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.

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High-density wiring

Our new high-density wiring is a modular option for the Bluefors side-loading XLDSL dilution refrigerator system that enables a large scale-up of the experimental wiring, especially for high-frequency signals. It is easy to install and to maintain.
Beyond tracking
Silicon-pixel detectors developed for particle physics have also had a major impact on medical imaging, for example via the CERN–Ied Medipix and Timepix collaborations (p22). 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 detect dark matter and the incredible promise of TESS as a way to map the exoplanets of the universe (p20). Also in our summer edition, learn about the fascinating potential of particle accelerators to detect gravitational waves (p18), the detection of the first collider-neutrino candidates (p7), the latest attempts to detect dark matter and the incredible promise of TESS as a way to map the exoplanets of the universe (p20). Also in our summer edition, 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 detect dark matter and the incredible promise of TESS as a way to map the exoplanets of the universe (p20). Also in our summer edition, 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 detect dark matter and the incredible promise of TESS as a way to map the exoplanets of the universe (p20). Also in our summer edition, 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 detect dark matter and the incredible promise of TESS as a way to map the exoplanets of the universe (p20).
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, 1.5 m downstream from the ATLAS experiment. Designed to detect neutrinos produced in a hitherto unexplored pseudorapidity range (2.2 < η < 8.6), the experiment will complement and extend the physics reach of the other LHC experiments – in particular FASER, which was approved last year. Construction of FASER, which is located in an unused service tunnel on the opposite side of ATLAS along the LHC beamline (covering |η| > 8.1), 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 expansions to the LHC-experiment family are poised to make the first observation of collider neutrinos while opening new search avenues for boosty interacting particles and other new physics.

Neutrinos galore
SND@LHC will comprise a small and inexpensive stack of tungsten plates interleaved with emulsion films and electronic tracker planes based on scintillating fibres. The emulsion acts as a vertex detector with micro 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 down-stream by a muon-identification system.

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

During its first phase of operation, SND@LHC is expected to collect an integrated luminosity of 100 fb⁻¹, corresponding to more than 1000 high-energy neutrino interactions. Since electron neutrinos and antineutrinos are predominantly produced by charmed-hadron decay 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 5% and 2%, respectively, in the ratio between $\nu_e$ and $\bar{\nu}_e$, and about 10% for both uncertainties in the ratio between $\nu_\mu$ and $\bar{\nu}_\mu$ 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 feeby 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.”

FASER 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 1.35 × 0.25 × 1.3 m and weighing 1.2 tonnes, FASER 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 10⁻⁶ 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–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 FASER team reported the detection of the first neutrino–interaction candidate, based on a measured 3.2σ 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 abundantly larger, be exposed to much more luminosity, have muon identification capability, and be able to link observed neutrino interactions in the emulsion to 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
**NEWS ANALYSIS**

**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). Though with a much lower significance, a similar situation may also be influencing the electron’s behaviour.

Depending on which of two recent independent measurements of the fine-structure constant is used in the theoretical calculation of $a_e$, one obtains at Berkeley in 2019 or the other at Kaikōura, New Zealand, in 2020 – the Standard Model prediction stands 2.4 higher or 1.6 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.

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 possible to exclude the presence of a massless X boson.

NA64 searches for X bosons by directing rates is a spectacular feature of quantum mechanics. The phenomenon arises because, depending on which of two recent model-independent searches for a pseudoscalar X17, more recently, they searched for a pseudoscalar X17, which has a lifetime about half that of the vector X17 for the same coupling strength. Re-analysing a sample of approximately $10^{12}$ electrons-on-target collected in 2017 and 2018 with 100 and 195 GeV electrons, respectively, the collaboration has now excluded couplings in the range 2.1–3.2\,\times\,10^{-6}$ 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 determine the CKM matrix-element $V_{ud}$,” says Gninenko.

Further reading


Neutron lifetime

KEK tackles neutron-lifetime puzzle

More than a century after its discovery, the neutron remains a source of intrigue, its charge oscillating between $e^+$ and $e^-$ that are the focus of intense study (CERN Courier May/June 2019 p38). But what of its most fundamental property? In recent years, discrepancies between measurements of the neutron lifetime using different methods constitute a puzzle with potential implications for cosmology and particle physics. How, and when they decay, offer a sensitive probe of physics beyond the Standard Model. Using a large sample of $e^–_e^+$ decays, the new measurement improves upon the previous world’s best determination by a factor of two: $\tau_n = 8.4^{+0.8}_{-0.9}\,\times\,10^{-13}\,$ seconds.

Way to go

The apparatus in which neutrons from J-PARC are stored.

The decay rate and the reaction rate are determined by simultaneously tracking the decay of the neutron and protons from the reaction $n^- + H \rightarrow p + \bar{p} + \gamma + \nu_e$, removing some of the systematic uncertainties associated with previous beam methods. The experiment is still in its early stages, while the first results have been released in February 2021, 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 analysis of the new experimental uncertainties are underway. “We think it will take two years to achieve a competitive result from our experiment.”

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

Further reading


“in the future we hope to discover that the so-called ‘vector CP violation’ in the charm sector, and the system and the precision and luminosity expected from LHCb allow the second generation of charm–meson oscillations to be observed. Indeed, the new measurements of neutral–charm–meson oscillations follow hot on the heels of the first observation confirming the process in 2012. The collaboration looked for small changes in the flavour mixture of $D^0$ mesons as a function of the time at which they decay via the $K^0\text{e}^–\bar{\nu}_e$ final state.

The “bottle” method uses a trap in which the axes of the plot are the squares of the invariant masses $m_{XX}$ and $m_{YY}$, respectively, and while the first results have been released in February 2021, the uncertainty is currently too large to draw conclusions.

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Further reading

**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 in 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 Krējsjāns Kariņš. As an Associate Member State, Latvia will be entitled to appoint representatives to attend meetings of the CERN Council and Finance Committee. Its scientists 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.”

**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 not 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.

**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 28,000m², 18 wide-field-of-view Cherenkov telescopes and a 1km 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 within the Earth's atmosphere. The EDs detect the shower profile and incoming angle, using charge and timing information of the detector arrays, 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 than the largest existing fixed-site detector on Earth, 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 nebula as a source in which electrons are accelerated beyond PeV energies, which in turn are responsible for the gamma rays through inverse Compton scattering. 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 spectroscopy 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 the iceberg when it comes to high-energy gamma rays.

**Further reading**

When Compromise is Not an Option

High-Performance Digitizers for Big Physics Applications

Digitizers from Teledyne SP Devices utilize patented calibration technology, the latest data converters, and state-of-the-art FPGAs in order to achieve an unrivaled combination of high resolution and sampling rate. Their versatility makes them ideal for applications such as beam position monitoring, Thomson scattering plasma diagnostics, and more.

Supported features include:

- Up to 10 GSPS sampling rate with 14 bits resolution
- Open FPGA for custom real-time signal processing
- Multiple form factors including MTCA.4, PXIe, and PCIe
- Multi-channel synchronization capabilities
- White Rabbit synchronization (MTCA.4 only)
- Peer-to-peer streaming to GPU (PCIe only)
- Application-specific firmware shortens design time

An electronic bunch (centre) from 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 105001, 2021).

Wave-in-leptonogenesis

Early attempts to explain the origin of the baryon asymmetry of the universe using CP-violating decays of massive (QFT) particles were spoiled by electroweak “sphaleron” processes that non-perturbatively wash-out baryon-plus-lepton number. This prompted an alternative explanation called leptonogenesis, during which the CP-violating decays of hypothetical right-handed neutrinos (RHs) create a lepton asymmetry that is then converted by Standard Model interactions (including sphalerons) into a baryon asymmetry. By generalising standard 4 “freeze-out” leptogenesis, such that all conserved charges at the time of leptogenesis are allowed to take arbitrary values, CERN’s Valérie Domcke, Ryohei Mukaida, Kai Schmitz and colleagues have recently made an important contribution to the theory that lowers the possible mass range of the RHs down to a few 10s eV, actively “washing in” the observed baryon asymmetry (arXiv:2011.09352).

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

Leptoquarks and H

Andreas Crivellin (CERN), Darío Müller (PSI) and Francesco Serretta (Bari) have shown that leptoquarks (LQs) are not only well motivated by hints of lepton-flavour-universality violation (CERN Courier May 2021) 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:2011.26761, accepted in Phys. Rev. Lett.). Should LQs prove to be the true-explanation of the 2.5 σ tension in the muon g-2 reported by Fermilab in April (CERN Courier May 2021), the effect of LQs should also be observable in future precision measurements of RH(−1,1). The first evidence for this decay was reported by CERN and ATLAS in August last year, with signal strengths with respect to the Standard Model of 1.2 ± 0.4 and 3.3 ± 0.6, respectively (CERN Courier September/October 2020).

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 Kashima, Chiba, 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, and studies for the International Linear Collider. The lab will be directed by Michel Coin (CERN) and Nobu-Ikezaki Takashi 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 100 detection units – each zoom tail and comprising silicon 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, formed 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 the predecessor telescope in the northern hemisphere, ANTARES.

Sergio Argüeso Cuéllar adjusts the RADES detector.

RADES reports results

The Bielefeld Axion Dark-Matter Exploratory set-up (RADES) haloscope at CERN has reported the results of its first search for axions (arXiv:2004.17396). The detector was installed inside one of the CACTF experiment’s dipole magnet bores in 2018. While CAST seeks to observe electric-field oscillations in a resonant cavity – evidence, according to the Standard Model of 1.2 ± 0.4 and 3.3 ± 0.6, respectively (CERN Courier September/October 2020).

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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 22 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 fb, which is consistent with the Standard Model prediction of 12.0 ± 2.4 fb (within 2σ; 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.

Further reading
**CMS**

**Gauge–boson polarisation observed in WZ production**

At the collision energies of the LHC, diboson processes have relatively high production cross sections, but they are strongly suppressed in diboson processes with relative clean final states with two or more charged leptons. Consequently, multi-lepton final states resulting from diboson processes are powerful signatures towards the probe of the electroweak sector of the Standard Model. In particular, WZ production is sensitive to the strength of the triple gauge coupling, which characterises the WZ vertex, versus 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 3 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 methods 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 of WZ diboson production was measured with a simultaneous fit to the signal–enriched region and three different control regions. These elaborately fitting schemes 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).

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 W decay. This choice, coupled with the precisely measured fractions of the three leptons and the requirement that the 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 $f_W$ and $f_Z$, which correspond to the proportion of bosons in the left, right, and longitudinally polarised states in WZ production. The measured polarisation fractions are consistent with zero within 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 W bosons with respect to the production of the W boson with and without the Z boson was set to be $\sim 5.0$ standard deviations. This result has been used in the final result of differential cross sections for WZ production.

These new results 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

ALICE Collaboration, 2021 CMS–PAS–MPH–20–004, The ALICE collaboration has recently performed a study of strangeness production in the central collision region, using data collected during Run 2 of the LHC. The results provide new insights into the mechanisms of strangeness production, showing that the production of strange particles is strongly correlated with the energy density and the collision geometry.

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 happens, the partons have to rely on measurements, and measurement-driven modelling. This is because the strong interactions among partons that govern hadronisation are characterised by a scale $\Lambda_{QCD}$, which is much larger than the typical distance of hadrons—about 1 fm—and cannot be calculated perturbatively.

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 studies of baryon–meson transitions, but the comparison is particularly interesting in heavy–ion collisions, where a large baryon–meson enhancement is often referred to as the “baryon anomaly.” A characteristic maximum at intermediate transverse momenta ($p_T < 10$ GeV) is found in hadron systems, but in $pp$–$p$–$p$–$p$–$p$ 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–parton “radial” flow associated with the production and expansion of a quark–gluon plasma.

The ALICE collaboration has studied baryon–meson polarisations extensively. A recent result adds an extra twist to the study of strange baryons and mesons by studying the ratio of $K^0$–$K^0\bar{K}^0$ production in two different final states: $pp$–$p$–$p$–$p$–$p$ collisions and $p$–$p$–$p$–$p$–$p$ collisions. Taking advantage of the fact that the production of strange particles is strongly correlated with the energy density and the collision geometry, the ALICE collaboration has performed a study of strangeness production in the central collision region, using data collected during Run 2 of the LHC. The results provide new insights into the mechanisms of strangeness production, showing that the production of strange particles is strongly correlated with the energy density and the collision geometry.

The measured $K^0\bar{K}^0$ production ratio is consistent with the previous LHCb measurement, suggesting that the production of strange particles is strongly correlated with the energy density and the collision geometry.

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**LHCb**

**New charmed-baryon lifetime hierarchy cast in stone**

The charmed-baryon lifetime puzzle has now been resolved by a new measurement from LHCb using a much larger sample of $D^0$ and $D^\pm$ mesons produced directly in $p$–$p$ collisions. Both particles are detected in the final state of $u$–d, $c$–b decays (LHCb SL) and now from proton–proton collisions directly. The measurement is made from hard pp collisions using PYTHIA 8 (2018/19)

Fig. 1. The enhancement in the production of a baryon with respect to $K^0$ mesons at intermediate transverse momenta (orange circles) is largely due to $\tau^+$–$\tau^-\pi^0$–$\pi^+$–$\pi^0$ charged–particle jets (open circles), and it is seen for the $\tau^+$–$\tau^-$ decay products found inside them (red and open triangles). The dotted curves represent PYTHIA 8 simulations of $p$–$p$ collisions outside (black) and inside (red) jets.

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Accelerators meet gravitational waves

Gravitational waves (GWs) create 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 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 LIGO and VIRGO detectors, and as new, larger storage rings are being proposed in Europe and China, this question has gained renewed relevance. We are on the cusp of the GW gravitation astronomy — a young and dynamic domain of research with much to discover, in which particle accelerators could conceivably play a major role.

On January 31 to 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 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 high-frequency, tiny ones. Their wavelengths are measured in nanometres, or even smaller, compared to the kilometres that are probed through other transient phenomena; spinning neutrinos, supernovae, or the Sun moving through the Galaxy.

Theoretically, GWs would be difficult to detect, given their minuscule size. However, in 1969, scientists including Joseph Weber (at the University of Illinois) and Jürgen Schallock (at the German aerospace agency DLR) proposed a detection scheme that relies on the inelastically scattered photons produced in the passage of GWs.

In the opening session of the workshop, Jorge Cervantes (INNUK Mexico) discussed 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 a beam circulating in a storage ring. Typical betatron frequencies for the LHC are a few kHz, way beyond the range of detectability for GWs with frequencies of a similar order of magnitude. Starting from a standard LHC ring, Oide proposed special beam–optical insertions with a large beta function, which would serve as “GW antennae” to enhance the resonance strength, resulting in 37.5 pm–long optical resonances. Among several parameters, the sensitivity is highly dependent on the size of the ring.

Raffaele D’Agostino (INFN Rome) discussed an analysis of the longitudinal betatron resonances excited by GWs. The GW source, which is useful for electromagnetic synchrotron radiation (EMSR), is converted into GWs.

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 Virgo. Accelerator-based detection methods and sources are superimposed on optimistic assumptions that require future confirmation.

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

Extraordinarily, gravitational waves could act not only as GW detectors, but also as observable sources of GWs without any backgrounds, as h ≪ 1, and listed three possible paths to further improve the sensitivity by several orders of magnitude. Rau 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 2023. This would improve the sky-localisation of the GW source, which is useful for electromagnetic follow–up studies with astronomical telescopes.

**Out of the ordinary**

More exotic accelerators were also mooted. A “coasting-beam” experiment might have zero restoring voltage and no synchrotron oscillations. Cold “stainless-steel” beams of stable ordered 1D, 2D or 3D “super-cold” beams of stable ordered 1D, 2D or 3D...
field notes

Gravitations could be the vector of gravitational beamstrahlung.

As discussed in this emerging field, detectors are designed to be sensitive to different kinds of interactions in the universe. For example, the detection of gravitational waves requires the use of detectors that are highly sensitive to the movement of objects in space. This sensitivity is achieved through the use of advanced cryogenic detectors, which are capable of detecting the tiniest movements of matter in the universe.

In ATLAS and CMS, charged, gaseous detectors, form the backbone of the experiments' muon systems. The ATLAS detector is a large collider experiment, which is sensitive to a wide range of particle collisions. The CMS detector is a large hadron collider experiment, which is sensitive to the production of Higgs bosons and other new particles.

The new silicon photomultipliers could reduce chromatic errors and increase photon yield, potentially allowing for the replacement of other components. In the future, new silicon photomultipliers will improve signal quality and efficiency, allowing for the replacement of other components.

A new CMOS sensor detector, 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.

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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.

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 scans.

THE AUTHOR
Manuela Cirilli
CERN.

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.

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Making our world more productive
In these images, Timepix chips were combined with a silicon detector to produce (a) 640 MeV protons, (b) 220 MeV protons, (c) 89 MeV) carbon ions and (d) 430 MeV/u carbon ions. In each case, secondary particles are present only at the higher energy.

Radiosotopes in the MEDIKIT project, non-conventional isotopes are collected by mass separation.

For example, the avalanche photodiodes developed for the CMS electromagnetic calorimeter were adapted for the ClearPET 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.

Crystal clear

In the onion-like configuration of a collimator 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 p.17). 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 TOP–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.

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-auto-radiography 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. In this chip, images are no longer black and white, but in colour (see “Colour X-ray” image).

Although the primary aim of the Timepix chip was applications outside of particle physics, its development also led directly to new solutions in high-energy physics, such as the VELox chip for the ongoing LHC 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 2004, for example, Timepix3 was employed to determine the exposure of medical personnel to ionising radiation in an interventional radiology theatre located in New Zealand. The chip was able to map the radiation flux and energy spectrum of the scattered photon field that reaches the practitioners, and was also able to reveal which parts of the body are most exposed to radiation.

Meanwhile, 3GEMPix detectors are being evaluated for radiation therapy. GEMPix detectors couple gas electron multipliers (GEMs) – a type of gaseous ionisation detector developed at CERN – with the Medipix3 chip 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 in CERN collaboration with the Holst Centre in the Netherlands. A version of the GEMPix chip called GEMTEG is also currently under development at CERN for use in “microdosimetry”, which studies the interactions of absorbed energy measurements in addition to hit counting. Medipix3 and Timepix3 both allow 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, time – off chip. Most recently, the Medipix3 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...
faster, and more precise. 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 SkIRM concept, which was 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 ions 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 already been 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 will 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 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 radioisotope facilities for medical research. In nuclear medicine, radioisotopes are used both for diagnostic and treatment purposes. The development of new radioisotopes has always been connected to the availability of novel radioisotope sources. Here, CERN has capitalised on the experience of its ISOLDE facility, which during the past 50 years has the proton beam from the CERN PS Booster to produce >1000 different isotopes from 75 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 $^{111}$In or $^{125}$I 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 Geanta, 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 model-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 the world, the theories of relativity and quantum mechanics were considered abstract and esoteric when they were developed; a century later, we owe them the remarkable provision 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 is increasingly finding applications in the biomedical field.
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 10x-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 jet quenching and exotic heavy nuclear states, 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-momentum (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 10^7 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 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 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 detectors.
ALPIDE journeys. A schematic cross-section of the ALPIDE chip. When a charged particle traverses the silicon sensor’s active volume, it generates charge carriers (electrons 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 $N_D$) and geometry (thickness of sensitive material, pixel pitch, electrode shape) as well as the electric field configuration (electrode potential and geometry) of the sensor.

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 large-scale application of CMOSAPS technology in a collider experiment was the STAR PDL detector at Brookhaven’s Relativistic Heavy-Ion Collider in 2014 (CERN Courier October 2015, p6). The ALICE ITS2 has benefited 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 sensors

ALPIDE, which is the result of an intensive R&D effort, is the building block of the ITS2. Since the 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 55 × 35 mm$^2$ in area and contains more than half a million pixels organised in 2024 columns and 512 rows. Its very low power consumption (< 40 mW/cm$^2$) and excellent spatial resolution (<5 μm) are perfect for the inner tracker of ALICE.

The ITS2 consists of seven layers covering a radial extension from 22 to 43 m 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 $|\eta| < 1.2$ for 90% of the most luminous beam interaction region, extending over a total surface of 10 $m^2$ and containing about 250,000 pixels with binary readout, and is operated at room temperature using water cooling.

The small size of the ALPIDE (4.5 cm$^2$) sensors is tilted-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: 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).

Another important feature of ALPIDE is the use of ap–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 significant enhancements to the performance of the ALICE detector will enable the exploration of new phenomena. The ALICE detector will be able to record detailed, quantitative characteristics of the high-density, high-temperature phase of strongly interacting matter, together with the exploration of new phenomena. The ALTS 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 ALTS 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 offers an insight into the bulk properties and space-time evolution of the QGP.

More in store

The full potential of the ALPIDE chip underpinning the ITS2 is yet to be fully exploited. For example, a variant of the 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 MINERvA experiment at BNL, and the inner tracking system for the NuMI-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 HEPDiC0 detector for the Chinese–Italian CSES-02 mission, meanwhile, includes a charged-particle tracker made of three layers of ALPIDE sensors that represent 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
G Aglieri et al. 2013 JINST 8 C12043.

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Installation of Best 70 MeV Cyclotron at INFN, Legnaro, Italy
**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 Mathieu 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 $10^{33}$ 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 2023, 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 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 utilizing 65 nm CMOS technology. The overall system is much bigger than the Phase-1 device (~3 m$^3$ compared to 1.75 m$^3$) with nearly twice as much channel density (~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.

**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.

Flaking the sensors little by little as possible to the primary proton–proton interactions requires the whole VELO system to sit inside the LHC vacuum pipes (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 $10^{28}$ protons, the original VELOs are now being replaced with a new, one to prepare for a factor five increase in luminosity over HL–LHC.

The entirety of the new VELO will be read out at a rate of 40 MHz, requiring a huge data bandwidth, up to 20 GHz (5.7 times the highest, A3C, and 3 TB/s in total. Cooling using the minimum of material is another major challenge. The upgraded VELO will be kept at ~20°C in the radiation environment of evaporative CO$_2$ circulating in 120 + 200 mm channels within a silicon substrate (see “Fine structure (right)”, which is now in the final stages of R&D and moving into production. After that, the collaboration is actively investigating all options, with detailed technical design reports expected towards the middle of the decade.

**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, 30 sensors at large angles and CO$_2$ cooling, and the pixel tracker will continue to serve ATLAS throughout LHC Run 3. Like CMS, the device will have a total of 5.1 Gpixels – 55 times more than the current one.

The collaboration has long been working towards the replacement of the full inner tracker during the next long shutdown expected in 2023–2024 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 to times larger than that of the current device. With 33 μm of active silicon across five barrel layers and two end caps, the pixel detector contributes 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$_2$. The ATLAS ITk pixel detector is shown undergoing 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, is now under way, with installation in LHCb scheduled to start in August. The VELO upgrade 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 vetoeing will pose a significant challenge. Proposals under consideration include a new “14×” pixel detector with time–stamp information per hit, which could conceivably be achieved by moving to a smaller CMOS node. As this stage, how the collaboration is actively investigating all options, with detailed technical design reports expected towards the middle of the decade.
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.
FEATURE PIXEL DETECTORS

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. When 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 part in particle tracking, with nuclear emulsions, cloud chambers and bubble chambers. The silicon chip, first unveiled to the world in 1964, 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 “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). William 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 appropriately address the pixel array that defines the pixel’s 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 circuit and a voltage signal is sequentially read out from each by an on-chip switching or “scanning” circuit. Both architectures followed rapid development paths, and within a couple of decades had completely displaced photographic films in cameras.

For NIM, silicon vertex detectors, CC’s, had the initial lead, which passed to MAPS by about 1995. For scientific imaging, CCs are preferred for most astronomical applications (most recently the 3.2 gigapixel optical camera for the Vera Rubin Observatory), while MAPS are the preferred option for fast imaging such as super-resolution microscopy, cryoelectrophoresis microscopy and pioneering studies of two-dimensional phototransistors at 2 K. MAPS are also superior to CMOS imagers with very small, low-capacitance pixels achieving sufficiently low noise to detect single electrons. A third member of the family is the hybrid pixel detector (HPD), a hybrid with a CMOS imager on which is MAPS-like in that the signals are read out by scanning circuitry, but in which the changes are generated in a separate passivolume of the pixel and then 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 whom it is humbly apologise. Space constraints have also led to a focus on the detector themselves, while ignoring the exciting work in ROC development, cooling systems, mechanical supports, not to mention the advanced software for device simulation, the simulation of physics performance, and so forth.

CDM design inspiration

The early developments in CCD detectors were disregarded by the particle-detection community. This is because gaseous drift chambers, with a precision of around ±0.1 mm, were thought to be adequate for all tracking applications. However, the 1974 predictions of an American physicist, the man that particles containing charm quarks “might have lifetimes measurable in emissions”, 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 microstrip tubes became fibre-pitched; etc. The ACCEMOR Collaboration (Amsterdam, CERN, Cracow, Munich, Oxford, RAL) built a powerful multi-particle spectrometer, operating at CERN’s Super Proton Synchrotron, to search for the recently-discovered charm particles, and make the first measurements of their lifetimes. We in the RAL group picked the idea of CCDs for MAPS technology, as proposed by the University of Cambridge, who were beginning to see deeper miniaturisation. (Image credits: RAL; PSI)

Unlike in a CCD, signal charges never get lost and can be accumulated, enabling a low-mass tracker, even potentially bent into cylinders round the beam pipe. The CCD (where is the image area, R) the readout register, the transfer gate, CT, the collection diode, and I, O, the source, drain and gate of the sensor transistor) is pipelined in the 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 transistor, this is sensed, and transmitted off-chip as an analog signal. In a MAPS chip, pipelination is implemented by orthogonal channel stops and signal charges are sensed in- pixel by a tiny front-end transistor. With a depth of about 1 µm below the surface, each pixel contains complex CMOS electronics. The simplest readout is “rolling shutter”, in which parallel 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 chip is generated in a separate silicon layer that is connected, pixel by pixel, to a readout integrated circuit. Bump-bonding interconnections technology is used to keep up with pixel miniaturisation. (Image credits: RAL, PSI)

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

Illustrations of a CCD (left), MAPS (middle) and hybrid chip (right). The first two typically contain silicon pixels, up to 4.4 × 4.0 beyond “stitching”, with an active layer thickness of depleted (of about 10 µm) and a highly doped bulk layer back-thinned to around 10 µm, enabling a low-mass tracker, even potentially bent into cylinders round the beam pipe. The MAPS pipelined (left), pixel by pixel on a front-end transistor. With a depth of about 1 µm below the surface, each pixel contains complex CMOS electronics. The simplest readout is “rolling shutter”, in which parallel 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 chip is generated in a separate silicon layer that is connected, pixel by pixel, to a readout integrated circuit. Bump-bonding interconnections technology is used to keep up with pixel miniaturisation. (Image credits: RAL, PSI)
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 vertexers, 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 Parler 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 inreadable 8 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 \( \mu \text{m} \). Assembling these dedicated 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 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 expensive and complicated milestone 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.

### 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 on 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 expensive and complicated milestone 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,
**FEATURE PIXEL DETECTORS**

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 2009 by Ivan Perić of RIT, in which the collection electrode is expanded to cover most of the pixel area, below the level of the CMOS electronics, so that 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 ATLAS 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 smaller sensor capacitance. Both approaches have strong backing from talented design groups, but the eventual outcome is unclear.

**Advanced MAPS**

While no devices were proposed for detectors at the International Linear Collider (ILC) in 2008 Konstantin Stefanovic of the Open University suggested that MAPS-chips could provide an overall tracking system of about 30 x 30 cm² with performance far beyond the baseline options at the time, which were silicon microstrip and a gaseous time-projection chamber. This development was shelved due to the delay of the ILC, but the dream of integrating MAPS into a real detector has become a reality in the future in the MAPS-based tracking system for the ALICE detector at the LHC, which builds on the impressive ALPIDE chip development by Walter Snoeck and his collaborators. The ALICE ITS-2 system, with 12.5 Gpixels, sets the record for pixel detectors with three layers: a sensor tier (300 μm thick, for efficient X-ray processing) and a digital signal-processing tier (each 15 μm thick). Functional sketch (not to scale) of a Fermilab/BNL stacked sensor tier detector.

**Stacking for physics**

_Figure 1: Conceptual drawing of a multi-tiered pixel detector with three layers, a sensor tier (300 μm thick, for efficient X-ray rejection), an analogue tier and a digital signal-processing tier (each 15 μm thick)._
FEATURE: PIXEL DETECTORS

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 × 10 cm² 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 5.5 million wafers per annum, offers these capabilities at their 32 and 14 nm nodes.

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 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, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina, one of its many pinnacles in the eye of an eagle, with its amazing “stacked” data processing behind the retina. Today, the high-quality vertex detector, and the thin planar sensor-layer systems, and moving into the third dimension to create the most advanced pixels, which are obligatory for some exciting physics goals.

Further reading

H M Brey 2012 Radiation Resistors and Interconnects for High-Performance Integrated Circuits (The Institution of Engineering and Technology).

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**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.

In the early 1990s, 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 topography.

Modern climate models were developed in the 1970s, 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, gauging 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.

**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.

**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. The briefing highlights the European Union’s “Destination Earth” project, which is part of its Green Deal programme – a €1 trillion 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.
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Shining light Licia Verde is ICREA professor at the Instituto de Ciencias del Cosmos, University of Barcelona.

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 we can 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.

This explains your current interest in the Hubble tension. 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, something is wrong. The Hubble tension is certainly one of the most intriguing problems in cosmology.

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 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 is 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 A, 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 ACDM 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 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 to describe the shape of the expansion history of the universe, which is close to ACDM. Or we could modify it locally. We’ve tested GR at the solar-system scale, and the accuracy of GPS is a wonderful 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 ACDM. There is some wiggle room here, but the change A within the error bars is not enough to fix the mismatch. Basically, there is such a good agreement between the ACDM 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 methods, with different missions, with the error bars showing the 68% confidence-level values from SH0ES and Planck, respectively. Source: arXiv:2103.01183 (accepted by CQG).

What about possible sources of experimental errors? 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 the cosmological constant value is 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 70 km s\(^{-1}\) Mpc\(^{-1}\). It’s a beautiful measurement, as the velocity of the GW source comes from the optical counterpart and its redshift. The detection of the GW190521 event enabled researchers to estimate the Hubble constant to be 70±5 m 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.

**How can results from particle physics help?**

If we are lucky gravitational waves with optical counterparts will bring in another important piece of the puzzle. Branch technique, with more results to come, observations of multiple images from strong gravitational lensing is another promising avenue that is actively pursued, and if we are lucky, gravitational waves with optical counterparts will bring in another important piece of the puzzle. Branch technique, with more results to come, observations of multiple images from strong gravitational lensing is another promising avenue that is actively pursued, and if we are lucky, gravitational waves with optical counterparts will bring in another important piece of the puzzle.
A relational take on quantum mechanics

Norbert Wermes (University of Bonn), Hermann Kolanoski (Helmholtz–Bosch, noted experimental 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 (Helmholtz 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–physicist books covering slightly different aspects of detector technology. Techniques for thick detectors and Particle Physics Experiments by W. R. Lee and Detectors for Particle Radiation Detection and Applications combines in a single volume the syllabus also found in two well-known textbooks covering slightly different aspects of detection. The book begins with a 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 instructive, physics background. Relational quantum mechanics claims to be compatible with several of Bohr’s ideas. In some ways it goes back in the original ideas of Heisenberg 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.

Heisenberg’s vacation

A bird’s-eye view of Helgoland from around the turn of the previous century.

Heisenberg 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 uninformed. There is certainly a high level of understanding of quantum mechanics. The point, however, 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 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 discussion 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 very good, 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.

Relational quantum mechanics was introduced by Rovelli in an original technical article in 1996 (Int. J. Theor. Phys. 35 595). 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 previous knowledge.

Particle Detectors – Fundamentals and Applications

By Hermann Kolanoski and Norbert Wermes

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 (Helmholtz 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–physicist physics textbooks and will probably attract a slightly more advanced population of physics students and researchers. This new textbook promises to become a particle–physicist analogue of the legendary experimental-nuclear-physics textbook Radiation Detection and Measurement by Glenn Knoll.

By Carlo Rovelli

Allen Lane

Carlo Rovelli’s ‘What is Real?’ (2019) and Adam Becker’s ‘What Is It?’ (2018). 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 It?’ (2018).

Nikolas Rompotis University of Liverpool
A reference for lectures on experimental methods in particle and nuclear physics

Le Neutrino de Majorana
By Nils Barrellon
Jigal Editions
Naples, 1998. 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.

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

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 physicist, be they a master’s student, PhD student or accomplished researcher looking for detector details outside of their expertise.

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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.

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 panelist, Zofia Rudjor, used to work on the ATLAS trigger system and the measurement of the Higgs–boson decay 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 panelist 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 Riffcharge, a company that helps electric car drivers reduce the cost of charging and use cleaner energy sources. Before taking the plunge into the environmental industry, Cook explained, notting the different men “lingo” in the finance world. A stint at Octo Business School on climate-change management and finance, which helped him “learn the lingo” in the finance world, was a key step.

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 difference in mentality from academia. “At CERN you have the luxury to really focus on your research, down to the tiny details – now, (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.”

I would say CERN is the ‘Champions League’ of technology!

From CERN to the environment

Marie’s mission: Panelist Marie Michan’s (left) company, Daphne Technology, aims to minimise air pollution for the maritime industry.
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: Tsuboyuki Sjöstrand (below) (Lund University) and Bryan Webber (below) (University of Cambridge) have won the 2021 EPS-HEPP Prize for the concept, 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 Cenciotti Prize has been awarded to the Borexino Collaboration for its observation of solar neutrinos from the pp chain and CN cycle, while the 2021 Gribbin Medal goes to Berndt Minibeger (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 seminal contributions to the study of QCD mixing in the B- and D-meson measurements of CP violation and discovery of pentaquarks, and the LHCb experiment, including the outstanding contributions to 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 Thuren Qaist (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 May, experimental astroparticle physicist Ignasi Taboada of the Georgia Institute of Technology began his two-year term as spokesperson of the IceCube collaboration, replacing Darren Grant who served as spokesperson for the South Pole neutrino observatory since 2017.

Taboada, currently leads a research 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 Haoyuan 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 nucleus, 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 held the position on an interim basis after Berndt Müller’s departure last year.

**Olga Igonkina fellowship**
LEIRI 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 ‘Olja’ Igonkina, who passed away in 2019 at the age of 45, will enable Danilina to participate in the Rencontres de Bâle conference in October, where she will present calculations of the decay of B-mesons to four leptons.
The future is in laser technologies

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

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A brilliant nuclear theorist

Vladimir Kukulin 1939–2020

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 1999 and head of the laboratory for atomic nucleus theory in 2002. 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 Turin.

Vladimir’s research interests embraced theoretical hadronic, nuclear and atomic physics, few-body physics, nuclear astrophysics, quantum scattering theory, mathematical and –
Leaving a legacy in superconducting cavities

Experimental physicist Herbert Lengeler, who made great contributions to the understanding 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 Switzerland. 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 1959 on the construction of a propane bubble chamber, going on to perform experiments with this instrument on electron–positron collisions at PETRA in Hamburg. Following this, in 1987, he was appointed a team member in the track chamber and accelerator research divisions. He was involved in the construction, testing, and commissioning of RF particle separators for bubble chambers. In 1976, he then joined a collaboration between CERN, SPS, and HEP in Serpukhov, in the Soviet Union, within which he led the construction of an RF particle separator for both SPS and JINR. The team included a young American, Matthias Bachmann, who replaced Herbert’s daughter on the team of CERN experimenters.

In 1983, Herbert started the SRF upgrade programme at CERN, among other key projects.

In 1993, the value of SRF cavities for improved continuous-wave particle beams was recognised. This necessitated the use of SRF cavities with strong fields and high powers to overcome the limitations of low-frequency superconducting technology in Germany, Herbert joined in

Herbert Lengeler led the SRF upgrade at CERN, among other key projects.

the research centre on behalf of CERN. In the following pioneering period up to 1999, he led the development of SRF cavities at CERN, which were initiated in 1980. A first SRF cavity with its auxiliaries (RF couplers, frequency tuner, cryostat) was installed and successfully operated in the PETRA collider at DESY in Hamburg. Following this, in 1987, an SRF cavity with all auxiliaries and a new high-fieldrf (HFRF) cavity was installed and tested at CERN’s SPS. In parallel, Herbert continued to work on SRF cavities as a cheaper alternative to bulk niobium. Gradually, additional SRF cavities were implemented in the LEP collider, resulting in a doubling of its beam energy by the end of its commissioning period.

From 1989 onwards, Herbert gradually retired from the LEPS 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 neutrino 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 work at the intermediate energy facilities, sharing his work at SPS, and HEP in Serpukhov, in the Soviet Union, within which he led the construction of an RF particle separator for both SPS and JINR. The team included a young American, Matthias Bachmann, who replaced Herbert’s daughter on the team of CERN experimenters.

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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.

Daniel Bertrand
and
Laurent Favart
Université libre de Bruxelles.
BACKGROUND

Notes and observations from the high-energy physics community

From hadron therapy to medical imaging, techniques from particle physics have had a major impact on biological applications. An Australia-based team now propose to turn the favour, reporting the first proof-of-concept simulations of detectors based on biomaterials.

“The DNA detector,” writes Claran 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-seeded 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 (5 25 degree axial resolution for low-energy 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 medical medicine that we should all be excited about!”

Thomas Cocolios of EU Leuven speaking to Medical News Today (18 May) about CERN–MEDICIS

“Alexa, play music of the inﬁnity, please…”

Le Monde journalist David Larousserie waxed lyrical on L’infinitum petit…”

“Adieu, planète Neptune de l’inﬁniment petit…”

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

“If you touch a resonating wire, you can convine yourself you’re feeling the universe coming into being.”

Aidan, playwright of 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.”

Til Swenend particle physicist Dominik Stöckinger quoted in German news site MDR (10 May).

“11,000 km”

When LEPI 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 CERN Courier’s issue dedicated a special feature to the interest among particle physicists in applying microelectronics to reject unwanted data. Back then, triggering was largely restricted to hardware. 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.

“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

Margareta Ribner’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 p70) emerged from several individuals at different institutes.

From the archive: July/August 1981

Dreaming large and small

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 LEPI,” 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 Bøggild 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 logical units capable of carrying out increasingly complex operations at higher speed and at lower cost. While the frontiers 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. 

Editor’s note

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(*) CONET - CAEN Optical Network - proprietary protocol for the optical link