precision of 4.5 μm in x and y, and two-track resolution of 40 μm. Nothing like this had been seen before in an electronic detector. Downstream of us, in the same week, a Yale group led by Bill Willis obtained signals from a small liquid-argon calorimeter. A bottle of champagne was shared!

It was then a simple step to add two CCDs to the ACCMOR spectrometer and start looking for charm particles. During 1984, on the initial shift, we found our first candidate (see "First charm" figure), which, after adding the information from the downstream microstrips, drift chambers (with two large aperture magnets for momentum measurement), plus a beautiful assembly of Cherenkov hodoscopes from the Munich group, proved to be a $D^+ \to K^-\pi^+\pi^+$ event.

Pixel architectures



Illustrations of a CCD (left), MAPS (middle) and hybrid chip (right). The first two typically contain 1k×1k pixels, up to 4k×4k or beyond by "stitching", with an active layer thickness (depleted) of about 20 μm and a highly doped bulk layer back-thinned to around 100 μm, enabling a low-mass tracker, even potentially bent into cylinders round the beampipe.

The CCD (where I is the imaging area, R the readout register, TG the transfer gate, CD the collection diode, and S, D, G the source, drain and gate of the sense transistor) is pixellised in the I direction by conducting gates. Signal charges are shifted in this direction by manipulating the gate voltages so that the image is shifted down, one row at a time. Charges from the bottom row are tipped into the linear readout register, within which they are transferred, all together in the orthogonal direction, towards the output node. As each signal charge reaches the output node, it modulates the voltage on the gate of the output transistor; this is sensed, and transmitted off-chip as an analog signal.

In a MAPS chip, pixellisation is implemented by orthogonal channel stops and signal charges are sensed in-pixel by a tiny front-end transistor. Within a depth of about 1 μm below the surface, each pixel contains complex CMOS electronics. The simplest readout is "rolling shutter", in which peripheral logic along the chip edge addresses rows in turn, and analogue signals are transmitted by column lines to peripheral logic at the bottom of the imaging area. Unlike in a CCD, the signal charges never move from their "parent" pixel.

In the hybrid chip, like a MAPS, signals are read out by scanning circuitry. However, the charges are generated in a separate silicon layer that is connected, pixel by pixel, to a readout integrated circuit. Bump-bonding interconnection technology is used to keep up with pixel miniaturisation. (Image credits: RAL; PSI)

It was more challenging to develop a CCD-based vertex detector for the SLAC Large Detector (SLD) at the SLAC Linear Collider (SLC), which became operational in 1989. The level of background radiation required a 25 mm-radius beam pipe, and the physics demanded large solid-angle coverage, as in all general-purpose collider detectors. The physics case for SLD had been boosted by the discovery in 1983 that the lifetime of particles containing b quarks was longer than for charm, in contrast to the theoretical expectation of being much shorter. So the case for deploying high-quality vertex detectors at SLC and LEP, which were under construction to study Z^0 decays, was indeed compelling (see "Vertexing" figure). All four LEP experiments employed a silicon-microstrip vertex detector.

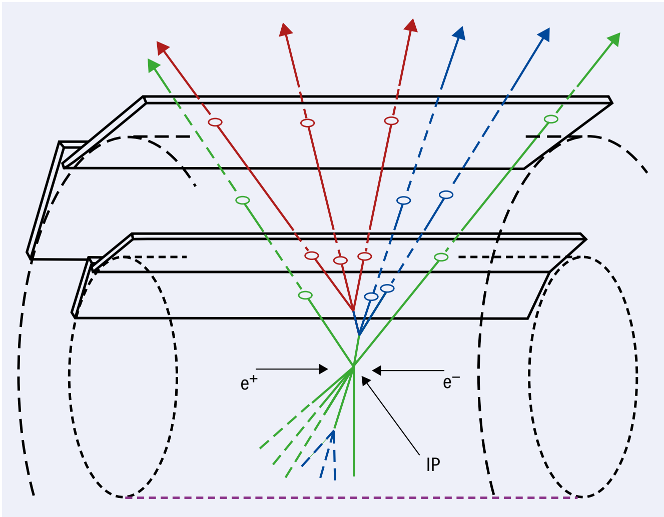
Early in the silicon vertex-detector programme, e2V perfected the art of "stitching" reticles limited to an area of 2×2 cm², to make large CCDs (8×1.6 cm² for SLD). This enabled us to make a high-performance vertex detector that operated from 1996 until SLD shut down in 1998, and which delivered a cornucopia of heavy-flavour physics from Z^0 decays (see "Pioneering pixels" figure). During this time, the LEP beam pipe, limited by background to 54 mm radius, permitted its experiments' microstrip-based vertex detectors to do pioneering b physics. But it had reduced capability for the more elusive charm, which was shorter lived and left fewer decay tracks.

Between LEP with its much higher luminosity and SLD with its small beam pipe, state-of-the-art vertex detector and highly polarised electron beam, the study of Z^0 decays yielded rich physics. Highlights included very detailed studies of an enormous sample of gluon jets from $Z^0 \to b\bar{b}g$ events, with cleanly tagged b jets at LEP, and A_c, the parity-violation parameter in the coupling of the Z^0 to c-quarks, at SLD. However, the most exciting discovery of that era was the top quark at Fermilab, in which the SVX microstrip detector of the CDF detector played an essential part (see "Top detector" figure). This triggered a paradigm shift. Before then, vertex detectors were an "optional extra" in experiments; afterwards, they became obligatory in every energy frontier detector system.

Hybrid devices

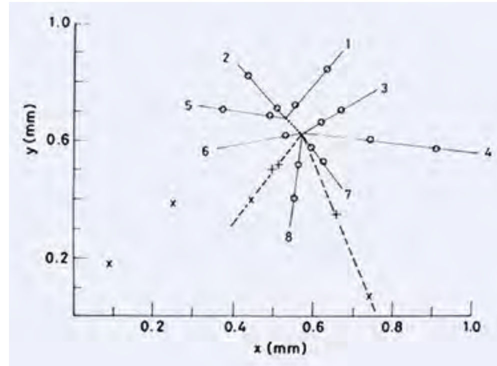
While CCDs pioneered the use of silicon pixels for precision tracking, their use was restricted by two serious limitations: poor radiation tolerance and long readout time (tens of ms due to the need to transfer the charge signals pixel by pixel through a single output circuit). There was clearly a need for pixel detectors in more demanding environments, and this led to the development of hybrid pixel detectors. The idea was simple: reduce the strip length of well-developed microstrip technology to equal its width, and you had your pixel sensor. However, microstrip detectors were read out at one end by ASIC (application-specific integrated circuit) chips having their channel pitch matched to that of the strips. For hybrid pixels, the ASIC readout required a front-end circuit for each pixel, resulting in modules with the sensor chip facing the readout chip, with electrical connections made by metal bump-bonds (see right figure in "Pixel architectures" panel). The use of relatively thick sensor layers (compared to CCDs) com-

CERNCOURIER
VOLUME 61 NUMBER 4 JULY/AUGUST 2021
IOP Publishing



SLD Collab.

Vertexing *An ideal vertex detector at an e^+e^- collider, where space-points measured with few-micron precision distinguish between tracks from the primary, secondary and tertiary vertices (green, blue and red).*



ACCMOR Collab.

First charm *The first charm decay seen with a silicon detector by the ACCMOR Collaboration in 1984, using a thin target followed by CCDs at 1 and 2 cm beyond (view along beam direction). The decay tracks were clearly recognised in the online display in just 1 mm² of CCD area.*

pensated for the higher node capacitance associated with the hybrid front-end circuit.

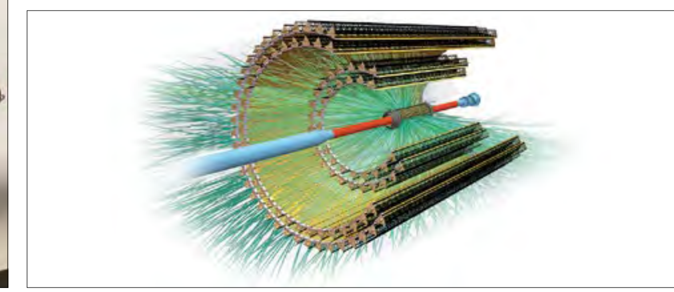
Although the idea was simple, its implementation involved a long and challenging programme of engineering at the cutting edge of technology. This had begun by about 1988, when Erik Heijne and colleagues in the CERN microelectronics group had the idea to fit full nuclear-pulse processing electronics in every pixel of the readout chip, with additional circuitry such as digitisation, local memory and pattern recognition on the chip periphery. With a 3 µm feature size, they were obliged to begin with relatively large pixels (75 × 500 µm), and only about 80 transistors per pixel. They initiated the RD19 collaboration, which eventually grew to 150 participants, with many pioneering developments over a decade, leading to successful detectors in at least three experiments: WA97 in the Omega Spectrometer; NA57; and forward tracking in DELPHI. As the RD19 programme developed, the steady reduction in feature size permitted the use of in-pixel discriminators and fast shapers that enhanced the noise performance, even at high rates. This would be essential for operation of large hybrid pixel systems in harsh environments, such as ATLAS and CMS at the LHC. RD19 initiated a programme of radiation hardness by design (enclosed-gate transistors, guard rings, etc), which was further developed and broadly disseminated by the CERN microelectronics group. These design techniques are now used universally across the LHC detector systems. There is still much to be learned, and advances to a smaller feature size bring new opportunities but also surprises and challenges.

The advantages of the hybrid approach include the ability to choose almost any commercial CMOS process and combine it with the sensor best adapted to the application. This can deliver optimal speed of parallel processing, and radiation hardness as good as can be engineered in the two component chips. The disadvantages include a complex and expensive assembly procedure, high power dissipation due to large node capacitance, and more material than is desirable for a tracking system. Thanks to the sustained efforts of many experts, an impressive collection of hybrid pixel tracking detectors has been brought to completion in a number of detector facilities. As vertex detectors, their greatest triumph has been in the inferno at the heart of ATLAS and CMS where, for example, they were key to the recent measurement of the branching ratio for $H \rightarrow b\bar{b}$.

Facing up to the challenge

The high-luminosity upgrade to the LHC (HL-LHC) is placing severe demands on ATLAS and CMS, none more so than developing even more powerful hybrid vertex detectors to accommodate a "pileup" level of 200 events per bunch crossing. For the sensors, a 3D variant invented by Sherwood Parker has adequate radiation hardness, and may provide a more secure option than the traditional planar pixels, but this question is still open. 3D pixels have already proved themselves in ATLAS, for the insertable B layer (IBL), where the signal charge is drifted transversally within the pixel to a narrow column of n-type silicon that runs through the thickness of the sensor. But for HL-LHC, the innermost pixels need to be at least five times smaller in area than the IBL, putting extreme pressure on the readout chip. The RD53 collaboration led by CERN has worked for years on the development of an ASIC using 65 nm feature size, which enables the huge amount of radiation-resistant electronics to fit within the pixel area, reaching the limit of 50 × 50 µm². Assembling these delicate modules, and dealing with the thermal stresses associated with the power dissipation in the warm ASICs mechanically coupled to the cold sensor chips, is still a challenge. These pixel tracking systems (comprising five layers of barrel and forward trackers) will amount to about 6 Gpixels – seven times larger than before. Beyond the fifth layer, conditions are sufficiently relaxed that microstrip tracking will still be adequate.

SLD collab.



ALICE collab.

Pioneering pixels *Left: half of the SLD vertex detector, consisting of 307 Mpixels, three barrels and a pixel size of 20 × 20 × 20 µm³. Each ladder of 16 cm active length contains two 8 cm-long stitched CCDs. Top right: CGI of the original ATLAS pixel detector, comprising 92 Mpixels (50 × 400 µm² for the external layers and 50 × 250 µm² for the innermost layer). Bottom right: simulated tracks in the MAPS-based ALICE ITS2, containing 12.5 Gpixels and a 10 m² active area (see p29). To offer a sense of scale, the entire SLD vertex detector would fit within the innermost layer of the ATLAS pixel detector.*

The latest experiment to upgrade from strips to pixels is LHCb, which has an impressive track record of b and charm physics. Its adventurous Vertex Locator (VELO) detector has 26 disks along the beamline, equipped with orthogonally oriented r and φ microstrips, starting from inside the beampipe about 8 mm from the LHC beam axis. LHCb has collected the world's largest sample of charmed hadrons, and with the VELO has made a number of world-leading measurements including the discovery of CP violation in charm. LHCb is now statistics-limited for many rare decays and will ramp up its event samples with a major upgrade implemented in two stages (see p36).

For the first upgrade, due to begin operation early next year, the luminosity will increase by a factor of up to five, and the additional pattern recognition challenge will be addressed by a new pixel detector incorporating 55 µm pixels and installed even closer (5.1 mm) to the beam axis. The pixel detector uses evaporative CO_2 microchannel cooling to allow operation under vacuum. LHCb will double its efficiency by removing the hardware trigger and reading out the data at the beam-crossing frequency of 40 MHz. The new "VeloPix" readout chip will achieve this with readout speeds of up to 20 Gb/s, and the software trigger will select heavy-flavour events based on full event reconstruction. For the second upgrade, due to begin in about 2032, the luminosity will be increased by a further factor of 7.5, allowing LHCb to eventually accumulate 10 times its current statistics. Under these conditions, there will be, on average, 40 interactions per beam crossing, which the collaboration plans to resolve by enhanced timing precision (around 20 ps) in the VELO pixels. The upgrade will require both an enhanced sensor and readout chip. This is an adventurous long-term R&D programme, and LHCb retain a fallback option with timing layers downstream of the VELO, if required.

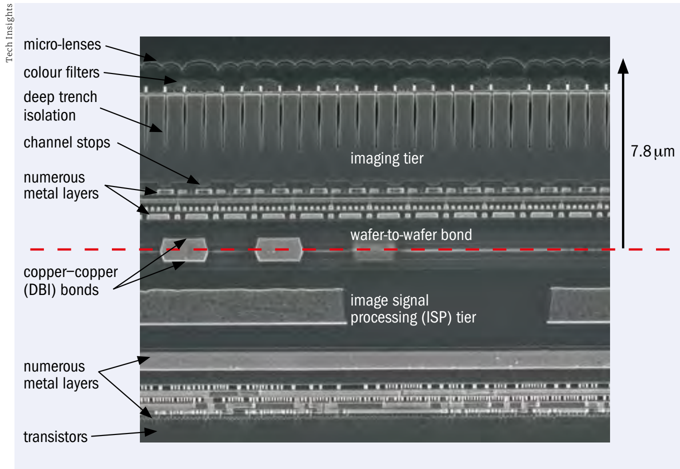
Monolithic active pixels

Being monolithic, the architecture of MAPS is very similar to that of CCDs (see middle figure in "Pixel architectures" panel). The fundamental difference is that in a CCD, the signal charge is transported physically through some centimetres of silicon to a single charge-sensing circuit in the corner of the chip, while in a MAPS the communication between the signal charge and the outside world is via in-pixel electronics, with metal tracks to the edge of the chip. The MAPS architecture looked very promising from the beginning, as a route to solving the problems of both CCDs and hybrid pixels. With respect to CCDs, the radiation tolerance could be greatly increased by sensing the signal charge within its own pixel, instead of transporting it over thousands of pixels. The readout speed could also be dramatically increased by in-pixel amplitude discrimination, followed by sparse readout of only the hit pixels. With respect to hybrid pixel modules, the expense and complications of bump-bonded assemblies could be eliminated, and the tiny node capacitance opened the possibility of much thinner active layers than were needed with hybrids.

MAPS have emerged as an attractive option for a number of future tracking systems. They offer small pixels where needed (notably for inner-layer vertex detectors) and thin layers throughout the detector volume, thereby minimising multiple scattering and photon conversion, both in barrels and endcaps. Excess material in the forward region of tracking systems such as time-projection and drift chambers,

An impressive collection of hybrid pixel tracking detectors has been brought to completion in a number of detector facilities

CERNCOURIER
Volume 61 Number 4 July/August 2021
IOP Publishing



Up close *SEM view of a slice through the imaging region of a stacked Sony CMOS image sensor or CIS. The imaging wafer has been thinned to around 6 µm, while the ISP wafer is much thicker, to provide the required stiffness. The peripheral structures, including the numerous electrical connections between the two wafers (using direct-bond interconnects (DBIs) and through-silicon vias), are outside the field of view.*

Top detector *Bert Gonzalez with the SVX microstrip vertex detector of the CDF experiment at the Tevatron in 1993, which was instrumental in the co-discovery of the top quark.*

with their heavy endplate structures, has in the past led to poor track reconstruction efficiency, loss of tracks due to secondary interactions, and excess photon conversions. In colliders at the energy frontier (whether pp or e^+e^-), however, interesting events for physics are often multi-jet, so there are nearly always one or more jets in the forward region.

The first MAPS devices contained little more than a collection diode, a front-end transistor operated as a source follower, reset transistor and addressing logic. They needed only relaxed charge-collection time, so diffusive collection sufficed. Sherwood Parker's group demonstrated their capability for particle tracking in 1991, with devices processed in the Centre for Integrated Studies at Stanford, operating in a Fermilab test beam. In the decades since, advances in the density of CMOS digital electronics have enabled designers to pack more and more electronics into each pixel. For fast operation, the active volume below the collection diode needs to be depleted, including in the corners of the pixels, to avoid loss of tracking efficiency.

The Strasbourg group led by Marc Winter has a long and distinguished record of MAPS development. As well as highly appreciated telescopes in test beams at DESY for general use, the group supplied its MIMOSA-28 devices for the first MAPS-based vertex detector: a 356 Mpixel two-layer barrel system for the STAR experiment at Brookhaven's Relativistic Heavy Ion Collider. Operational for a three-year physics run starting in 2014, this detector enhanced the capability to look into the quark–gluon plasma, the extremely hot form of matter that characterised the birth of the universe.

Advances in the density of CMOS digital electronics have enabled designers to pack more and more electronics into each pixel

An ingenious MAPS variant developed by the Semiconductor Laboratory of the Max Planck Society – the Depleted P-channel FET (DEPFET) – is also serving as a high-performance vertex detector in the Belle II detector at SuperKEKB in Japan, part of which is already operating. In the DEPFET, the signal charge drifts to a "virtual gate" located in a buried channel deeper than the current flowing in the sense transistor. As Belle II pushes to even higher luminosity, it is not yet clear which technology will deliver the required radiation hardness.

The small collection electrode of the standard MAPS pixel presents a challenge in terms of radiation hardness, since it is not easy to preserve full depletion after high levels of bulk damage. An important initiative to overcome this was initiated in 2007 by Ivan Perić of KIT, in which the collection electrode is expanded to cover most of the pixel area, below the level of the CMOS electronics, so the charge-collection path is much reduced. Impressive further developments have been made by groups at Bonn University and elsewhere. This approach has achieved high radiation resistance with the ATLASpix prototypes, for instance. However, the standard MAPS approach with small collection electrode may be tunable to achieve the required radiation resistance, while preserving the advantages of superior noise performance due to the much lower sensor capacitance. Both approaches have strong backing from talented design groups, but the eventual outcome is unclear.

Advanced MAPS

Advanced MAPS devices were proposed for detectors at the International Linear Collider (ILC). In 2008 Konstantin Stefanov of the Open University suggested that MAPS chips could provide an overall tracking system of about 30 Gpixels with performance far beyond the baseline options at the time, which were silicon microstrips and a gaseous time-projection chamber. This development was shelved due to delays to the ILC, but the dream has become a reality in the MAPS-based tracking system for the ALICE detector at the LHC, which builds on the impressive ALPIDE chip development by Walter Snoeys and his collaborators. The ALICE ITS-2 system, with 12.5 Gpixels, sets the record for any pixel system (see p29). This beautiful tracker has operated smoothly on cosmic rays and is now being installed in the overall ALICE detector. The group is already pushing to upgrade the three central layers using wafer-scale stitching and curved sensors to significantly reduce the material budget. At the 2021 International Workshop on Future Linear Colliders held in March, the SiD concept group announced that they will switch to a MAPS-based tracking system. R&D for vertexing at the ILC is also being revived, including the possibility of CCDs making a comeback with advanced designs from the KEK group led by Yasuhiro Sugimoto.

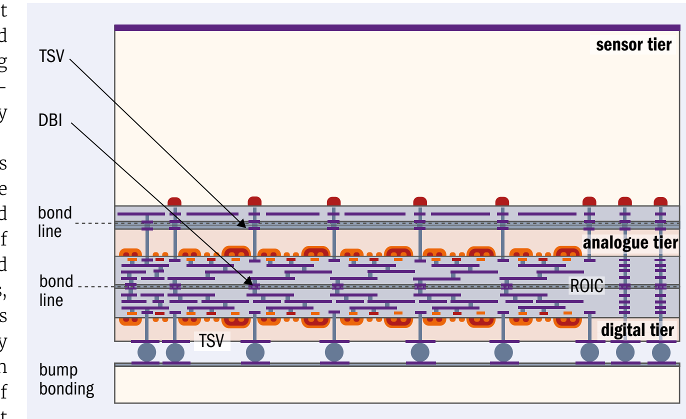
The most ambitious goal for MAPS-based detectors is for the inner-layer barrels at ATLAS and CMS, during the second phase of the HL-LHC era, where smaller pixels would provide important advantages for physics. At the start of high-luminosity operation, these layers will be equipped with hybrid pixels of 25×100 µm² and 150 µm active thickness, the pixel area being limited by the readout chip, which is based on a 65 nm technology node. Encouraging work led by the CERN ATLAS and microelectronics groups and the Bonn group is underway, and could result in a MAPS option of 25×25 µm², requiring an active-layer thickness of only about 20 µm, using a 28 nm technology node. The improvement in tracking precision could be accompanied by a substantial reduction in power dissipation. The four-times greater pixel density would be more than offset by the reduction in operating voltage, plus the much smaller node capacitance. This route could provide greatly enhanced vertex detector performance at a time when the hybrid detectors will be coming to the end of their lives due to radiation damage. However, this is not yet guaranteed, and an evolution to stacked devices may be necessary. A great advantage of moving to monolithic or stacked devices is that the complex processes are then in the hands of commercial foundries that routinely turn out thousands of 12 inch wafers per week.

High-speed and stacked

During HL-LHC operations there is a need for ultra-fast tracking devices to ameliorate the pileup problems in ATLAS, CMS and LHCb. Designs with a timing precision of tens of picoseconds are advancing rapidly – initially low-gain avalanche diodes, pioneered by groups from Torino, Barcelona and UCSC, followed by other ultra-fast silicon pixel devices. There is a growing list of applications for these devices. For example, ATLAS will have a layer adjacent to the electromagnetic calorimeter in the forward region, where the pileup problems will be severe, and where coarse granularity (~1 mm pixels) is sufficient. LHCb is more ambitious for its stage-two upgrade, as already mentioned. There are several experiments in which such detectors have potential for particle identification, notably π/K separation by time-of-flight up to a momentum limit that depends on the scale of the tracking system, typically 8 GeV/c.

Monolithic and hybrid pixel detectors answer many of the needs for particle tracking systems now and in the future. But there remain challenges, for example the innermost layers at ATLAS and CMS. In order to deliver the required vertexing capability for efficient, cleanly separated b and charm identification, we need pixels of dimensions about 25×25 µm, four times below the current goals for HL-LHC. They should also be thinner, down to say 20 µm, to preserve precision for oblique tracks.

Solutions to these problems, and similar challenges in the much bigger market of X-ray imaging, are coming into view with stacked devices, in which layers of CMOS-processed silicon are stacked and interconnected. The processing technique, in which wafers are bonded face-to-face, with electrical contacts made by direct-bond interconnects and through-silicon vias, is now a mature technology and is in the hands of leading companies such as Sony and Samsung. The CMOS imaging chips for phone cameras must be one of the most spectacular examples of modern engineering (see "Up close" figure).



Stacking for physics *Functional sketch (not to scale) of a Fermilab/BNL stacked pixel detector with three layers: a sensor tier (300 µm thick, for efficient X-ray response), an analogue tier and a digital signal-processing tier (each 15 µm thick). Direct-bond interconnects (DBIs) and through-silicon vias (TSVs) of dimensions 1×6 µm provide inter-tier electrical connections.*

Commercial CMOS image sensor development is a major growth area, with approximately 3000 patents per year. In future these developers, advancing to smaller-node chips, will add artificial intelligence, for example to take a number of frames of fast-moving subjects and deliver the best one to the user. Imagers under development for the automotive industry include those that will operate in the short-wavelength infrared region, where silicon is still sensitive. In this region, rain and fog are transparent, so a driverless car equipped with the technology will be able to travel effortlessly in the worst weather conditions.

While we developers of pixel imagers for science have not kept up with the evolution of stacked devices, several academic groups have over the past 15 years taken brave initiatives in this direction, most impressively a Fermilab/BNL collaboration led by Ron Lipton, Ray Yarema and Grzegorz Deptuch. This work was done before the technical requirements could be serviced by a single technology node, so they had to work with a variety of pioneering companies in concert with excellent in-house facilities. Their achievements culminated in three working prototypes, two for particle tracking and one for X-ray imaging, namely a beautiful three-tier stack comprising a thick sensor (for efficient X-ray detection), an analogue tier and a digital tier (see "Stacking for physics" figure).

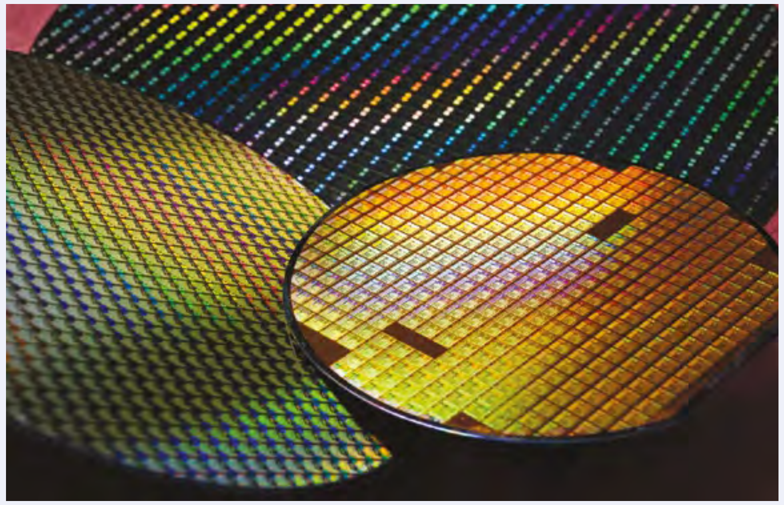
For the HL-LHC inner layers, one could imagine a stacked chip comprising a thin sensor layer (with excellent noise performance enabled by an on-chip front-end circuit for each pixel), followed by one or more logic layers. Depending

Face-to-face wafer bonding is now a commercially mature technology

CERNCOURIER
Volume 61 Number 4 July/August 2021
IOP Publishing

Technology nodes

The relatively recent term "technology node" embraces a number of aspects of commercial integrated circuit (IC) production. First and foremost is the feature size, which originally meant the minimum line width that could be produced by photolithography, for example the length of a transistor gate. With the introduction of novel transistor designs (notably the FinFET), this term has been generalised to indicate the functional density of transistors that is achievable. At the start of the silicon-tracker story, in the late 1970s, the feature size was about 3 µm. The current state-of-the-art is 5 nm, and the downward Moore's law trend is continuing steadily, although such narrow lines would of course be far beyond the reach of photolithography. There are other aspects of ICs that are included in the description of any technology node. One is whether they support stitching, which means the production of larger chips by step-and-repeat of reticles, enabling the production of single devices of sizes $10\times10\,\mathrm{cm}^2$ and beyond, in principle up to the wafer scale (which these days is a diameter of 200 or 300 mm, evolving soon to 450 mm). Another is whether they support wafer stacking, which is the production of multi-layer sandwiches of thinned devices using various interconnect technologies such as through-silicon vias and direct-bond interconnects. A third aspect is whether they can be used for imaging devices, which implies optimised control of dark current and noise. For particle tracking, the most advanced technology nodes are unaffordable (the development cost of a single 5 nm ASIC is typically about $500 million, so it needs a large market). However, other features that are desirable and becoming essential for our needs (imaging capability, stitching and stacking) are widely available and less expensive. For example, Global Foundries, which produces 3.5 million wafers per annum, offers these capabilities at their 32 and 14 nm nodes.



TSMC

Wafer thin *12 inch silicon wafers fabricated by Taiwan Semiconductor Manufacturing Company.*

on the technology node, one should be able to fit all the logic (building on the functionality of the RD53 chip) in one or two layers of 25 × 25 µm pixels. The overall thickness could be 20 µm for the imaging layer, and 6 µm per logic layer, with a bottom layer sufficiently thick (~100 µm) to give the necessary mechanical stability to the relatively large stitched chips. The resulting device would still be thin enough for a high-quality vertex detector, and the thin planar sensor-layer pixels including front-end electronics would be amenable to full depletion up to the 10-year HL-LHC radiation dose.

There are groups in Japan (at KEK led by Yasuo Arai, and at RIKEN led by Takaki Hatsui) that have excellent track records for developing silicon-on-insulator devices for particle tracking and for X-ray detection, respectively. The RIKEN group is now believed to be collaborating with Sony to develop stacked devices for X-ray imaging. Given Sony's impressive achievements in visible-light imaging, this promises to be extremely interesting. There are many applications (for example at ITER) where radiation-resistant X-ray imaging will be of crucial importance, so this is an area in which stacked devices may well own the future.

Outlook

The story of frontier pixel detectors is a bit like that of an art form – say cubism. With well-defined beginnings 50 years ago, it has blossomed into a vast array of beautiful creations. The international community of designers see few boundaries to their art, being sustained by the availability of stitched devices to cover large-area tracking systems, and moving into the third dimension to create the most advanced pixels, which are obligatory for some exciting physics goals.

Just like the attribute of vision in the natural world, which started as a microscopic light-sensitive spot on the surface of a unicellular protozoan, and eventually reached one of its many pinnacles in the eye of an eagle, with its amazing "stacked" data processing behind the retina, silicon pixel devices are guaranteed to continue evolving to meet the diverse needs of science and technology. Will they one day be swept away, like photographic film or bubble chambers? This seems unthinkable at present, but history shows there's always room for a new idea. ●

Further reading

C Chu 2010 *Modern Semiconductor Devices for Integrated Circuits* (Pearson/Prentice Hall).
E H M Heijne 2021 *Radiat. Meas.* **140** 106436.
H Kolanoski and N Wermes 2020 *Particle Detectors: Fundamentals and Applications* (Oxford University Press).
M Riordan and L Hoddeson 1997 *Crystal Fire* (WW Norton and Co).

OPINION
VIEWPOINT

'A CERN for climate change'

An exascale computing facility modelled on the organisation of CERN would enable a step-change in quantifying climate change, argue Tim Palmer and Bjorn Stevens.

Univ. Oxford

Tim Palmer *is the Royal Society research professor in climate physics at the University of Oxford.*

MPI

Bjorn Stevens *is the managing director of the Max Planck Institute for Meteorology.*

In the early 1950s, particle accelerators were national-level activities. It soon became obvious that to advance the field further demanded machines beyond the capabilities of single countries. CERN marked a phase transition in this respect, enabling physicists to cooperate around the development of one big facility. Climate science stands to similarly benefit from a change in its topology.

Modern climate models were developed in the 1960s, but there weren't any clear applications or policy objectives at that time. Today we need hard numbers about how the climate is changing, and an ability to seamlessly link these changes to applications – a planetary information system for assessing hazards, planning food security, aiding global commerce, guiding infrastructural investments, and much more. National centres for climate modelling exist in many countries. But we need a centre "on steroids": a dedicated exascale computing facility organised on a similar basis to CERN that would allow the necessary leap in realism.

Shutterstock/Benoit Bruchez

High-energy approach *Out of computational necessity, existing climate models suffer from a degree of abstraction that decouples clouds from air currents, for example.*

Quantifying climate

To be computationally manageable, existing climate models solve equations for quantities that are first aggregated over large spatial and temporal scales. This blurs their relationship to physical laws, to phenomena we can measure, and to the impacts of a changing climate on infrastructure. Clouds, for example, are creatures of circulation, particularly vertical air currents. Existing models attempt to infer what these air currents would be given information about much larger scale 2D motion fields. There is a necessary degree of abstraction, which leads to less useful results. We don't know if air is going up or down an individual mountain, for instance, because we don't have individual mountains in the model, at best mountain ranges.

In addition to more physical models, we also need a much better quantification of model uncertainty. At present this is estimated by comparing solutions across many low-resolution models, or by perturbing parameters of a given low-resolution model. The particle-physics analogy might be that everyone runs their own low-energy accelerators hoping that coordinated experiments will provide high-energy insights. Concentrating efforts on a few high-resolution climate models, where uncertainty is encoded through stochastic mathematics, is a high-energy effort. It would result in better and more useful models, and open the door to cooperative efforts to systematically explore the structural stability of the climate system and its implications for future climate projections.

Working out climate-science's version of the Standard Model thus provides the intellectual underpinnings for a "CERN for climate change". One can and should argue about the exact form such a centre should take, whether it be a single facility or a federation of campuses, and on the relative weight it gives to particular questions. What is important is that it creates a framework for European climate, computer and computational scientists to cooperate, also with application communities, in ways that deliver the maximum benefit for society.

Building momentum

A number of us have been arguing for such a facility for more than a decade. The idea seems to be catching on, less for the eloquence of our arguments, more for the promise of exascale computing. A facility to accelerate climate research in developing and developed countries alike has emerged as a core element of one of 12 briefing documents prepared by the Royal Society in advance of the United Nations Climate Change Conference, COP26, in November. This briefing flanks the European Union's "Destination Earth" project, which is part of its Green Deal programme – a €1 billion effort over 10 years that envisions the development of improved high-resolution models with better quantified uncertainty. If not anchored in a sustainable organisational concept, however, this risks throwing money to the wind.

Giving a concrete form to such a facility still faces internal hurdles, possibly similar to those faced by CERN in its early days. For example, there are concerns that it will take away funding from existing centres. We believe, and CERN's own experience shows, that the opposite is more likely true. A "CERN for climate change" would advance the frontiers of the science, freeing researchers to turn their attention to new questions, rather than maintaining old models, and provide an engine for European innovation that extends far beyond climate change.

Exploring the Hubble tension

Cosmologist and theoretical physicist Licia Verde discusses the current tension between early- and late-time measurements of the expansion rate of the universe.

Did you always want to be a cosmologist?
One day, around the time I started properly reading, somebody gave me a book about the sky, and I found it fascinating to think about what's beyond the clouds and beyond where the planes and the birds fly. I didn't know that you could actually make a living doing this kind of thing. At that age, you don't know what a cosmologist is, unless you happen to meet one and ask what they do. You are just fascinated by questions like "how does it work?" and "how do you know?".

Was there a point at which you decided to focus on theory?
Not really, and I still think I'm somewhat in-between, in the sense that I like to interpret data and am plugged-in to observational collaborations. I try to make connections to what the data mean in light of theory. You could say that I am a theoretical experimentalist. I made a point to actually go and serve at a telescope a couple of times, but you wouldn't want to trust me in handling all of the nitty-gritty detail, or to move the instrument around.

What are your research interests?
I have several different research projects, spanning large-scale structure, dark energy, inflation and the cosmic microwave background. But there is a common philosophy: I like to ask how much can we learn about the universe in a way that is as robust as possible, where robust means as close as possible to the truth, even if we have to accept large error bars. In cosmology, everything we interpret is always in light of a theory, and theories are always at some level "spherical cows" – they are approximations. So, imagine we are missing something: how do I know I am missing it? It sounds vague, but I think the field of cosmology is ready to ask these questions because we are swimming in data, drowning in data, or soon will be, and the statistical error bars are shrinking.

F Camallonga

Shining light *Licia Verde is ICREA professor at the Instituto de Ciencias del Cosmos, University of Barcelona.*

This explains your current interest in the Hubble constant. What do you define as the Hubble tension?
Yes, indeed. When I was a PhD student, knowing the Hubble constant at the 40–50% level was great. Now, we are declaring a crisis in cosmology because there is a discrepancy at the very-few-percent level. The Hubble tension is certainly one of the most intriguing problems in cosmology today. Local measurements of the current expansion rate of the universe, for example based on supernovae as standard candles, which do not rely heavily on assumptions about cosmological models, give values that cluster around 73 km s^{-1} Mpc^{-1}. Then there is another, indirect route to measuring what we believe is the same quantity but only within a model, the lambda-cold-dark-matter (ΛCDM) model, which is looking at the baby universe via the cosmic microwave background (CMB). When we look at the CMB, we don't measure recession velocities, but we interpret a parameter within the model as the expansion rate of the universe. The ΛCDM model is extremely successful, but the value of the Hubble constant using this method comes out at around 67 km s^{-1} Mpc^{-1}, and the discrepancy with local measurements is now 4σ or more.

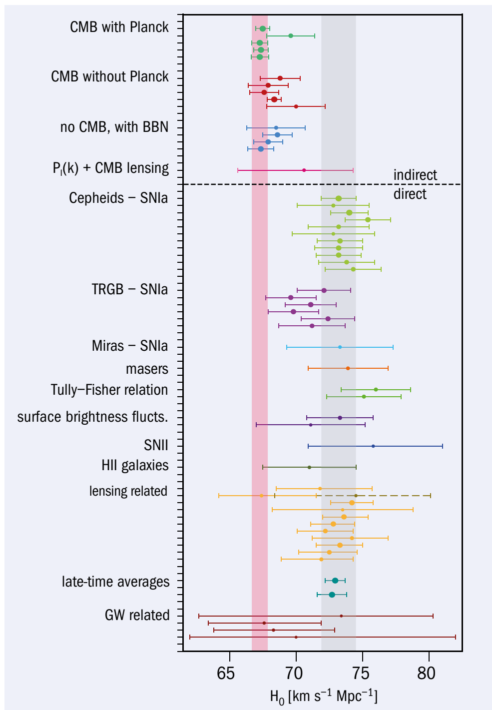
It is really becoming make-or-break for the ΛCDM model

What are the implications if this tension cannot be explained by systematic errors or some other misunderstanding of the data?
The Hubble constant is the only cosmological parameter in the ΛCDM universe that can be measured both directly locally and from classical cosmological observations such as the CMB, baryon acoustic oscillations, supernovae and big-bang nucleosynthesis. It's also easy to understand what it is, and the error bars are becoming small enough that it is really becoming make-or-break for the ΛCDM model. The Hubble tension made everybody wake up. But before we throw the model out of the window, we need something more.

How much faith do you put in the ΛCDM model compared to, say, the Standard Model of particle physics?
It is a model that has only six parameters, most constrained at

the percent level, which explains most of the observations that we have of the universe. In the case of Λ, which quantifies what we call dark energy, we have many orders of magnitude between theory and experiment to understand, and for dark matter we are yet to find a candidate particle. Otherwise, it does connect to fundamental physics and has been extremely successful. For 20 years we have been riding a wave of confirmation of the ΛCDM model, so we need to ask ourselves: if we are going to throw it out, what do we substitute it with? The first thing is to take small steps away from the model, say by adding one parameter. For a while, you could say that maybe there is something like an effective neutrino species that might fix it, but a solution like this doesn't quite fit the CMB data any more. I think the community may be split 50/50 between being almost ready to throw the model out and keeping working with it, because we have nothing better to use.

Could it be that general relativity (GR) needs to be modified?
Perhaps, but where do we modify it? People have tried to tweak GR at early times, but it messes around with the observations and creates a bigger problem than we already have. So, let's say we modify in middle times – we still need it to describe the shape of the expansion history of the universe, which is close to ΛCDM. Or we could modify it locally. We've tested GR at the solar-system scale, and the accuracy of GPS is a vivid illustration of its effectiveness at a planetary scale. So, we'd need to modify it very close to where we are, and I don't know if there are modifications on the market that pass all of the observational tests. It could also be that the cosmological constant changes value as the universe evolves, in which case the form of the expansion history would not be the one of ΛCDM. There is some wiggle room here, but changing Λ within the error bars is not enough to fix the mismatch. Basically, there is such a good agreement between the ΛCDM model and the observations that you can only tinker so much. We've tried to put "epicycles" everywhere we could, and so far we haven't found anything that actually fixes it.



Hubble trouble *Values of the Hubble constant from direct and indirect measurements by different missions, with the grey and pink bands showing the 68% confidence-level values from SHOES and Planck, respectively. Source: arXiv:2103.01183 (accepted by CQG).*

What about possible sources of experimental error?
Systematics are always unknowns that may be there, but the level of sophistication of the analyses suggests that if there was something major then it would have come up. People do a lot of internal consistency checks; therefore, it is becoming increasingly unlikely that it is only due to dumb systematics. The big change over the past two years or so is that you typically now have different data sets that give you the same answer. It doesn't mean that both can't be wrong, but it becomes increasingly unlikely. For a while people were saying maybe there is a problem with the CMB data, but now we have removed those data out of the equation completely and there are different lines of evidence that give a local value hovering around $73\,km\,s^{-1}\,Mpc^{-1}$, although it's true that the truly independent ones are in the range $70–73\,km\,s^{-1}\,Mpc^{-1}$. A lot of the data for local measurements have been made public, and although it's not a very glamorous job to take someone else's data and re-do the analysis, it's very important.

If we are lucky, gravitational waves with optical counterparts will bring in another important piece of the puzzle

Is there a way to categorise the very large number of models vying to explain the Hubble tension?
Until very recently, there was an interpretation of early versus late models. But if this is really the case, then the tension should show up in other observables, specifically the matter density and age of the universe, because it's a very constrained system. Perhaps there is some global solution, so a little change here and a little in the middle, and a little there ... and everything would come together. But that would be rather unsatisfactory because you can't point your finger at what the problem was. Or maybe it's something very, very local – then it is not a question of cosmology, but whether the value of the Hubble constant we measure here is not a global value. I don't know how to choose between these possibilities, but the way the observations are going makes me wonder if I should start thinking in that direction. I am trying to be as model agnostic as possible. Firstly, there are many other people that are thinking in terms of models and they are doing a wonderful job. Secondly, I don't want to be biased. Instead I am trying to see if I can think one-step removed, which is very difficult, from a particular model or parameterisation.

What are the prospects for more precise measurements?
For the CMB, we have the CMB-S4 proposal and the Simons Array. These experiments won't make a huge difference to the precision of the primary temperature-fluctuation measurements, but will be useful to disentangle possible solutions that have been proposed because they will focus on the polarisation of the CMB photons. As for the local measurements, the Dark Energy Spectroscopic Instrument, which started observations in May, will measure baryon acoustic oscillations at the level of galaxies to further nail down the expansion history of the low-redshift universe. However, it will not help at the level of local measurements, which are being pursued instead by the SH0ES collaboration. There is also another programme in Chicago focusing on the so-called tip of the red-giant-branch technique, with more results to come out. Observations of multiple images from strong gravitational lensing is another promising avenue that is very actively pursued, and, if we are lucky, gravitational waves with optical counterparts will bring in another important piece of the puzzle.

How do we measure the Hubble constant from gravitational waves?
It's a beautiful measurement, as you can get a distance measurement without having to build a cosmic distance ladder, which is the case with the other local measurements that build distances via Cepheids, supernovae, etc. The recession velocity of the GW source comes from the optical counterpart and its redshift. The detection of the GW170817 event enabled researchers to estimate the Hubble constant to be $70\,km\,s^{-1}\,Mpc^{-1}$, for example, but the uncertainties using this novel method are still very large, in the region of 10%. A particular source of uncertainty comes from the orientation of the gravitational-wave source with respect to Earth, but this will come down as the number of events increases. So this route provides a completely different window on the Hubble tension. Gravitational waves have been dubbed, rather poetically, "standard sirens". When these determinations of the Hubble constant become competitive with existing measurements really depends on how many events are out there. Upgrades to LIGO, VIRGO, plus next-generation gravitational-wave observatories will help in this regard, but what if the measurements end up clustering between or beyond the late- and early-time measurements? Then we really have to scratch our heads!

How can results from particle physics help?
Principally, if we learn something about dark matter it could force us to reconsider our entire way to fit the observations, perhaps in a way that we haven't thought of because dark matter may be hot rather than cold, or something else that interacts in completely different ways. Neutrinos are another possibility. There are models where neutrinos don't behave like the Standard Model yet still fit the CMB observations. Before the Hubble tension came along, the hope was to say that we have this wonderful model of cosmology that fits really well and implies that we live in a maximally boring universe. Then we could have used that to eventually make the connection to particle physics, say, by constraining neutrino masses or the temperature of dark matter. But if we don't live in a maximally boring universe, we have to be careful about playing this game because the universe could be much, much more interesting than we assumed.

Interview by **Matthew Chalmers**.

OPINION
REVIEWS

A relational take on quantum mechanics

Helgoland
By Carlo Rovelli
Allen Lane

It is often said that "nobody understands quantum mechanics" – a phrase usually attributed to Richard Feynman. This statement may, however, be misleading to the uninitiated. There is certainly a high level of understanding of quantum mechanics. The point, moreover, is that there is more than one way to understand the theory, and each of these ways requires us to make some disturbing concessions.

Carlo Rovelli's *Helgoland* is therefore a welcome popular book – a well-written and easy-to-follow exploration of quantum mechanics and its interpretation. Rovelli is a theorist working mainly on quantum gravity and foundational aspects of physics. He is also a very successful popular author, distinguished by his erudition and his ability to illuminate the bigger picture. His latest book is no exception.

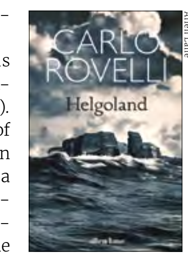
Helgoland is a barren German island of the North Sea where Heisenberg co-invented quantum mechanics in 1925 while on vacation. The extraordinary sequence of events between 1925 and 1926, when Heisenberg, Jordan, Born, Pauli, Dirac and Schrödinger formulated quantum mechanics, is the topic of the opening chapter of the book.

Rovelli only devotes a short chapter to discuss interpretations in general. This is certainly understandable, since the author's main target is to discuss his own brainchild: relational quantum mechanics. This approach, however, does not do justice to popular ideas among experts, such as the many-worlds interpretation. The reader may be surprised not to find anything about the Copenhagen (or, more appropriately, Bohr's) interpretation. This is for very good reason, however, since it is not generally considered to be a coherent interpretation. Having mostly historical significance, it has served as inspiration to approaches that keep the spirit of Bohr's ideas, like consistent histories (not mentioned in the book at all), or Rovelli's relational quantum mechanics.


Unknown

Heisenberg's vacation
A bird's-eye view of Helgoland from around the turn of the previous century.

Relational quantum mechanics was introduced by Rovelli in an original technical article in 1996 (*Int. J. Theor. Phys.* **35** 1637). *Helgoland* presents a simplified version of these ideas, explained in more detail in Rovelli's article, and in a way suitable for a more general audience. The original article, however, can serve as very nice complementary reading for those with some physics background. Relational quantum mechanics claims to be compatible with several of Bohr's ideas. In some ways it goes back to the original ideas of Heisenberg by formulating the theory without a reference to a wavefunction. The properties of a system are defined only when the system interacts with another system. There is no distinction between observer and observed system. Rovelli meticulously embeds these ideas in a more general historical and philosophical context, which he presents in a captivating manner. He even speculates whether this way of thinking can help us understand topics that, in his opinion, are unrelated to quantum mechanics, such as consciousness.

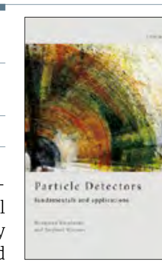


Allen Lane

Helgoland's potential audience is very diverse and manages to transcend the fact that it is written for the general public. Professionals from both the sciences and the humanities will certainly learn something, especially if they are not acquainted with the nuances of the interpretations of modern physics. The book, however, as is explicitly stated by Rovelli, takes a partisan stance, aiming to promote relational quantum mechanics. As such, it may give a somewhat skewed view of the topic. In that respect, it would be a good idea to read it alongside books with different perspectives, such as Sean Carroll's *Something Deeply Hidden* (2019) and Adam Becker's *What is Real?* (2018).

Nikolaos Rompotis *University of Liverpool.*

Particle Detectors – Fundamentals and Applications
By Hermann Kolanoski and Norbert Wermes
Oxford University Press



Oxford University Press

Throughout the history of nuclear, particle and astroparticle physics, novel detector concepts have paved the way to new insights and new particles, and will continue to do so in the future. To help train the next generation of innovators, noted experimental particle physicists Hermann Kolanoski (Humboldt University Berlin and DESY) and Norbert Wermes (University of Bonn) have written a comprehensive textbook on particle detectors. The authors use their broad experience in collider and underground particle-physics experiments, astroparticle physics experiments and medical-imaging applications to confidently cover the spectrum of experimental methods in impressive detail.

Particle Detectors – Fundamentals and Applications combines in a single volume the syllabus also found in two well-known textbooks covering slightly different aspects of detectors: *Techniques for Nuclear and Particle Physics Experiments* by W R Leo and *Detectors for Particle Radiation* by Konrad Kleinknecht. Kolanoski and Wermes' book supersedes them both by being more up-to-date and comprehensive. It is more detailed than *Particle Detectors* by Claus Grupen and Boris Shwartz – another excellent and recently published textbook with a similar scope – and will probably attract a slightly more advanced population of physics students and researchers. This new text promises to become a particle-physics analogue of the legendary experimental-nuclear-physics textbook *Radiation Detection and Measurement* by Glenn Knoll.

The book begins with a comprehensive warm-up chapter on the interaction of charged particles and photons with matter, going well beyond a typical textbook level. This is followed by a very interest- ▷

ing discussion of the transport of charge carriers in media in magnetic and electric fields, and – a welcome novelty – signal formation, using the method of "weighting fields". The main body of the book is devoted first to gaseous, semiconductor, Cherenkov and transition-radiation detectors, and then to detector systems for tracking, particle identification and calorimetry, and the detection of cosmic rays, neutrinos and exotic matter. Final chapters on electronics readout, triggering and data acquisition complete the picture.

Particle Detectors – Fundamentals and Applications is best considered a reference for lectures on experimental methods in particle and nuclear physics for postgraduate-level students. The book is easy to read, and conceptual discussions are well supported by numerous examples, plots and illustrations of excellent quality. Kolanoski and Wermes have undoubtedly written a gem of a book, with value for any experimental particle physicist, be they a master's student, PhD student or accomplished researcher looking for detector details outside of their expertise.

A reference for lectures on experimental methods in particle and nuclear physics

Peter Krizan *University of Ljubljana.*

Le Neutrino de Majorana
By Nils Barrellon
Jigal Editions

Naples, 1938. Ettore Majorana, one of the physics geniuses of the 20th century, disappears mysteriously and never comes back. A tragedy, and a mystery that has captivated many writers.

The latest oeuvre, Nils Barrellon's *Le Neutrino de Majorana*, is a French-language detective novel situated somewhere at the intersection of physics history and science outreach. Beginning with Majorana's birth in 1906, Barrellon highlights the events that shaped and established quantum mechanics. With factual moments and original letters, he focuses on Majorana's personal and scholarly life, while putting a spotlight on the *ragazzi di via Panisperna* and other European physicists who had to face the Second World War. In parallel, a present-day neutrino physicist is found killed right at the border of France and Switzerland. Majorana's *volumetti* (his unpublished research notes) become the leitmotif unifying the two stories. Barrellon compares the two eras of research by entangling the storylines to reach a dramatic climax.

Using the crime hook as the predominant storyline, the author keeps the lay reader on the edge of their seat, while comically playing with subtleties most Cernois would recognise, from cultural differences between the two bordering countries to clichés about particle physicists, via passably detailed procedures of access to the experimental facilities – a clear proof of the author (who is also a physics school teacher) having been on-site. The novel feels like a tailor-made detective story for the entertainment of physicists and physics enthusiasts alike.

And, at the end of the day, what explanation for Majorana's disappearance could be more soothing than a love story?

Cristina Agrigoroae *CERN.*

PEOPLE CAREERS

From CERN to the environment

A recent CERN Alumni Network event highlighted how skills developed in high-energy physics can be transferred to careers in the environmental industry, writes Craig Edwards.

Daphne Technology

Mario's mission *Panellist Mario Michan's (left) company, Daphne Technology, aims to minimise air and sea pollution for the maritime industry.*

CERN technologies and personnel make it a hub for so much more than exploring the fundamental laws of the universe. In an event organised by the CERN Alumni Relations team on 30 April, five CERN alumni who now work in the environmental industry discussed how their high-energy physics training helped them get to where they are today.

One panellist, Zofia Rudjor, used to work on the ATLAS trigger system and the measurement of the Higgs-boson decays to tau leptons. Having spent 10 years at CERN, and with the discovery of the Higgs still fresh in the memory, she now works as a data scientist for the Norwegian Institute for Water Research (NIVA). "For my current role, a lot of the skills that I acquired at CERN, from solving complex problems to working with real-time data streams, turned out to be very key and useful," she said at the virtual April event. Similar sentiments were shared by fellow panellist Manel Sanmarti, a former cryogenic engineer who is now the co-founder of Bamboo Energy Platform: "CERN is kind of the backbone of my career – it's really excellent. I would say it's the 'Champions League' of technology!"

However, much learning and preparation is also required to transition from particle physics to the environment. Charlie Cook began his career as an engineer at CERN and is now the founder of Rightcharge, a company that helps electric car drivers reduce the cost of charging and to use cleaner energy sources. Before taking the plunge into the environmental industry, he first completed a course at Imperial College Business School on climate-change management and finance, which helped him "learn the lingo" in the finance world. A stint at Octopus Electric Vehicles was followed by driving a domestic vehicle-to-grid demonstration project called Powerloop, which launched at the beginning of 2018. "Sometimes it's too easy to start talking in abstract terms about sustainability, but, to really understand things I like to see the numbers behind everything," he said.

Mario Michan, CEO of Daphne Technology (a company focused on enabling industries to decarbonise), and a former investigator of antihydrogen at CERN's Antiproton Decelerator, also stressed the importance of being familiar with how the sector works, pointing out the role that policymakers take: "Everything that is happening in the environmental field today is all because of policymakers," he remarked.

> **I would say CERN is the 'Champions League' of technology!**

Another particle physicist who made the change is Giorgio Cortiana, who now works at E.ON's global advanced analytics and artificial intelligence, leading several data-science projects. His scientific background in complex physics data analysis, statistics, machine learning and object-oriented programming is ideal for extracting meaningful insights from large datasets, and for coping with everyday problems that need quick and effective solutions, he explained, noting the different mentality from academia. "At CERN you have the luxury to really focus on your research, down to the tiny details – now, I have to be a bit more pragmatic," he said. "Here [at E.ON] we are instead looking to try and make an impact as soon as we can."

Leaving the field

The decision to leave the familiar surroundings of high-energy physics requires perseverance, stressed Rudjor, stating that it is important to pick up the phone to find out what type of position is really being offered. Other panellists also noted that it is vital to spend some time to look at what skills you can bring for a specific posting. "I think there are many workplaces that don't really know how to recruit people with our skills – they would like the people, but they typically don't open positions because they don't know exactly how to specify the job," said Rudjor.

The CERN Alumni Network's "Moving Out of Academia" events provide a rich source of candid advice for those seeking to change direction, while also demonstrating the impact of high-energy physics in broader society. The environment-industry event follows others dedicated to careers in finance, industrial engineering, big data, entrepreneurship and medical technologies. More are in store, explains head of CERN Alumni Relations, Rachel Bray. "One of our goals is to support those in their early careers – if and when they decide to leave academia for another sector. In addition to the Moving Out of Academia events, we have recently launched a new series that brings together early-career scientists and the companies seeking the talents and skills developed at CERN."

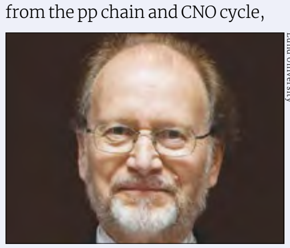
Craig Edwards *CERN.*

Appointments and awards

2021 EPS prizes announced
The European Physical Society (EPS) High Energy and Particle Physics (HEPP) division has announced the recipients of its 2021 awards. Torbjörn Sjöstrand (below) (Lund University) and


T Sjöstrand

Bryan Webber (below) (University of Cambridge) have won the 2021 EPS–HEPP Prize for the conception, development and realisation of parton-shower Monte Carlo simulations, which have been key to the experimental validation of the Standard Model and searches for new physics. The 2021 Giuseppe and Vanna Cocconi Prize has been awarded to the Borexino Collaboration for its observation of solar neutrinos from the pp chain and CNO cycle,


Lund University

while the 2021 Gribov Medal goes to Bernhard Mistlberger (SLAC) for his contributions to multi-loop computations in QCD and to high-precision predictions of Higgs- and vector-boson production at hadron colliders. The 2021 Young Experimental Physicist Prize has been awarded to Nathan Jurik (CERN) for outstanding contributions to the LHCb experiment, including the discovery of pentaquarks, and the measurements of CP violation and mixing in the B- and D-meson systems, and to ATLAS physicist Ben Nachman (LBNL Berkeley) for exceptional and innovative contributions to the study of QCD jets. Last but not least, the three winners of the 2021 Outreach Prize have been named as Uta Bilow (TU Dresden) and Kenneth Cecire (University of Notre Dame) for their contributions to the International Particle Physics Master Classes, and Sascha Mehlhase (LMU München) for the creation of the LEGO ATLAS and other models. The five prizes will be presented during the EPS–HEP Conference on 26 July, which will take place online.

Recognition for Ballarino
Amalia Ballarino of CERN has been named the recipient of the 2021 IEEE James Wong Award for her significant and continuing contributions to superconductor materials. In particular, Ballarino was recognised for leading successful R&D programmes with the high-temperature superconductor MgB$_2$, including the development of MgB$_2$ wire suitable for cabling, for promoting fruitful cooperation between


CERN

research and industry, and for launching R&D activity in superconductors for future particle accelerators. The award, which comes with a $5000 honorarium and a pure-niobium medal, has been granted annually since 2000, with CERN being home to more winners than any other institution.

Guido Altarelli Award
The 2021 Guido Altarelli Award, established in 2016 for outstanding contributions by junior scientists to deep-inelastic scattering (DIS) and related subjects, goes

to Eleni Vryonidou (bottom left) of the University of Manchester "for seminal contributions to precision collider phenomenology, specifically in the development of the effective field theory approach", and Benjamin Nachman (below), who is also a winner of the 2021 EPS Young Experimental Physicist Prize (see left), "for precision measurements

of observables sensitive to jet substructure and use of innovative machine learning techniques". The award, announced in April during the DIS2021 workshop, is named after the late CERN theorist Guido Altarelli, who made seminal contributions to QCD.

CMS celebrates theses
The CMS collaboration has recognised Matteo Defranchis (University of Hamburg), Cristina Martin Perez (Institut Polytechnique de Paris) and Thorben Quast (RWTH Aachen University) with the 2020 CMS Thesis Award. The three theses, selected from a total of 24 nominations, focus, respectively, on the first experimental determination of the running of the top-quark mass, the optimisation of algorithms identifying hadronic tau decays in top–Higgs associated production, and the development of the CMS high-granularity calorimeter.

New ICECUBE spokesperson
On 1 May, experimental astroparticle physicist Ignacio Taboada of the Georgia Institute of Technology began his two-year term as spokesperson of the IceCube collaboration, replacing Darren Grant who has served as spokesperson for the South Pole neutrino observatory since 2019. Taboada currently leads a research


Georgia Tech

group at the Center for Relativistic Astrophysics at Georgia Tech, which has made significant contributions to IceCube by using data to search for neutrinos from transient sources, including blazar flares.

Brookhaven hires Gao
Experimental nuclear physicist Haiyan Gao (below) has been appointed associate laboratory director for nuclear and particle physics at Brookhaven National Laboratory (BNL), beginning 1 June. Gao, whose research interests include the structure of the nucleon, searches for exotic QCD states and new physics in electroweak interactions, is a professor at Duke University, and has previously held positions at Argonne and MIT. At BNL she replaces Dmitri Denisov, who has held the position on an interim basis after Berndt Müller's departure last year.


Duke University

Olga Igonkina fellowship
LHCb researcher Anna Danilina of Moscow State University has been awarded the 2021 Olga Igonkina travel grant for young Russian talent in physics. The award, which was established in memory of the late Russian–Dutch ATLAS physicist Olga "Olya" Igonkina, who passed away in 2019 at the age of 45, will enable Danilina to participate in the Rencontres de Blois conference in October, where she will present calculations of the decay of B-mesons to four leptons.

RECRUITMENT

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

CERNCOURIER
Volume 61 Number 4 July/August 2021
IOP Publishing

For our location in Zeuthen we are seeking:

Senior Scientist Accelerator Physics – Tenure Track

Limited: initially limited to 5 years with the possibility of conversion to a permanent position | Starting date: earliest possible | ID: APMA012/2021 | Deadline: 15.07.2021

DESY, with its 2700 employees at its two locations in Hamburg and Zeuthen, is one of the world's leading research centres. Its research focuses on decoding the structure and function of matter, from the smallest particles of the universe to the building blocks of life. In this way, DESY contributes to solving the major questions and urgent challenges facing science, society and industry. With its ultramodern research infrastructure, its interdisciplinary research platforms and its international networks, DESY offers a highly attractive working environment in the fields of science, technology and administration as well as for the education of highly qualified young scientists.

The photo-injector test facility at DESY in Zeuthen (PITZ, near Berlin) will be expanded to advance the research and development of tumor therapies with short irradiation durations at high dose rates as well as high electron beam energy (so-called FLASH and VHEE radiotherapies). These promise better tumor control with fewer side effects in healthy tissue. The extremely wide parameter range for electron beams available at PITZ and the high flexibility of the facility allow unique research opportunities for future tailored applications in humans. We are looking for a project leader with strong accelerator experience, who will lead the expansion of the facility for this project and keep an eye on all major influencing factors together with local and international cooperation partners.

About the role:

- Project management for radiation biology, FLASH and VHEE radiotherapy at PITZ
- Close collaboration with e.g. dosimetry experts, biologists, physicians
- Representation of the project internally and externally
- Participation in the research operation of the PITZ accelerator

To be successful in this role:

- Master's degree in physics with PhD or equivalent qualification
- Profound and several years of experience in development, technology and operation of accelerator facilities and their applications
- Experience in beam dynamics
- Experience in project management
- Well-developed skills in interdisciplinary communication and cooperation in international collaborations
- Business fluent German and English
- Experience in radiation biology, biophysics, medical technology, especially cancer therapy is advantageous

For further information please contact Dr. Frank Stephan at +49 33762 7-7338 (frank.stephan@desy.de).

Applications (in German or English) should include a detailed curriculum vitae, publication list, explanations and evidence of experience background and 3 names for references.

DESY promotes the professional development of women and therefore strongly encourages women to apply for the position to be filled. In addition, severely handicapped persons with equal aptitude are given preferential consideration. The advertised positions are basically suitable for part-time employment.

You can find further information here: www.desy.de/career

Deutsches Elektronen-Synchrotron DESY
Human Resources Department | Notkestraße 85 | 22607 Hamburg
Phone: +49 40 8998-3392

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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

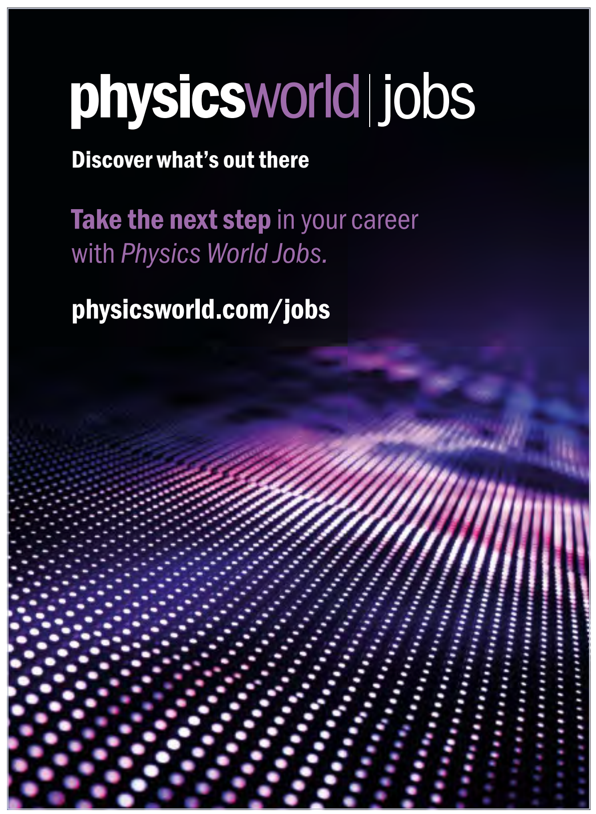
AegiQ
Career Opportunities

- Quantum Photonics Engineer
- Systems & Automation Engineer
- Delivery Lead

AegiQ is a dynamic company developing high-performance photonic systems across applications in quantum security, next generation imaging and quantum information processing.

Recently spun-out from the University of Sheffield, AegiQ is backed by Innovate UK and leading venture capital funds. We are recruiting a cross-disciplinary team to develop our product portfolio.

Apply at www.aegiq.com



The ELI (Extreme Light Infrastructure) Project is an integral part of the European plan to build the next generation of large research facilities. ELI-Beamlines as a cutting edge laser facility is currently being constructed near Prague, Czech Republic. ELI delivers ultra-short, ultra-intense laser pulses lasting typically a few tens of femtoseconds with peak power projected to reach 10 PW. It will make available time synchronized laser beams over a wide range of intensities for multi-disciplinary applications in physics, medicine, biology, material science etc. The high intensities of the laser pulse will be also used for generating secondary sources of e- and p+ and high-energy photons.
Our research groups are expanding and recruiting physicists and engineers.

In our team we therefore have the following positions available:

- Junior Scientist
- Senior Scientist
- Laser Physicist
- Junior Engineer
- Senior Engineer
- Vacuum Technician
- Mechanical Designer
- Control System Specialist
- Safety Engineer
- Optical Engineer
- X-ray Scientist
- Opto-mechanics

eli beamlines

For more information
see our website www.eli-beams.eu
and send your application, please.

MINISTRY OF EDUCATION, YOUTH AND SPORTS

EUROPEAN UNION
European Structural and Investing Funds
Operational Programme Research, Development and Education

PEOPLE OBITUARIES

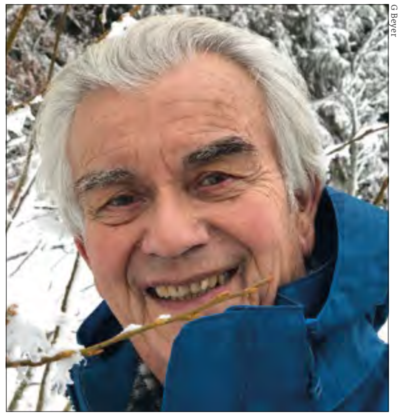
Gerd-Jürgen Beyer 1940–2021

A pioneer of applied nuclear physics

Gerd Beyer, who passed away on 20 January aged 81, played a major role in the development of biomedical research, both at CERN's ISOLDE facility and at many other laboratories. He will be remembered as a tireless worker in the field of nuclear and applied nuclear physics combined with new radiochemical methods.

Gerd was born in Berlin in 1940 and studied radiochemistry at the Technical University of Dresden (TUD). He then joined the Joint Institute for Nuclear Research (JINR) in Dubna, where he developed advanced production methods of rare short-lived radioisotopes for use in nuclear spectroscopy. At the Central Institute for Nuclear Research in Rossendorf, he became proficient in the use of the U-120 cyclotron and the RFR research reactor to produce medical radioisotopes, and in the development of the associated radiopharmaceuticals. He completed his Dr. habil. at TUD on the production of radionuclides by means of rapid radiochemical methods in combination with mass separation.

In 1971 Gerd was invited to ISOLDE, joining Helge Ravn to prepare extremely pure samples of rare long-lived nuclei for studies of their electron-capture decay, in view of their potential for determining neutrino masses. Back in Rossendorf, he continued to develop radiopharmaceuticals and to introduce them into nuclear medicine in the former East Germany and the Eastern Bloc countries. He developed a number of new methods for labelling and synthesising radiopharmaceuticals, in particular the rather difficult problem of efficiently separating fission-produced ^{99}Mo from large samples of low-enriched uranium. This brought him into many collaborations all over the world, with a view to transferring his know-how to other laboratories. As head of cyclotron radiopharmaceuticals, he took the initiative to introduce a PET scanner programme in the German Democratic Republic (GDR), based on the Rossendorf positron camera, using gas detectors derived from pioneering work at CERN.


Gerd Beyer's work on the production of radiopharmaceuticals saved innumerable lives.

During his visits to CERN, Gerd spotted the potential of the ISOLDE mass-separation technique to allow the introduction and use of better-suited but hitherto unavailable nuclides.

In 1985, in close collaboration with ISOLDE, he began to prepare for the future use of large facilities to produce such radionuclides. He reactivated ISOLDE's contacts with the University Hospital of Geneva (HUG), starting a collaboration on the use of exotic positron-emitting nuclides for PET imaging, which resulted in the development of new radiopharmaceuticals based on radionuclides of the rare earths and actinides.

Shortly after the fall of the GDR, Gerd lost his job at Rossendorf and had to start a new career elsewhere. Via a CERN scientific associateship, he became a guest professor at HUG and, later, head of its radiochemistry group, with responsibility for setting up and operating a new cyclotron. This allowed him to continue his work on developing new approaches to labelling monoclonal antibodies and peptides with exotic lanthanide positron emitters produced at ISOLDE, determining their *in vivo* stability and demonstrating their promising imaging properties. Gerd was also the first to demonstrate the promising therapeutic properties of the alpha emitter ^{149}Tb.

When he retired from HUG, Gerd co-proposed that CERN build a new radiochemical laboratory in connection with ISOLDE. Here, the large knowledge base on target and mass-separator techniques for the production and handling of radionuclides could be used to make samples of these high-purity nuclides available for use in a broader biomedical research programme. Years later, Gerd's initial idea was eventually realised with the creation of the CERN-MEDICIS facility.

Gerd was a first-rate experimental scientist, highly skilled in the laboratory, and he stayed professionally active to the very end. As a guest professor, a member of numerous professional societies and a holder of many consultancy positions, he spared no effort in sharing and transferring his know-how, recently to the young generation of scientists at MEDICIS.

During Gerd's outstanding career, his work on the production of radiopharmaceuticals saved innumerable lives. His R&D towards new radiopharmaceuticals and, in particular, his pioneering work on ^{149}Tb for targeted alpha therapy, is opening up new perspectives for efficient cancer treatment. It is therefore particularly tragic that the development of efficient antiviral drugs came too late to support Gerd in his brave fight against COVID-19.

His friends and colleagues.

Vladimir Kukulin 1939–2020

A brilliant nuclear theorist

On 22 December we lost our colleague and friend, a brilliant theoretical nuclear physicist, Vladimir Kukulin.

Vladimir Kukulin was born in Moscow in 1939. He graduated with honours from the Moscow Engineering Physics Institute in 1965, where he started his physics studies under the supervision of Arkady Migdal. Vladimir obtained his PhD in 1971 and his DSc in 1991. For more than 55 years, he worked in the Institute of Nuclear Physics at Moscow State University (MSU), becoming professor of theoretical physics in 1997 and head of the laboratory for atomic nucleus theory in 2012.

Vladimir had many close scientific relations, including the supervision of students' work, at JINR (Dubna), KazNU (Almaty) and other leading physics institutes in Russia, Kazakhstan, Uzbekistan and Ukraine. He worked as a visiting professor and gave lectures at universities in the Czech Republic, Germany, the UK, Italy, Belgium, France, the US, Canada, Mexico, Japan and Australia, and since 1996 had maintained a scientific cooperation between MSU and the University of Tübingen.

Vladimir's research interests embraced theoretical hadronic, nuclear and atomic physics, few-body physics, nuclear astrophysics, quantum scattering theory, mathematical and com- ▷

putational physics, among others. Many of the approaches he developed, such as the multi-cluster model of light nuclei, the method of orthogonalising pseudopotentials, and the stochastic variational method, opened new directions in nuclear physics and quantum theory of few- and many-body scattering. During the past two decades, Vladimir and his co-workers developed the effective wave-packet continuum discretisation approach for quantum scattering, and proposed a scheme for the ultra-fast quantum scattering calculations on a graphics processing unit.

A deep understanding of nuclear and mathematical physics allowed Vladimir to suggest, in 1998, a new mechanism for the short-range nucleon–nucleon (NN) interaction based on the formation of the intermediate six-quark bag dressed by meson clouds (the dressed dibaryon). He developed, with his colleagues from MSU and the University of Tübingen, the original dibaryon concept for the nuclear force, which received new experimental confirmation with the discovery of hexaquark states at COSY (Jülich) in 2011. More recently, Vladimir and his coauthors demonstrated the decisive role of dibaryon resonances in NN elastic scattering and NN-induced meson production at intermediate energies.

Vladimir Kukulin carried out pioneering research at the intersection of physics, mathematics, chemistry and engineering.

A combination of strong intuition, comprehensive knowledge, and experience in various fields of science and technology, enabled Vladimir to generate new ideas and carry out pioneering interdisciplinary research at the intersection of physics, mathematics, chemistry and engineering. He made an indispensable contribution to solving important applied problems, such as controlled thermonuclear fusion, cleaning of natural gas, fire-fighting and neutron-capture cancer therapy.

Vladimir was distinguished by non-standard thinking, humanity, a sparkling sense of humour and an inexhaustible love of life. His enthusiasm and intellectual freedom inspired several generations of his colleagues and students. We will always remember Vladimir as an outstanding scientist, a wise teacher and a good friend.

Maria Platonova, Olga Rubtsova, Vladimir Pomerantsev, Igor Obukhovsky *Moscow State University* and **Heinz Clement** *Eberhard Karls University of Tübingen.*

HERBERT LENGELER 1931–2021

Leaving a legacy in superconducting cavities

Experimental physicist Herbert Lengeler, who made great contributions to the development of superconducting radiofrequency (SRF) cavities, passed away peacefully on 26 January, just three weeks short of his 90th birthday.

Herbert was born in 1931 in the German-speaking region of Eastern Belgium. He studied mathematics and engineering at the Université Catholique de Louvain in Belgium, and experimental physics at RWTH Aachen University in Germany. He worked there as a scientific assistant and completed his PhD in 1963 on the construction of a propane bubble chamber, going on to perform experiments with this instrument on electron-shower production at the 200 MeV electron synchrotron of the University of Bonn.

In 1964 Herbert was appointed as a CERN staff member in the track chamber and accelerator research divisions. He was involved in the construction, testing and operation of an RF particle separator for a bubble chamber. In 1967 he then joined a collaboration between CERN and IHEP in Serpukhov, in the Soviet Union, within which he led the construction of an RF particle separator for both IHEP and the French bubble-chamber Mirabelle, which was installed in the same institution.

In 1971 the value of SRF separators for improved continuous-wave particle beams was recognised. This necessitated the use of SRF systems with high fields and low RF losses. Since a development programme for SRF had just been initiated at the Karlsruhe Institute of Technology in Germany, Herbert joined the research centre on behalf of CERN. In the following pioneering period up to 1978, he led the development of full-niobium SRF cavities operated at liquid-helium temperatures, with all required auxiliary systems.

Herbert Lengeler led the SRF upgrade of LEP, among other key projects.

The success of the SRF separator led to ambitious plans for upgrading the energy of LEP at CERN, which were initiated in 1981. A first SRF cavity with its auxiliaries (RF couplers, frequency tuner, cryostat) was installed and successfully tested in 1983 in the PETRA collider at DESY in Hamburg. Following this, in 1987, an SRF cavity with all auxiliaries and a new helium refrigerator was installed and tested at CERN's SPS. In parallel, Herbert orchestrated the development of niobium sputtering on copper cavities as a cheaper alternative to bulk niobium. Gradually, additional SRF cavities were installed in the LEP collider, resulting in a doubling of its beam energy by the end of its running period in 2000.

From 1989 onwards, Herbert gradually retired from the LEP upgrade programme and devoted more time to other activities at CERN, such as consultancy for SRF activities at KEK, DESY and Jefferson Lab. In 1993 he was appointed project leader for the next-generation neutron source for Europe, the European Spallation Source, a position he held until his retirement from the project and CERN in 1996.

Herbert was always interested in communicating his experience to younger people. From 1989 to 2001 he frequently gave lectures on accelerator physics and technology as an honorary professor at the Technical University of Darmstadt in Germany. In 1998 he was awarded an honorary doctorate from the Russian Academy of Sciences for his contribution to the CERN–IHEP collaboration.

Herbert was an enthusiastic musician. He had been married since 1959 to Rosmarie Müllender-Lengeler, and the couple had four children and 10 grandchildren.

Enrico Chiaveri *CERN*; **Herbert's friends and colleagues**.

LUC PAPE 1939–2021

A remarkable and complete physicist

Our colleague and friend Luc Pape passed away on 9 April after a brief illness. Luc's long and rich career covered all aspects of our field, from the early days of bubble-chamber physics in the 1960s and 1970s, to the analysis of CMS data at the LHC.

In the former, Luc contributed to the development of subtle methods of track reconstruction, measurement and event analysis. He participated in important breakthroughs, such as the first evidence for scaling violation in 1978 in neutrino interactions in BEBC and early studies of the structure of the weak neutral current. Luc developed software to allow the identification of produced muons by linking the extrapolated bubble-chamber tracks to the signals of the external BEBC muon identifier.

Luc's very strong mathematical background was instrumental in these developments. He acquired a deep expertise in software and stayed at the cutting edge of this field. He also exploited clever techniques and rigorous methods that he adapted in further works. At the end of the bubble-chamber era, Luc was among the experts studying the computing environment of future experiments. He was also one of the people involved in the origin of the Physics Analysis Workstation (PAW) tool.

After this, Luc joined the DELPHI collaboration. Analysing the computing needs of the LEP experiments, he was among the first to realise the necessity of moving from shared central computing to distributed farms for large experiments. He thus conceived, pushed and, with motivated collaborators, built and exploited the DELPHI farm (DELFARM), allowing physicists to rapidly analyse DELPHI data and produce data-summary (DST) files for the whole collaboration. Using his strong expertise in most available software tools, Luc progressively improved track analysis, quality checking and event viewing. DELPHI users will remember TANAGRA (track analysis and graphics package), the backbone of the DELANA (DELPHI analysis) program, and DELGRA for event visualisation.

Luc Pape had outstanding competence and rigour.

Luc's passion for physics never faded. Open minded, but with a predilection for supersymmetry (SUSY), the subtle phenomenology of which he mastered brightly, he became the very active leader of the DELPHI, and then of the full LEP SUSY groups.

After retiring from CERN in 2004, he enjoyed the hospitality of the ETH Zurich group in CMS, to which he brought his expertise on SUSY. Collaborating closely with many young physicists, he introduced into CMS the "stransverse mass" method for SUSY searches, and pioneered several leptonic and hadronic SUSY analyses. He first convened the CMS SUSY/BSM group (2003–2006), then the SUSY physics analysis group (2007–2008), preparing various topological searches to be performed with the first LHC collisions. Responsible for SUSY in the Particle Data Group from 2000–2012, he helped define SUSY benchmark scenarios within reach of hadron colliders, present and future. Comforted by the discovery of a light scalar boson in 2012 (a necessary feature of but not proof of SUSY), he continued exploring novel analysis methods and strategies to interpret any potential evidence for SUSY particles.

We will remember Luc for the exceptional combination of a genuine enthusiasm for physics, an outstanding competence and rigour in analysis, incorporating quite technical matters, and a deep concern about young colleagues with whom he interacted beautifully. Luc had a strong interest in other domains, including cosmology, African ethnicities and arts, and Mesopotamian civilisations. With his wife, he also undertook some quite demanding Himalayan treks.

We have lost a most remarkable and complete physicist, a man of great integrity, devoid of personal ambition, a rich personality, interested by many aspects of life, and a very dear friend.

His friends and colleagues.

JEAN SACTON 1934–2021

Father of Belgian experimental particle physics

Jean Sacton, who put Belgium at the forefront of major discoveries in fundamental physics and the development of associated technologies, died peacefully in his home in Brussels on 12 February, aged 86. He combined his scientific qualities with great human ones, as a firm boss but always present, attentive, warm and intentioned.

Sacton was involved in the first direct observation of charged charmed particles in nuclear emulsions

Jean Sacton defended his bachelor's thesis on mesic atoms in nuclear emulsion at Université Libre de Bruxelles (ULB) in 1956, continuing there for his PhD. From 1960 to 1965, he surrounded himself with young researchers focusing on the properties of hyper-fragments produced by the interactions of K mesons in nuclear emulsions, which required significant human resources to scan the emulsion foils with microscopes. He defended his thesis in 1961 and, three years later as an associate lecturer, became head of the newly created department of elementary particle physics.

At the end of the 1960s, Sacton became professor and a member of various committees, including the management of the Belgian Interuniversity Laboratory for High Energies.

The foundation in 1972 of the Interuniversity Institute for High Energies (IIHE) was largely due to his efforts during the preceding decade. Co-directed for many years by its two founders (Sacton for ULB and Jacques Lemonne for Vrije Universiteit Brussel), IIHE has become the main centre for experimental research in particle physics in Belgium, and promotes close collaboration with other Belgian institutes.

In the 1970s the IIHE strongly contributed to the scanning and analysis of data from the giant bubble chambers GARGAMELLE and BEBC. In 1973 IIHE staff scanned one of the three events that spectacularly confirmed ▷

CERNCOURIER
VOLUME 61 NUMBER 4 JULY/AUGUST 2021
IOP Publishing

the existence of the weak neutral current, for which Sacton, together with the other members of the Gargamelle collaboration, received the European Physical Society's High Energy and Particle Physics Prize in 2009. Other firsts that Sacton was involved in during the bubble-chamber era included the first direct observation of charged charmed particles in nuclear emulsions, and the measurement of the violation of scale invariance in deep-inelastic scattering.

Later, the IIHE, in collaboration with the University of Antwerpen and the University of Mons-Hainaut, contributed to the DELPHI experiment at LEP, for which they built the electronics for the muon chambers. The laboratory also engaged in the H1 collaboration at HERA, DESY. The Belgian contribution to H1 included the construction of two cylindrical multi-wire proportional chambers and associated data acquisition all of the detector's multi-wire proportional chambers, during which Sacton continuously ensured that technical staff were retrained to keep up with the rapid pace of change.

At the same time, he became a member of the European Committee for Future Accelerators (as chair from 1984 to 1987), the CERN Super Proton Synchrotron Committee, the CERN Scientific Policy Committee, and the extended Scientific Council of DESY. While dean of the ULB sciences faculty from 1991–1995, he remained active as director of the laboratory, leaving to his teams the task of analysing DELPHI, H1 and CHORUS data, and preparing the IIHE contribution to the CMS experiment. In 1994 he became president of the particles and fields commission of the International Union for Pure and Applied Physics and a member of the International Committee for Future Accelerators, and from 1991–1994 chaired the High-Energy Physics Computer Coordinating Committee. He formally retired in 1999.

Jean Sacton lived a major scientific adventure starting from the discovery of the first mesons to the completion of the Standard Model. Through his quiet strength, professionalism, foresight and entrepreneurial spirit, he founded, developed and sponsored this field of research at ULB and made it shine far beyond.

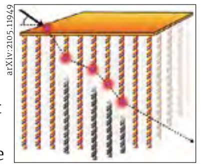
Jean Sacton co-founded the Interuniversity Institute for High Energies.

Daniel Bertrand *and* **Laurent Favart**
Université libre de Bruxelles.

BACKGROUND

Notes and observations from the high-energy physics community

Detectors come to life



From hadron therapy to medical imaging, techniques from particle physics have had a major impact on biological applications. An Australia-based team now proposes to return the favour, reporting the first proof-of-concept simulations of detectors based on biomaterials. The "DNA detector", writes Ciaran O'Hare of the University of Sydney and co-workers, could be a cost-effective, portable and powerful new technology for a low-energy particle tracker for dark matter and other searches. The idea, first proposed in 2012 (arXiv:1206.6809), is to create a "forest" of precisely-sequenced single or double-stranded nucleic acids: incoming particles break a series of strands along a roughly co-linear chain and the severed segments fall to a collection area. Since the sequences of base pairs in DNA molecules can be precisely amplified and measured, the original position of each broken strand can be reconstructed with nanometre precision. Particle identification and energy reconstruction might be challenging without a significant scale-up, admits the team, but Monte Carlo simulations show excellent potential angular and spatial resolution (≲ 25 degree axial resolution for keV particles and nanometre-scale track segments) that demonstrates the feasibility of the concept (arXiv:2105.11949). "We hope that this first explorative study will inspire imminent experimental investigation to resolve many of the outstanding issues we have laid out," they conclude.

Media corner

"This is a unique opportunity to support breakthroughs in nuclear medicine that we should all be excited about!"

Thomas Cocolios of KU Leuven speaking to *Medical News Today* (18 May) about CERN-MEDICIS and the European medical isotope programme.

"What we really need is 'a disinformation CERN'"

Alicia Wanless of the Carnegie Endowment for International Peace, speaking in a panel discussion about how democracies can collaborate on disinformation (*The Strategist*, 18 May).

"Adieu, planète Neptune de l'infiniment petit…"

Le Monde journalist **David Larousserie** waxes lyrical on the "coup de théâtre" of the Budapest-Marseille-Wuppertal group publishing new theoretical calculations at the same time as Fermilab's "somewhat barbarically named" Muon g-2 experiment unveiled its first measurement (7 April).

"Scientists are usually happy when their theories are confirmed by experiments. This is different with the Standard Model."

TU Dresden particle physicist **Dominik Stöckinger** quoted in German news site MDR (10 May).

"If you touch a resonating wire, you can convince yourself you're feeling the universe coming into being."

Guardian journalist **Stuart Jeffries** reviewing *Halo*, the CERN-inspired artwork by artistic duo *Semiconductor* (19 May).

From the archive: July/August 1981

Dreaming large and small

LEP Project Leader Designate Emilio Picasso reviewing the project status at Villars.

Over 400 physicists gathered in the relaxed environment of the Swiss alpine resort Villars, 1–7 June, for the European Committee for Future Accelerators ECFA 'General Meeting on LEP', a very high energy electron–positron machine. This was in the long tradition of broad consultation across the European HEP community before taking major decisions on CERN projects. As Danish physicist Hans Boggild reported: 'There once was a place called Villars, where there was more than one star. They talked about LEP and the future of HEP, but decisions were made in the bar.'

During recent years, new methods have been perfected which enable complex electronic logic to be mass-produced in small integrated circuits or 'chips', whose dimensions are typically measured in millimetres. The dramatic rate of progress has provided logic units capable of carrying out increasingly complex operations at higher speed and at lower cost. While the frontier of programmable intelligence is gradually being extended, physicists can still only dream of the day when they will have fully programmable triggers with on-line event analysis providing digital displays of the physics parameters!

● Based on text on pp240–242 and pp235–236 of *CERN Courier* July/August 1981.

Editor's note

When LEP was approved for construction 40 years ago, microprocessors were objects of fascination. Reporting on the first ever "Topical Conference on the Application of Microprocessors to High Energy Physics Experiments" that year, the July/August issue described a great interest among particle physicists in applying microelectronics to reject unwanted data. Back then, triggering was largely restricted to hardwiring. Jump forward to the latest silicon-pixel upgrades to the inner trackers of the LHC experiments, and physicists are able to read out tens of millions of channels at a rate of 40 MHz.

11,000 km

Total length of the 250 µm scintillating fibres in LHCb's new "SciFi tracker", the first sections of which were lowered underground in May.

Correction and clarification

Margarida Ribeiro's correct title (*CERN Courier* May/June 2021 p55) is EIROforum liaison officer in the European Commission Directorate-General for Research and Innovation. The concept behind an accelerator-driven critical system (*CERN Courier* May/June 2021 p11) emerged from several individuals at different institutes.

CERNCOURIER
VOLUME 61 NUMBER 4 JULY/AUGUST 2021
IOP Publishing


CAEN
A4818
USB 3.0 to CONET Adapter
LINK


CAEN
CAEN
CAEN
CAEN
VME BRIDGE