WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September/October 2024 issue of *CERN Courier*.

The four accelerators spliced together in our cover image span all seven decades of CERN's history. They also tell much of the experimental story of the electroweak sector of the Standard Model of particle physics. The Proton Synchrotron generated the neutrino beam used to discover neutral currents. The W and Z bosons were discovered with the Super Proton Synchrotron. The Large Electron–Positron collider (LEP) constrained the model. And the Higgs boson was discovered at the Large Hadron Collider, which – quite remarkably – now rivals LEP in electroweak precision (p29). What comes next?

With the third update to the European strategy for particle physics underway, the debate now starts in earnest, and you are invited to contribute (p7). Early-career researchers have a vital role to play. The heart of this edition is devoted to 13 of their viewpoints on the future of high-energy physics (p46).

Also in this edition: experts from across CERN look back to the future (p53); an interview with the president of the CERN Council (p63); technology transfer from the LHC to medicine and industry (p37); new physics could be hiding in the Higgs self-coupling (p61); lattice QCD suggests there is less new physics in muon g–2 than previously hoped (p21); the German community debates CERN's future (p22); and BASE cuts the time to cool antiprotons from 15 hours to eight minutes (p8).

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EDITOR: MARK RAYNER, CERN
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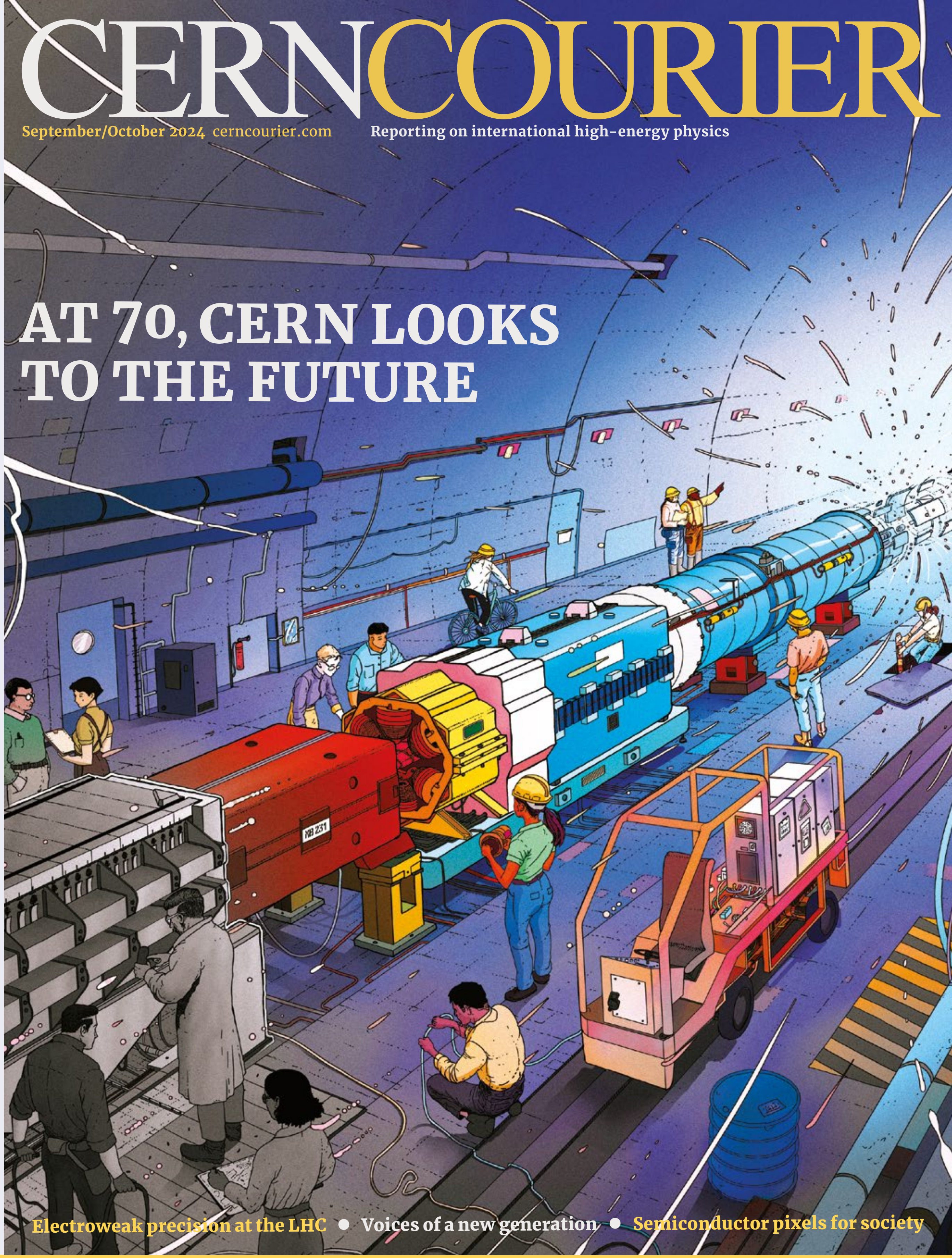

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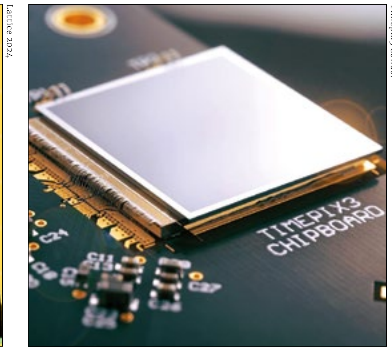

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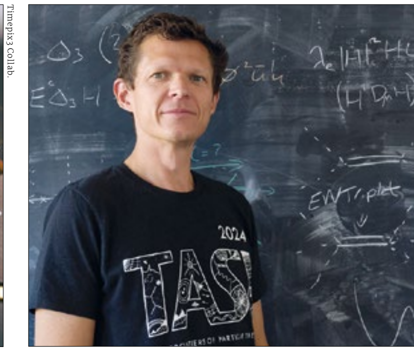

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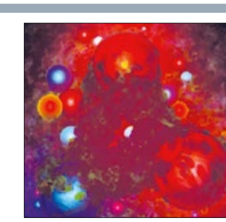

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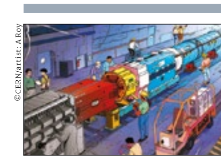

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FROM THE EDITOR

At 70, CERN looks to the future

Mark Rayner
Editor

"The future is extremely brilliant," said CERN's Fabiola Gianotti at a panel discussion for lab directors at ICHEP in Prague this July. "If I was 40 years younger, I would for sure undertake a career in particle physics."

The shape of the future is still in flux. With the third update to the European strategy for particle physics underway, the debate now starts in earnest, and you are invited to contribute (p7). Early-career researchers have a vital role to play. The heart of this edition is devoted to 13 of their viewpoints on the future of high-energy physics (p46).

Gianotti was joined on stage in Prague by Lia Merminga for Fermilab, Shoji Asai for KEK and Yifang Wang for IHEP. Each director championed a different project that could be hosted by their lab, be it the Future Circular Collider (FCC), a muon collider, the International Linear Collider, or the Circular Electron–Positron Collider (CEPC). There were seeds of cooperation. IHEP will not pursue CEPC if the FCC is approved, said Wang, and Asai and Merminga emphasised the international nature of their projects, should they be approved. There was no need for Gianotti to do so: this has been written into CERN's DNA since it was founded 70 years ago, on 29 September 1954.

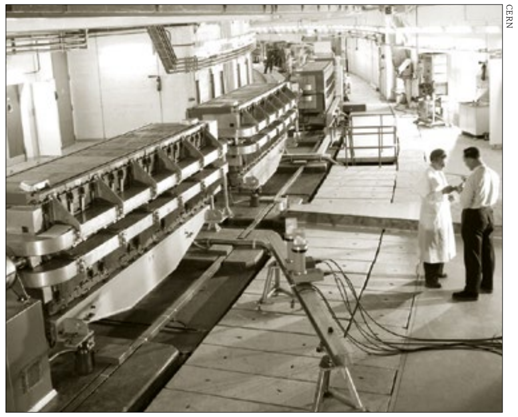
And so, as CERN turns 70, we ask experts from across the lab to reflect on how much has changed since the early years – and how much has stayed the same (p53). We also interview the president of the CERN Council (p63). Council has navigated geopolitical turmoil and economic upheaval in recent years, but it remains a symbol of the unifying power of science. Following Brazil's accession as an associate member state in March, Estonia has now become a full member of the CERN family (p9).

70 years in the electroweak playground

The accelerators spliced together in our cover image span seven decades of CERN's history. From left to right, they also tell much of the experimental story of the electroweak sector of the Standard Model of particle physics. The Proton Synchrotron generated the neutrino beam used to discover neutral currents. The W and Z bosons were discovered with the Super Proton Synchrotron. The Large Electron–Positron collider (LEP) constrained the model as only a lepton collider can. And the Higgs boson was discovered at the Large Hadron Collider (LHC), announcing the arrival of the lead actor to the experimental stage.

But back up a bit. Remarkably, the LHC now rivals LEP in electroweak precision (p29). The wealth of societal benefits generated by the LHC and its high-luminosity upgrade is no less remarkable. The hybrid pixel detector is a fine example, now applied in multiple sectors of medicine and industry (p37).

Also in this edition: new physics could be hiding in the Higgs self-coupling (p61); lattice QCD suggests there is less new physics in muon g–2 than previously hoped (p21); Vladimir Shiltsev reports on IPAC (p19); the German community debates CERN's future (p22); and BASE cuts the time to cool antiprotons from 15 hours to eight minutes (p8).



Nifty Fifties *The Proton Synchrotron serves CERN to this day.*

70 YEARS / ANS CERN

Reporting on international high-energy physics

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

IOP Publishing

Editor Mark Rayner
Editorial contributor Matthew Chalmers
Astrowatch contributor Arshia Ruina
Archive contributor Peggie Rimmer

E-mail cern.courier@cern.ch

Advisory board Gianluigi Arduini, Philippe Bloch, Roger Forty, Peter Jenni, Joachim Kopp, Christine Sutton

Laboratory correspondents
Argonne National Laboratory Tom LeCompte
Brookhaven National Laboratory Achim Franz
Cornell University D G Cassel
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UK STFC Stephanie Hills
SLAC National Accelerator Laboratory Melinda Lee
SNOLAB Samantha Kuula
TRIUMF Laboratory Marcello Pavan

Produced for CERN by IOP Publishing Ltd
No.2 The Distillery, Glassfields, Avon Street
Bristol BS2 0GR
Tel +44 (0)117 929 7481

Head of Media Jo Allen
Head of Media Business Development Ed Jost
Content and production manager Ruth Leopold
Technical illustrator Alison Tovey
Advertising sales Curtis Zimmermann
Recruitment sales Chris Thomas

Advertisement production Katie Graham
Marketing and circulation Gemma Hougham, Alison Gardiner

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

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

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

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

ISSN 0304-288X

European strategy update

A decider for CERN's next collider

The third update of the European strategy for particle physics, launched by the CERN Council on 21 March, is getting into its stride. At its June session, the Council elected former ATLAS spokesperson Karl Jakobs (University of Freiburg) as strategy secretary and established a European Strategy Group (ESG), which is responsible for submitting final recommendations to Council for approval in early 2026. The aim of the strategy update, states the ESG remit, is to develop "a visionary and concrete plan that greatly advances human knowledge in fundamental physics through the realisation of the next flagship project at CERN".

"Given the long timescales involved in building large colliders, it is vital that the community reaches a consensus to enable Council to take a decision on the next collider at CERN in 2027/2028," Jakobs told the *Courier*. To reach that consensus it is important that the whole community is involved, he says, emphasising that, compared to previous strategy updates, there will be more opportunities to provide input at different stages. "There is excellent progress with the LHC and no new indication that would change our physics priorities: understanding the Higgs boson much better and exploring further the energy frontier are key to the next project."

The European strategy for particle physics is the cornerstone of Europe's decision-making process for the long-term future of the field. It was initiated by the CERN Council in 2005, when completing the LHC was listed as the top scientific priority, and has been updated twice. The first strategy update, adopted in 2013, continued to prioritise the LHC and its high-luminosity upgrade, and stated that Europe needed to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next strategy update. The second strategy update, completed in 2020, recommended an electron–positron Higgs factory as the highest priority, and that a technical and financial feasibility study for a next-generation hadron collider should be pursued in parallel.

Building consensus *The timeline for the third update of the European strategy for particle physics, to be submitted for deliberation by the CERN Council in early 2026, is designed to maximise opportunities for community input.*

> **Given the long timescales involved in building large colliders, it is vital that the community reaches a consensus**

Significant progress has been made since then. A feasibility study for the proposed Future Circular Collider (FCC) at CERN presented a mid-term report in March 2024, with a final report expected in spring 2025 (*CERN Courier* March/April 2024 pp25–38). There is also a clearer view of the international landscape. In December 2023 the US "P5" prioritisation process stated that the US would support a Higgs factory in the form of an FCC-ee at CERN or an International Linear Collider (ILC) in Japan, while also exploring the feasibility of a high-energy muon collider at Fermilab (*CERN Courier* January/February 2024 p7). Shortly afterwards, a technical design report for the proposed Circular Electron Positron Collider (CEPC) in China was released (*CERN Courier* March/April 2024 p39). The ILC project has meanwhile established an international technology network in a bid to increase global support.

Alternative scenarios

In addition to identifying the preferred option for the next collider at CERN, the strategy update is expected to prioritise alternative options to be pursued if the chosen preferred plan turns out not to be feasible or competitive. "That we should discuss alternatives to the chosen baseline is important to this strategy update," says Jakobs. "If the FCC were chosen, for example, a linear collider and a muon collider are among the options that would likely be considered. However, in addition to differences in the physics potential we have to understand the technical feasibility and the timelines. Some of these alternatives may also require an extension of the physics exploitation at the HL-LHC."

The third strategy update will also indicate physics areas of priority for exploration complementary to colliders and add other relevant items, including accelerator, detector and computing R&D, theory developments, actions to minimise environmental impact and improve the sustainability of accelerator-based particle physics, initiatives ▷

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to attract, train and retain early-career researchers, and public engagement.

The particle-physics community is invited to submit written inputs by 31 March 2025 via an online portal that will appear on the strategy secretariat's web page. This will be followed by a scientific open symposium from 23 to 27 June 2025, where researchers will be invited to debate the future orientation of European particle physics. A "briefing book" based on the input and discussions will then be prepared by the physics preparatory group, the makeup of which was to be established by the Council in September before the *Courier* went to press. The briefing book will be submitted to the ESG by the end of September 2025 for consideration during a five-day-long drafting session, which is scheduled to take place from 1 to 5 December 2025. To allow the national communities to react to the submissions collected by March 2025 and to the content of the briefing book, they are offered further opportunities for input both ahead of the open symposium (with a deadline of 26 May 2025) and ahead of the drafting session (with a deadline of 14 November 2025). The ESG is expected to submit the proposed strategy update to the CERN Council by the end of January 2026.

"The timing is well chosen because at the end of 2025 we will have a lot of the relevant information, namely the final outcome of the FCC feasibility study plus, on the international scale, an update about what is going to happen in China," says Jakobs. "The national inputs, whereby national communities are also invited to discuss their priorities, are considered very important and ECFA has produced guidelines to make the input more coherent. Early-career researchers are encouraged to contribute to all submissions, and we have restructured the physics preparatory group such that each working group has a scientific secretary who is an early-career researcher. We look forward to a very fruitful process over the forthcoming one and a half years."

The national inputs, whereby national communities are invited to discuss their priorities, are considered very important

Further reading

europeanstrategyupdate.web.cern.ch.

ANTIMATTER

Antiprotons cooled in record time

To test the most fundamental symmetry of the Standard Model, CPT symmetry, which implies exact equality between the fundamental properties of particles and their antimatter conjugates, antimatter particles must be cooled to the lowest possible temperatures. The BASE experiment, located at CERN, has passed a major milestone in this regard. Using a sophisticated system of Penning traps, the collaboration has reduced the time required to cool an antiproton by a factor of more than 100. The considerable improvement makes it possible to measure the antiproton's properties with unparalleled precision, perhaps shedding light on the mystery of why matter outnumbers antimatter in the universe.

CERN-PHOTO-202407-168-7

Flash frozen *BASE physicist Barbara Latacz in front of the experiment's cryostat, which houses the system of traps used to cool and measure single antiprotons.*

Magnetic moments

BASE (Baryon Antibaryon Symmetry Experiment) specialises in the study of antiprotons by measuring properties such as the magnetic moment and charge-to-mass ratio. The latter quantity has been shown to agree with that of the proton within an experimental uncertainty of 16 parts per trillion. While not nearly as precise due to much higher complexity, measurements of the antiproton's magnetic moment provide an equally important probe of CPT symmetry.

To determine the antiproton's magnetic moment, BASE measures the frequency of spin flips of single antiprotons – a remarkable feat that requires the particle to be cooled to less than 200 mK. BASE's previous setup could achieve this, but only after 15 hours of cooling, explains lead author Barbara Latacz (RIKEN/CERN): "As we need to perform 1000 measurement cycles, it would have taken us three years of non-stop measurements, which would have been unrealistic. By reducing the cooling time to eight minutes, BASE can now obtain all of the 1000 measurements it needs – and thereby improve its precision – in less than a month." By cooling antiprotons to such low energies, the collaboration has been able to detect antiproton spin transitions with an error rate (< 0.000023) more than three orders of magnitude better than in previous experiments.

Underpinning the BASE breakthrough is an improved cooling trap. BASE takes antiprotons that have been decelerated by the Antiproton Decelerator and the Extra Low Energy Antiproton ring (ELENA) and stores them in batches of around 100 in a Penning trap, which holds them in place using electric and magnetic fields. A single antiproton is then extracted into a system made up of two Penning traps: the first trap measures its temperature and, if it is too high, transfers the antiproton to a second trap to be cooled further. The particle goes back and forth between the two traps until the desired temperature is reached.

The new cooling trap has a diameter of just 3.8 mm, less than half the size of that used in previous experiments, and is equipped with innovative segmented electrodes to reduce the amplitude of one of the antiproton oscillations – the cyclotron mode – more effectively. The readout electronics have also been optimised to reduce background noise. The new system reduces the time spent by the antiproton in the cooling trap during each cycle from 10 minutes to 5 seconds, while improvements to the measurement trap have also made it possible to reduce the measurement time fourfold.

"Up to now, we have been able to compare the magnetic moments of the antiproton and the proton with a precision of one part per billion," says BASE spokesperson Stefan Ulmer (Max Planck–RIKEN–PTB). "Our new device will allow us to reach a precision of a tenth of a billion and, on the very long-term, will even allow us to perform experiments with 10 parts-per-trillion resolution. The slightest discrepancy could help solve the mystery of the imbalance between matter and antimatter in the universe."

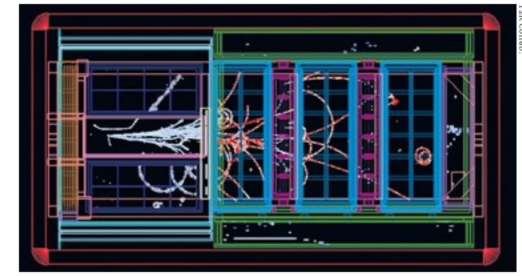
Further reading

BASE Collab. 2024 *Phys. Rev. Lett.* **133** 053201.

NEUTRINOS

Near-detector upgrade in place at T2K

Neutrino physics requires baselines both big and small, and neutrinos both artificial and astrophysical. One of the most prominent experiments of the past two decades is Tokai-to-Kamioka (T2K), which observes electron-neutrino appearance in an accelerator-produced muon-neutrino "superbeam" travelling coast to coast across Japan. To squeeze systematics in their hunt for leptonic CP violation, the collaboration recently brought online an upgraded near detector.



T2K Collab.

New and improved *One of the first neutrino interactions recorded in T2K's upgraded near detector ND280.*

"The upgraded detectors are precision detectors for a precision-physics era," says international co-spokesperson Kendall Mahn (Michigan State). "Our current systematic constraint is at the level of a few percent. To make progress we need to be able to probe regions we've not probed before."

T2K studies the oscillations of 600 MeV neutrinos that have travelled 295 km from the J-PARC accelerator complex in Tokai to Super-Kamiokande – a 50 kton gadolinium-doped water-Cherenkov detector in Kamioka that has also been used to perform seminal measurements of atmospheric neutrino oscillations and constrain proton decay. Since the start of data taking in 2010, the collaboration made the first observation of the appearance of a neutrino flavour due to quantum-mechanical oscillations and the most precise measurement of the θ_{23} parameter in the neutrino mixing matrix. As well as placing limits on sterile-neutrino oscillation parameters, the collaboration has constrained a wide range of the parameters that describe neutrino interactions with matter. The uncertainties of such measurements typically limit the precision of fits to the fundamental parameters of the three-neutrino paradigm, and constraining neutrino-interaction systematics is the main purpose of near detectors in superbeam experiments such as T2K and NOvA, and the future ones Hyper-Kamiokande and DUNE.

T2K's near-detector upgrade improves the acceptance and precision of particle reconstruction for neutrino interactions. A new fine-grained "SuperFGD" detector (pink rectangle, left) serves as the target for neutrino interactions in the new experimental phase. Comprised of two million 1 cm^3 cubes of scintillator strung with optical fibres, SuperFGD lowers the detection threshold for protons ejected from nuclei to 300 MeV/c, improving the reconstruction of neutrino energy. Two new time-projection chambers flank it above and below to more closely mimic the isotropic reconstruction of Super-Kamiokande. Finally, six new scintillator planes suppress particle backgrounds from outside the detector by measuring time of flight.

Following construction and testing at CERN's neutrino platform, the new detectors were successfully integrated in the experiment's global DAQ and slow-control system. The first neutrino-beam data with the fully upgraded detector was collected in June, with the collaboration also benefitting from an upgraded neutrino beam with 50% greater intensity. Beam intensity is set to increase further in the coming years, in preparation for commissioning the new 260 kton Hyper-Kamiokande water Cherenkov detector. Cavern excavation is underway in Kamioka, with first data-taking planned for 2027.

But much can already be accomplished in the new phase of the T2K experiment, says the team. As well as improving precision on θ_{23} and another key mixing parameter Δm^2_{23}, and refining the theoretical models used in neutrino generators, T2K will improve its fit to δ_{CP}, the fundamental parameter describing CP violation in the leptonic sector. Measuring its value could shed light on the question of why the universe is dominated by matter.

"T2K's current best fit to δ_{CP} is –1.97," says Mahn. "We expect to be able to observe leptonic CP violation at 3σ significance if the true value of δ_{CP} is $-\pi/2$."

CERN

Estonia becomes 24th Member State

On 30 August CERN welcomed Estonia as its 24th Member State, marking the end of a formal application process that started in 2018 and crowning a period of cooperation that stretches back three decades.

CERN

Pole position *Estonia and CERN have been collaborating for the past three decades.*

"Estonia is delighted to join CERN as a full member because CERN accelerates more than tiny particles, it also accelerates international scientific collaboration and our economies," said Estonia president Alar Karis. "We have seen this potential during our time as Associate Member State and are keen to begin our full contribution."

The bilateral relationship formally began in 1996, when Estonia and CERN signed a first cooperation agreement. Estonia has been part of the CMS collaboration since 1997, participating in data analysis and the Worldwide LHC Computing Grid, for which Estonia operates a Tier 2 centre in Tallinn. Researchers from Estonia also contribute to other experiments including CLOUD, COMPASS, NA66 and TOTEM, and to studies for future colliders, while Estonian theorists are highly involved in collaborations with CERN.

"Estonia and CERN have been collaborating closely for some 30 years, and I am very pleased to welcome Estonia to the ever-growing group of CERN Member States," said Director-General Fabiola Gianotti. "I am sure the country and its scientific community will benefit from increased opportunities in fundamental research, technology development, and education and training."

Estonia has held Associate Member State status in the pre-stage to membership of CERN since February 2021. As a full Member State, Estonia will now have voting rights in the CERN Council, enhanced opportunities for Estonian nationals to be recruited by CERN and for Estonian industry to bid for CERN contracts.

"On behalf of the CERN Council, I warmly welcome Estonia as the newest Member State of CERN," said Council president Eliezer Rabinovici. "I am happy to see the community of CERN Member States enlarging, and I am looking forward to the enhanced participation of Estonia in the CERN Council and to its additional scientific contributions to CERN."

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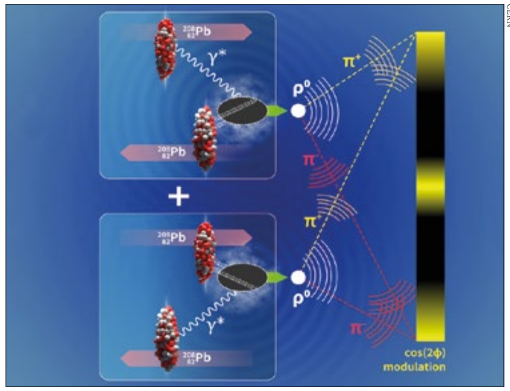
HEAVY-ION PHYSICS

ALICE does the double slit

In the famous double-slit experiment, an interference pattern consisting of dark and bright bands emerges when a beam of light hits two narrow slits. The same effect has also been seen with particles such as electrons and protons, demonstrating the wave nature of propagating particles in quantum mechanics. Typically, experiments of this type produce interference patterns at the nanometre scale. In a recent study, the ALICE collaboration measured a similar interference pattern at the femtometre scale using ultra-peripheral collisions between lead nuclei at the LHC.

In ultra-peripheral collisions, two nuclei pass close to each other without colliding. With their impact parameter larger than the sum of their radii, one nucleus emits a photon that transforms into a virtual quark–antiquark pair. This pair interacts strongly with the other nucleus, resulting in the emission of a vector meson and the exchange of two gluons. Such vector-meson photoproduction is a well-established tool for probing the internal structure of colliding nuclei.

In vector-meson photoproduction involving symmetric systems, such as two lead nuclei, it is not possible to determine which of the nuclei emitted the photon and which emitted the two gluons. Crucially, however, due to the short range of the strong force between the virtual quark–antiquark pair and the nucleus, the vector mesons must have been produced within or close to one of the two well-separated nuclei. Because of this and their relatively short lifetime, the vector mesons decay quite rapidly into other particles. These decay products form a quantum-mechanically entangled state and generate an interference pattern akin to that of a double-slit interferometer.



Lead–ion slits *The photoproduction of ρ^0 mesons in the proximity of one of two colliding lead ions – which cannot be known – generates an interference pattern akin to that of a double-slit interferometer.*

In the photoproduction of the electrically neutral ρ^0 vector meson, the interference pattern takes the form of a $\cos(2\phi)$ modulation of the ρ^0 yield, where ϕ is the angle between the two vectors formed by the sum and difference of the transverse momenta of the two oppositely charged pions into which the ρ^0 decays. The strength of the modulation is expected to increase as the impact parameter decreases.

Using a dataset of 57,000 ρ^0 mesons produced in lead–lead collisions at an energy of 5.02 TeV per nucleon pair during Run 2 of the LHC, the ALICE team measured the $\cos(2\phi)$ modulation of the ρ^0 yield for different values of the impact parameter. The measurements showed that the strength of the modulation varies strongly with the impact parameter. Theoretical calculations indicate that this behaviour is indeed the result of a quantum interference effect at the femtometre scale.

In the ongoing Run 3 of the LHC and in the next run, Run 4, ALICE is expected to collect more than 15 million ρ^0 mesons from lead–lead collisions. This enhanced dataset will allow a more detailed analysis of the interference effect, further testing the validity of quantum mechanics at femtometre scales.

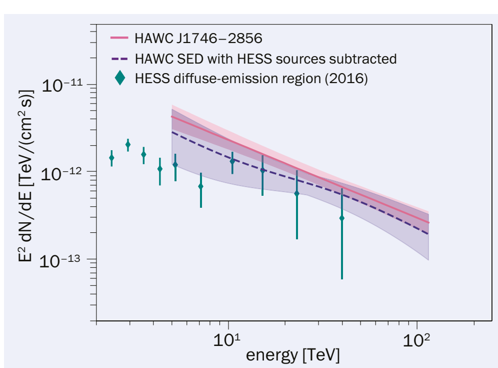
Further reading

ALICE Collab. 2024 arXiv:2405.14525.

ASTROWATCH

A pevatron at the galactic centre

The measured all-particle energy spectrum for cosmic rays (CRs) is famously described by a steeply falling power law. The spectrum is almost featureless from energies of around 30 GeV to 3 PeV, where a break (also known as the "knee") is encountered, after which the spectrum becomes steeper. It is believed that CRs with energies below the knee have galactic origins. This is supported by the observation of diffuse gamma rays from the galactic disk in the GeV range (a predominant mechanism for the production of gamma rays is via the decay of neutral pions created when relativistic protons interact with the ambient gas). The knee could be explained by either the maximum energy that galactic sources can accelerate CR particles to, or the escape of CR particles from the galaxy if they are energetic enough to overcome the confinement of galactic magnetic fields. Both scenarios, however, assume the presence



Below the knee *Best-fit HAWC spectral energy distribution (pink) for HAWC J1746–2856 and (dashed purple) after subtracting the two HESS point-source spectra. The latter, which agrees well with the diffuse gamma-ray emission from the galactic centre measured by HESS in 2016 (green), describes a point source with power-law spectrum extending to energies > 100 TeV, confirming the presence of a galactic pevatron.*

of astrophysical sources within the galaxy that could accelerate CR particles up to PeV energies. For decades, scientists have therefore been on the hunt for such sources, reasonably called "pevatrons".

Recently, researchers at the High-Altitude Water Cherenkov (HAWC) observatory in Mexico reported the observation of ultra-high energy (> 100 TeV) gamma rays from the central region of the galaxy. Using nearly seven years of data, the team found that a point source, HAWC J1746–2856, with a simple power-law spectrum and no signs of a cutoff from 6 to 114 TeV best describes the observed gamma-ray flux. A total of 98 events were observed at energies above 100 TeV.

To analyse the spatial distribution of the observed gamma rays, the researchers plotted a significance map of the galactic centre. On this map, they also plotted the point-like supernova remnant SNR G0.9+0.1 and an unidentified extended source HESS J1745–303, both located 1° away from the galactic centre. While supernova remnants have long been a favoured candidate for galactic pevatrons, HAWC did not observe any excess at either of these source positions. There are, however, two other interesting point sources in this region: Sgr A* (HESS J1745–290), the supermassive black hole in the galactic centre; and HESS J1746–285, an unidentified source that is spatially coincident with the galactic radio arc. Imaging atmospheric Cherenkov telescopes such as HESS, VERITAS and MAGIC have measured the gamma-ray emissions from these sources up to an energy of about 20 TeV, but HAWC has an angular resolution about six times larger at such energies and therefore cannot resolve them.

To eliminate the contamination to the flux from these sources, the authors assumed that their spectra cover the full HAWC energy range and then estimated the event count by convolving the reported best-fit model from HESS with the instrument-response functions of HAWC. The resulting HAWC spectral energy distribution, after subtracting these sources (see figure), seems to be compatible with the diffuse emission data points from HESS while still maintaining a power-law behaviour, with no signs of a cutoff and extending up to at least 114 TeV. This is the first detection of gamma rays at energies > 100 TeV from the galactic centre, thereby providing convincing evidence of the presence of a pevatron.

This is the first detection of gamma rays at energies > 100 TeV from the galactic centre

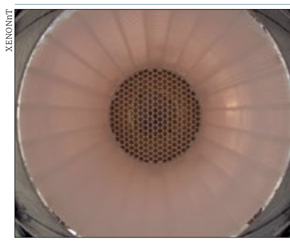
Furthermore, the diffuse emission is spatially correlated with the morphology of the central molecular zone (CMZ) – a region in the innermost 500 pc of the galaxy consisting of enormous molecular clouds corresponding to around 60 million solar masses. Such a correlation supports a hadronic scenario for the origin of cosmic rays, where gamma rays are produced via the interaction of relativistic protons with the ambient gas. In the leptonic scenario, electrons with energies above 100 TeV produce gamma rays via inverse Compton scattering, but such electrons suffer severe radiative losses; for a magnetic field strength of 100 μG, the maximum distance that such electrons can traverse is much smaller than the CMZ. On the other hand, in the hadronic case the escape time for protons is orders of magnitude shorter than the cooling time (via π^0 decay). The stronger magnetic field could confine them for a longer period but, as the authors argue, the escape time is also much smaller than the age of the galaxy, thereby pointing to a young source that is quasi-continuously injecting and accelerating protons into the CMZ.

The study also computes the energy density of cosmic-ray protons with energies above 100 TeV to be 8.1×10^{-3} eV/cm³. This is higher than the 1×10^{-3} eV/cm³ local measurement from the Alpha Magnetic Spectrometer in 2015, indicating the presence of newly accelerated protons in the energy range 0.1–1 PeV. The capabilities of this study did not extend to the identification of the source, but with better modelling of the CMZ in the future, and improved performances of upcoming observatories such as CTAO and SWGO, candidate sites in the galactic centre are expected to be probed with much higher resolution.

Further reading

A Albert *et al.* 2024 arXiv:2407.03682.

NEWS DIGEST



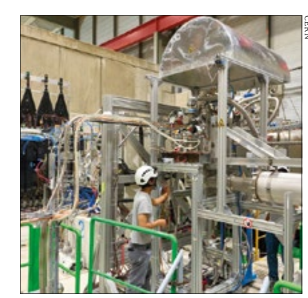
XENONnT photosensors.

XENONnT enters neutrino fog
It has long been predicted that neutrinos from the Sun could be observed in detectors built to search for dark-matter nuclear recoil signals. In this "neutrino fog", neutrino interactions would become a background to dark-matter searches. At the IDM 2024 workshop on 10 July, using data collected between 2021 and 2023, the XENONnT collaboration reported a 2.7σ excess of low-energy nuclear recoil events compatible with solar boron-8 neutrino interactions. The measurement confirms the understanding of the lowest-energy signals. XENONnT is a 5.9 tonne dual-phase liquid-xenon time-projection chamber located deep underground at the Gran Sasso National Laboratory in Italy. Neutrinos from the Sun can interact with the nuclei of the xenon atoms via coherent elastic neutrino–nucleus scattering – a process first observed in 2017 by the COHERENT experiment using higher energy neutrinos from the Spallation Neutron Source in Oak Ridge, Tennessee.

LZ squeezes WIMPs
Meanwhile in South Dakota, the LUX–ZEPLIN (LZ) collaboration has squashed the parameter space available for weakly interacting massive particles (WIMPs) above a mass of 9 GeV, finding no evidence for interactions of the dark-matter candidates in 10 tonnes of liquid xenon a mile underground at the Sanford Underground Research Facility (SURF). Announced at TeVPA 2024 on 26 August, the negative search is based on 280 of 1000 days of data taking planned before 2028. "These are new world-leading constraints by a sizable margin on dark matter and WIMPs," says spokesperson Chamkaur Ghag (University College London). The result is the first time that LZ has applied "salting" – a technique designed to avoid unconscious bias by adding fake signals during data collection.

AMS sees too many deuterons
The AMS collaboration has observed a surprising surplus of deuteron cosmic rays from its detector's pristine vantage point aboard the International Space Station (*Phys. Rev. Lett.* 2024 **132** 261001). Made up of a proton and a neutron, deuterons are thought to be secondary cosmic rays, formed in collisions between primary helium-4 nuclei and the interstellar medium, but AMS reports that their flux behaves like a primary cosmic ray above a rigidity (momentum divided by electrical charge) of 13 GV. "Our unexpected results continue to show how little we know about cosmic rays," says spokesperson Samuel Ting.

AMBER's first results
The AMBER experiment, the next-generation successor of the COMPASS experiment located in



The AMBER experiment.

CERN's North Area, released its first results at ICHEP this July, targeting the production cross section for antiprotons when a beam of protons interacts with a helium target. By modelling the production of these secondary cosmic rays in the interstellar medium, AMBER could shed light on the intriguing antiproton excess reported by AMS in 2016. Recent studies of antiprotons produced in proton–helium collisions by LHCb and of antihelium-3 production by ALICE are further assisting AMS in understanding its cosmic-ray data.

χ_{c1}(3872)'s compact nature
Two decades after its discovery at Belle, the $\chi_{c1}(3872)$ continues to intrigue: is it a compact charmonium or tetraquark state, or a $D^0\overline{D^{*0}} + \overline{D^0}D^{*0}$ molecular state? One way to find out is to compare the rate at which it decays to an excited charmonium state $\psi(2S)$ and a photon to the rate it decays to a J/ψ and a photon. Using the complete LHC Run 1 and Run 2 data sets, LHCb has now found this ratio to be non-vanishing with a significance exceeding 6σ. The result is inconsistent with a pure molecular hypothesis, they say, and strongly indicates a sizeable compact component (arXiv:2406.17006).

Door open to element 120
Researchers at Berkeley Lab have fabricated superheavy element 116 (livermorium) using a beam of titanium-50, an essential precursor in the pursuit of the heaviest element yet (Z = 120). Until now, elements above 114 had only been made with a calcium-48 beam, which has a "magic" configuration of neutrons and protons that helps it fuse with the target nuclei. Synthesising superheavy elements from non-magic titanium is much harder, but during 22 days of operations at the 88-Inch Cyclotron, the Berkeley team made two atoms of element 116 and claim element 120 can be reasonably searched for over the course of several years (arXiv:2407.16079). Element 120 is near the theorised island of stability, where superheavy elements could be long-lived, and would fall on the 8th row of the periodic table.

FAIR installation starts
The first superconducting dipole magnets for the FAIR (Facility for Antiproton and Ion Research)

First magnet for SIS100.

accelerator under construction at GSI Darmstadt were successfully lowered into their 17 m-deep tunnel in July, marking a decisive step forward for the facility. A total of 108 dipole magnets, each weighing around three tonnes, will be needed for the 1.1 km-circumference SIS100 machine, which will allow the acceleration of a wide range of ions for experiments ranging from heavy-ion and astrophysics to cancer research (*CERN Courier* July/August 2017 p41). Construction work for FAIR began in 2017 and the facility is expected to be operational from 2028.

CERN and JINR
An important item on the June CERN Council agenda was CERN's International Cooperation Agreement with the Joint Institute for Nuclear Research (JINR), an intergovernmental organisation located in Dubna, Russia, with which CERN has collaborated since 1957. As the Council decided not to terminate the agreement, the participation of JINR in CERN's activities continues. However, the measures concerning JINR adopted by the Council in March 2022 (*CERN Courier* May/June 2022 p7) remain in place.

ENERGY FRONTIERS

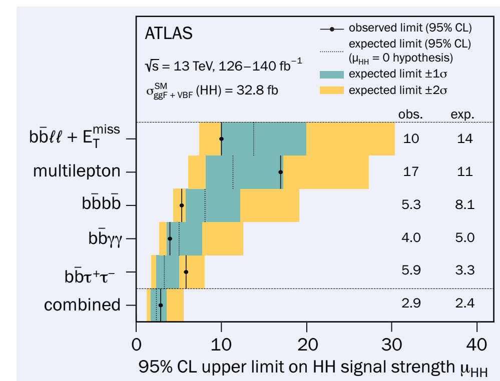
Reports from the Large Hadron Collider experiments

ATLAS

Exploring the Higgs potential at ATLAS

Immediately after the Big Bang, all the particles we know about today were massless and moving at the speed of light. About 10^{-12} seconds later, the scalar Higgs field spontaneously broke the symmetry of the electroweak force, separating it into the electromagnetic and weak forces, and giving mass to fundamental particles. Without this process, the universe as we know it would not exist.

Since its discovery in 2012, measurements of the Higgs boson – the particle associated with the new field – have refined our understanding of its properties, but it remains unknown how closely the field's energy potential resembles the predicted Mexican hat shape. Studying the Higgs potential can provide insights into the dynamics of the early universe, and the stability of the vacuum with respect to potential future changes.



ATLAS Collab. 2024 arXiv:2406.09971

Fig. 1. *95% confidence upper limits on the signal strength for inclusive gluon–gluon and vector–boson fusion HH production from each of the five analyses and their statistical combination.*

The Higgs boson's self-coupling strength λ governs the cubic and quartic terms in the equation describing the potential. It can be probed using the pair production of Higgs bosons (HH), though this is experimentally challenging as this process is more than 1000 times less likely than the production of a single Higgs boson. This is partly due to destructive interference between the two leading order diagrams in the dominant gluon–gluon fusion production mode.

The ATLAS collaboration recently compiled a series of results targeting HH decays to $bb\gamma\gamma$, $bb\tau\tau$, bbbb, $bb\ell\ell$ plus missing transverse energy (E_T^{miss}), and multilepton final states. Each analysis uses the full LHC Run 2 data set. A key parameter is the HH signal strength, μ_{HH}, which divides the measured HH production rate by the Standard Model (SM) prediction. This combination yields the strongest expected constraints to date on μ_{HH}, and an observed upper limit of 2.9 times the SM prediction (figure 1). The combination also sets the most stringent constraints to date on the strength of the Higgs boson's self-coupling of $-1.2 < \kappa_\lambda < 7.2$, where $\kappa_\lambda = \lambda/\lambda_{SM}$, its value relative to the SM prediction.

Each analysis contributes in a complementary way to the global picture of HH interactions and faces its own set of unique challenges.

Despite its tiny branching fraction of just 0.26% of all HH decays, $HH \to bb\gamma\gamma$ provides very good sensitivity to μ_{HH} thanks to the ATLAS detector's excellent di-photon mass resolution. It also sets the best constraints on λ due to its sensitivity to HH events with low invariant mass.

Studying the Higgs potential can provide insights into the dynamics of the early universe

The $HH \to bb\tau\tau$ analysis (7.3% of HH decays) exploits state-of-the-art hadronic-tau identification to control the complex mix of electroweak, multijet and top-quark backgrounds. It yields the strongest limits on μ_{HH} and the second tightest constraints on λ.

$HH \to bbbb$ (34%) has good sensitivity to μ_{HH} thanks to ATLAS's excellent b-jet identification, but controlling the multijet background presents a formidable challenge, which is tackled in a fully data-driven fashion.

The decays $HH \to bbWW$ and $HH \to bb\tau\tau$ in fully leptonic final states have very similar characteristics and are thus targeted in a single $HH \to bb\ell\ell + E_T^{miss}$ analysis. Contributions from the bbZZ decay mode, where one Z decays to charged light leptons and the other to neutrinos, are also considered.

Finally, the $HH \to$ multilepton analysis is designed to catch decay modes where the HH system cannot be fully reconstructed due to ambiguity in how the decay products should be assigned to the two Higgs bosons. The analysis uses nine signal regions with different multiplicities of light charged leptons, hadronic taus and photons. It is complementary to all the exclusive channels discussed above.

For the ongoing LHC Run 3, ATLAS designed new triggers to enhance sensitivity to the hadronic $HH \to bb\tau\tau$ and $HH \to bbbb$ channels. Improved b-jet identification algorithms will increase the efficiency in selecting HH signals and distinguishing them from background processes. With these and other improvements, our prospects have never looked brighter for homing in on the Higgs self-coupling.

Further reading

ATLAS Collab. 2024 arXiv:2406.09971.

CMS

Two charming results of data parking

The high data rate at the LHC creates challenges as well as opportunities. Great care is required to identify interesting events, as only a tiny fraction can trigger the detector's readout. With the LHC achieving record-breaking instantaneous luminosity, the CMS collaboration has innovated to protect and expand its flavour-physics programme, which studies rare decays and subtle differences between particles containing beauty and charm quarks. Enhancements in the CMS data-taking strategy such as "data parking" have enabled the detector to surpass its initial performance limits. This has led to notable advances in charm physics, including CMS's first analysis of CP violation in the charm sector and achieving world-leading sensitivity to the rare decay of the D^0 meson into a pair of muons.

The CMS collaboration has expanded its flavour-physics programme

Data parking stores subsets of unpro- ▷

cessed data that cannot be processed promptly due to computing limitations. By parking events triggered by a single muon, CMS collected an inclusive sample of approximately 10 billion b-hadrons in 2018. This sample allowed CMS to reconstruct D^0 and $\bar{D}^0$ decays into a pair of long-lived K^0_S mesons, which are relatively easy to detect in the CMS detector despite the high level of pileup and the large number of low-momentum tracks.

CP violation is necessary to explain the matter–antimatter asymmetry observed in the universe, but the magnitude of CP violation from known sources is insufficient. Charmed meson decays are the only meson decays involving an up-type quark where CP violation can be studied. CP violation would be evident if the decay rates for $D^0 \to K^0_S K^0_S$ and $\bar{D}^0 \to K^0_S K^0_S$ were found to differ. In the analysis, the flavour of the initial D^0 or $\bar{D}^0$ meson is determined from the charge of the pion accompanying its creation in the decay of a D^{*+} meson (see figure 1). To eliminate systematic effects arising from the charge asymmetry in production and detector response, the CP asymmetry is measured relative to that in $D^0 \to K^0_S \pi^+\pi^-$. The resulting asymmetry is found to be $A_{CP}(K_S K_S) = 6.2\% \pm 3.0\%$ (stat) $\pm$ 0.2% (syst) $\pm$ 0.8% (PDG), consistent with no CP violation within 2.0 standard deviations. Previous analyses by LHCb and Belle were consistent with no CP violation within 2.7 and 1.8 standard deviations, respectively. Before data parking, searching for direct CP violation in the charm sector with a fully hadronic final state was deemed unattainable for CMS.

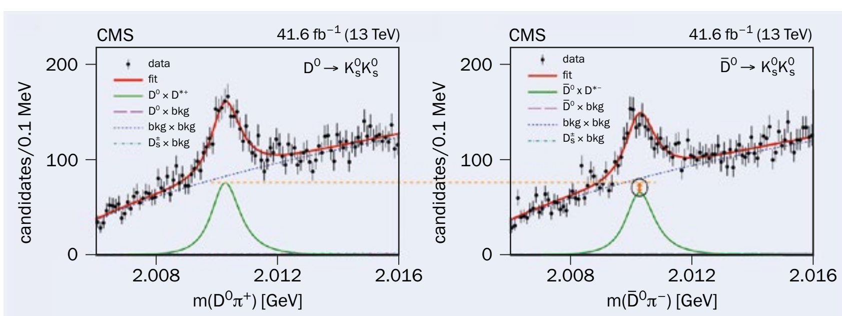


Fig. 1. *Invariant mass distributions of $D^{*+} \to D^0\pi^+$ (left) and $D^{*-} \to \bar{D}^0\pi^-$ (right), where the neutral D meson decays into $K^0_S K^0_S$, with the fit projections overlaid. The difference in signal yields is illustrated by the orange horizontal line.*

For Run 3 the programme was enhanced by introducing an inclusive dimuon trigger covering the low mass range up to 8.5 GeV. With improvements in the CMS Tier-0 prompt reconstruction workflow, Run-3 parking data is now reconstructed without delay using the former Run-2 high-level trigger farm at LHC Point 5 and European Tier-1 resources. In 2024 CMS is collecting data at rates seven times higher than the nominal rates for Run 2, already reaching approximately 70% of the nominal trigger rate for the HL-LHC.

Using the data collected in 2022 and 2023, CMS performed a search for the rare D^0-meson decay into a pair of muons, which was presented at the ICHEP conference in Prague. Rare decays of the charm quark, less explored compared to those of the bottom quark, offer an opportunity to probe new physics effects beyond the direct reach of current colliders, thanks to possible quantum interference by unknown heavy virtual particles. In 2023, the LHCb collaboration set an upper limit for the branching ratio at 3.5×10^{-9} at a 95% confidence using Run-2 data. CMS surpassed the LHCb result, achieving a sensitivity of 2.6×10^{-9} at a 95% confidence. Given that the Standard Model prediction is four orders of magnitude smaller, there is still considerable territory to explore.

Rare decays of the charm quark offer an opportunity to probe new physics effects beyond the direct reach of current colliders

Beginning with the 2024 run, the CMS flavour-physics programme will gain an additional data stream known as data scouting. This stream captures at very high-rate events triggered by new high-purity single muon level-one triggers in a reduced format. This format is suitable for reconstructing decays of heavy hadrons, offering performance comparable to standard data processing.

Further reading

CMS Collab. 2024 arXiv:2403.16134.
CMS Collab. 2024 arXiv:2405.11606.
CMS Collab. 2024 CMS-PAS-BPH-23-008.

ALICE

Strange correlations benchmark hadronisation

In high-energy hadronic and heavy-ion collisions, strange quarks are dominantly produced from gluon fusion. In contrast to u and d quarks, they are not present in the colliding particles. Since strangeness is a conserved quantity in QCD, the net number of strange and anti-strange particles must equal zero, making them prime observable to study the dynamics of these collisions. Various experimental results from high-multiplicity pp collisions at the LHC demonstrate striking similarities to Pb–Pb collision results. Notably, the fraction of hadrons carrying one or more strange quarks smoothly increases as a function of particle multiplicity in pp and p–Pb collisions to values consistent with those measured in peripheral Pb–Pb collisions. Multi-particle correlations in pp collisions also closely resemble those in Pb–Pb collisions.

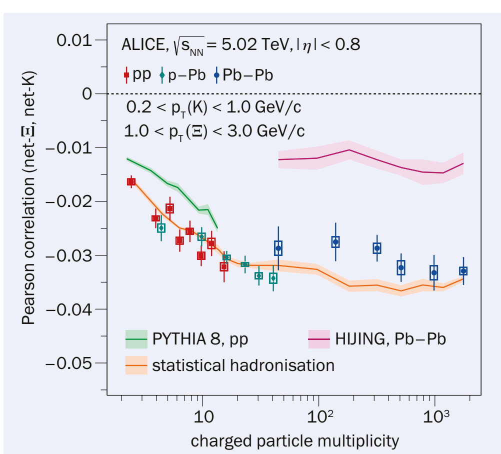


Fig. 1. *Pearson correlation coefficient between the net-Ξ number and net-kaon number, as a function of the charged-particle multiplicity of the collision. Model calculations are shown as coloured bands.*

Explaining such observations requires understanding the hadronisation mechanism, which governs how quarks and gluons rearrange into bound states (hadrons). Since there are no first-principle calculations of the hadronisation process available, phenomenological models are used, based on either the Lund string fragmentation (Pythia 8, HIJING) or a statistical approach assuming a system of hadrons and their resonances (HRG) at thermal and chemical equilibrium. Despite having vastly different ▷ approaches, both models successfully describe the enhanced production of strange hadrons. This similarity calls for new observables to decisively discriminate between these two approaches.

In a recently published study, the ALICE collaboration measured correlations between particles arising from the conservation of quantum numbers to further distinguish the two models. In the string fragmentation model, the quantum numbers are conserved locally through the creation of quark–antiquark pairs from the breaking of colour strings. This leads to a short-range rapidity correlation between strange and anti-strange hadrons. On the other hand, in the statistical hadronisation approach, quantum numbers are conserved globally over a finite volume, leading to long-range correlations between both strange–strange and strange–anti-strange hadron pairs. Quantum-number conservation leads to correlated particle production that is probed by measuring the yields of charged kaons (with one strange quark) and multistrange baryons (Ξ^- and $\bar{\Xi}^+$) on an event-by-event basis. In ALICE, charged kaons are directly tracked in the detectors, while Ξ baryons are reconstructed via their weak decay to a charged pion and a Λ-baryon, which is itself identified via its weak decay into a proton and a charged pion.

Figure 1 shows the first measurement of the correlation between the "net number" of Ξ baryons and kaons, as a function of the charged-particle multiplicity at mid-rapidity in pp, p–Pb and Pb–Pb collisions, where the net number is the difference between particle and antiparticle multiplicities. The experimental results deviate from the uncorrelated baseline (dashed line), and string fragmentation models that mainly correlate strange hadrons with opposite strange quark content over a small rapidity range fail to describe both observables. At the same time, the measurements agree with the statistical hadronisation model description that includes opposite-sign and same-sign strangeness correlations over large rapidity intervals. The data indicate a weaker opposite-sign strangeness correlation than that predicted by string fragmentation, suggesting that the correlation volume for strangeness conservation extends to about three units of rapidity.

The data indicate a weaker opposite-sign strangeness correlation than that predicted by string fragmentation

The present study will be extended using the recently collected data during LHC Run 3. The larger data samples will enable similar measurements for the triply strange Ω baryon, as well as the study of higher cumulants.

Further reading

ALICE Collab. 2024 arXiv.2405.19890.

LHCb

LHCb measures the weak mixing angle

At the International Conference on High-Energy Physics in Prague in July, the LHCb collaboration presented an updated measurement of the weak mixing angle using the data collected at the experiment between 2016 and 2018. The measurement benefits from the unique forward coverage of the LHCb detector.

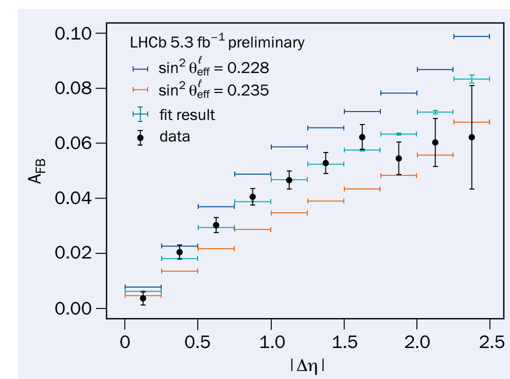


Fig. 1. *The LHCb measurement of the forward–backward asymmetry as a function of the absolute difference between the pseudorapidities of the two muons produced in the Z boson decay, |Δη|.*

The success of electroweak theory in describing a wide range of measurements at different experiments is one of the crowning achievements of the Standard Model (SM) of particle physics. It explains electroweak phenomena using a small number of free parameters, allowing precise measurements of different quantities to be compared to each other. This facilitates powerful indirect searches for beyond-the-SM physics. Discrepancies between measurements might imply that new physics influences one process but not another, and global analyses of high-precision electroweak measurements are sensitive to the presence of new particles at multi-TeV scales. In 2022 the entire field was excited by a measurement of the W-boson mass that is significantly larger than the value predicted within these global analyses by the CDF collaboration, heightening interest in electroweak measurements.

The weak mixing angle is at the centre of electroweak physics. It describes the mixing of the U(1) and SU(2) fields, determines couplings of the Z boson, and can also be directly related to the ratio of the W and Z boson masses. Excitingly, the two most precise measurements to date, from LEP and SLD, are in significant tension. This raises the prospect of non-SM particles potentially influencing one of these measurements, since the weak mixing angle, as a fundamental parameter of nature, should otherwise be the same no matter how it is measured. There is therefore a major programme measuring the weak mixing angle at hadron colliders, with important contributions from CDF, D0, ATLAS, CMS and LHCb.

Since the weak mixing angle controls Z-boson couplings, it can be determined from measurements of the angular distributions of Z-boson decays. The LHCb collaboration measured around 860,000 Z-boson decays to two oppositely charged muons, determining the relative rate at which negatively charged muons are produced closer to the LHC beamline than positively charged muons as a function of the angular separation of the two muons. Corrections are then applied for detector effects. Comparison to theoretical predictions based on different values of the weak mixing angle allows the value best describing the data to be determined (figure 1).

The unique angular coverage of the LHCb detector is well-suited for this measurement for two key reasons. First, the statistical sensitivity to the weak mixing angle is largest in the forward region close to the beamline that the LHCb detector covers. Second, the leading systematic uncertainties in measurements of the weak mixing angle at hadron colliders typically arise from existing knowledge of the proton's internal structure. These uncertainties are also smallest in the forward region.

The value of the weak mixing angle measured by LHCb is consistent with previous measurements and with SM expectations (see "Weak mixing angle" figure, p32). Notably, the precision of the LHCb measurement remains limited by the size of the data sample collected, such that further improvements are expected with the data currently being collected using the upgraded LHCb detector. In addition, while other experiments profile effects associated with the proton's internal structure to reduce uncertainties, the unique forward acceptance means that this is not yet necessary at LHCb. This advantage will also be important for future measurements: the small theoretical uncertainty means that the forthcoming Upgrade 2 of the LHCb experiment is expected to achieve a precision more than a factor of two better than the most precise measurements to date.

FIELD NOTES

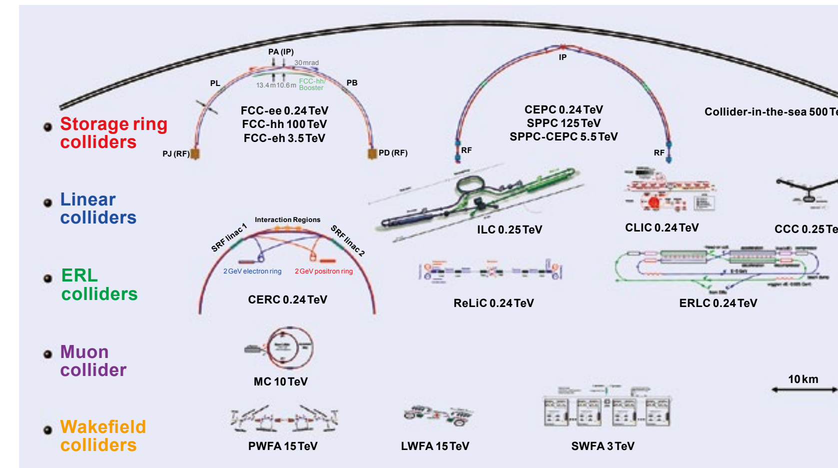
Reports from events, conferences and meetings

IPAC'24

Music city tunes in to accelerators

By some counts, there are more than 300 distinct branches of science, a number that continues to grow. In physics alone, which began with astronomy five millennia ago, there are now at least two dozen subdivisions in most taxonomies. Over the past three decades, the science of beams has evolved into a distinct discipline with its own subjects and methods, dedicated peer-reviewed journals – like *Physical Review Accelerators and Beams*, which turned 25 last year – and nearly two dozen regular regional and international conferences and workshops.

Today, around 5000 accelerator scientists and engineers work in more than 50 countries, collaborating with a pool of technical experts three to four times that size. While most are deeply involved in operations and upgrades, their careers also include designing and constructing new facilities, beam-physics research, developing critical technical components, and project leadership. Their work often involves technology transfer, industrial applications, education and training of future experts, and public and academic outreach.



T Roser

Thinking big *Thomas Roser's slide summarising the future-collider proposals discussed at IPAC'24.*

A global field

The need for regular meetings of the entire field has long been recognised. Historically, regional conferences like the biannual particle-accelerator conferences (PACs) in the US (1965–2009), the biannual EPACs in Europe (1988–2008) and the triannual APACs in Asia (1998–2007) served this purpose. These gatherings covered all types of accelerators, particles and use-cases. As the field became truly global, leaders established the series of international PACs (IPACs), which rotate through the regions in a three-year cycle, convening about 1500 attendees. The 15th IPAC took place from 19 to 24 May in Nashville, Tennessee, with almost 200 registrants from Asia, more than 400 from Europe and nearly 700 from the US.

The "beef" of the conference was in the reports from facilities, but no one person can summarise all the progress, and I must restrict myself to personal highlights in fields that are close to my heart. Fascinating progress was reported on energy-recovery linacs (ERLs) and associated technologies such as superconducting RF and fixed-field-alternating-gradient accelerators, following the recent success of the CBETA accelerator test facility at Cornell. Another hot topic in my eyes was design work and experimental studies towards strong hadron cooling for the Electron-Ion Collider. This year's progress in industrial and medical accelerators is also impressive, with noteworthy presentations on radioisotope production and radiotherapy (Oliver Kester, TRIUMF and Michael Galonska, GSI), light sources for semiconductor manufacturing (Bruce Dunham, SLAC), accelerator-driven fusion (Richard Magee, TAE Technologies), and 96 exhibitions from companies and institutions worldwide.

The "beef" of the conference was in the reports from facilities, but no one person can summarise all the progress

CERN's FCC-ee project was discussed in several sessions. Nuria Catalan-Lasheras (CERN) gave a memorable talk demonstrating impressive progress on high-power klystrons (RF sources). At present, klystrons have about 55% efficiency – RF power divided by wall-plug power – but she noted that they have the potential to go to as high as about 85% efficiency. The path is clear: increase voltage and decrease current, thereby reducing the "microperveance" of the klystrons. This will be crucial at FCC-ee, which must continuously replenish 100 MW of synchrotron radiation losses with 100 MW of RF power. The klystron efficiency improvement alone can save more than 60 MW – fully a third of the current power consumption of the CERN accelerator complex.

Muon colliders were presented as a unique opportunity to achieve a substantial energy increase compared to hadrons (Diktys Stratakis, Fermilab). Due to the point-like nature of the muon, the full centre-of-mass energy is available for probing new physics processes in every collision. Therefore, a 10 TeV muon collider can provide comparable high-energy-physics breakthroughs to a 100 TeV proton-proton collider, where colliding partons only carry a fraction of the proton's energy. Due to its compactness, the cost of a 10 TeV muon collider compares to that of the FCC-ee and is likely to be many times lower than any other alternative concept that can achieve 10 pCM (parton centre-of-mass) energies (T Roser *et al.* 2023 *JINST* **18** P05018). ▷

CERNCOURIER
Volume 64 Number 5 September/October 2024
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The challenge lies in developing technologies for muon production, cooling and acceleration in the next two decades. In the upcoming 19 to 25 years it should be technically feasible for the accelerator community to demonstrate the technologies of a) high-intensity and short proton bunches; b) high-power proton targets; c) muon cooling; d) fast muon acceleration; e) 10 to 12 T superconducting magnets lined with tungsten inserts to protect coils from the muon decay products, and; f) effective spreading of the narrow cones of ultra-high-energy neutrinos by wiggling the beams, to avoid damage caused by the chargeless neutrinos when the muons decay.

In the conference's closing talk, I reviewed three dozen future-collider proposals, analysed the ultimate energies potentially attainable in all types of colliding beams and accelerators within reasonable cost and power consumption limits, and laid out arguments that energies beyond a PeV (thousands of TeV) can be achieved, concluding that muons are the particles of the future for high-energy physics.

The prize session was a highlight, with acceptance speeches from KEK's Kaoru Yokoya (APS Wilson Prize) and SLAC's Gennady Stupakov (IEEE NPSS PAST Award). Yokoya outlined his participation in various electron–positron machines and proposals such as the TRISTAN e^+e^- collider and the ILC. Stupakov emphasised the importance of beam-dynamics theory in the age of computer modelling and simulations.

Ever since the first edition in Kyoto in 2010, I can attest to IPAC's success in fostering real-life interactions in the global accelerator landscape. After the conference, I counted more than a hundred encounters of 5 minutes or more – something that would be difficult to achieve at a smaller or more specialised conference. It was pleasing to see many Chinese colleagues attend this US-based conference, but I did not identify any participants from Russia – a concerning development for our science's international spirit. I hope political barriers will not interfere with next year's IPAC'25 in Taiwan.

I can attest to IPAC's success in fostering real-life interactions in the global accelerator landscape

On a personal note, I would like to thank the organisers for putting together great scientific and social programmes, and the dedicated Joint Accelerator Conferences Website team, whose tireless efforts ensured that virtually all conference proceedings – papers, talks and posters – were available online by the final day, setting a standard that other fields of high-energy physics could greatly benefit from.

Vladimir Shiltsev *Northern Illinois University.*

LATTICE 2024

Lattice calculations start to clarify muon g–2

University of Liverpool

Wilson's legacy *The participants of Lattice 2024 in Liverpool.*

In 1974, Kenneth G Wilson suggested modelling the continuous spacetime of quantum chromodynamics (QCD) with a discrete lattice – space and time would be represented as a grid of points, with quarks on the lattice points and gluons on the links between them. Lattice QCD has only grown in importance since, with international symposia on lattice field theory taking place annually since 1984. Since then the conference has developed and by now furnishes an important forum for both established experts and early-career researchers alike to report recent progress, and the published proceedings provide a valuable resource. The 41st symposium, Lattice 2024, welcomed 500 participants to the University of Liverpool from 28 July to 3 August.

Hadronic contributions

One of the highest profile topics in lattice QCD is the evaluation of hadronic contributions to the magnetic moment of the muon. For many years, the experimental measurements from Brookhaven and Fermilab have appeared to be in tension with the Standard Model (SM), based on theoretical predictions that rely on data from e^+e^- annihilation to hadrons. Intense work on the lattice by multiple groups is now maturing rapidly and providing a valuable cross-check for data-driven SM calculations.

At the lowest order in quantum electrodynamics, the Dirac equation accounts for precisely two Bohr magnetons in the muon's magnetic moment (g = 2) – a contribution arising purely from the muon interacting with a single real external photon representing the magnetic field. At higher orders in QED, virtual Standard Model particles modify that value, leading to a so-called anomalous magnetic moment g–2. The Schwinger term adds a virtual photon and a contribution to g–2 of approximately 0.2%. Adding individual virtual W, Z or Higgs bosons adds a well defined contribution a factor of a million or so smaller. The remaining relevant contributions are from hadronic vacuum polarisation (HVP) and hadronic light-by-light (HLBL) scattering. HVP and HLBL both add hadronic contributions integrated to all orders in the strong coupling constant to interactions between the muon and the external electric field, which also feature additional virtual photons. Though their contributions to g–2 are in the ballpark of the small electroweak contribution, they are more difficult to calculate, and dominate the error budget for the SM prediction of the muon's g–2.

Christine Davies (University of Glasgow) gave a comprehensive survey of muon g–2 that stressed several high-level points: the small HLBL contribution looks to be settled, and is unlikely to be a key piece to the puzzle; recent tensions among the e^+e^- experiments for HVP have emerged and need to be better understood; and in the most contentious region, all eight recent lattice-QCD calculations agree with each other and with the very recent $e^+e^- \rightarrow$ hadrons experiment CMD 3 (2024 *Phys. Rev. Lett.* **132** 231903), though not so much with earlier experiments. Thus, lattice QCD ▷

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and CMD 3 suggest there is "almost certainly less new physics in muon g–2 than previously hoped, and perhaps none," said Davies. We shall see: many groups are preparing results for the full HVP, targeting a new whitepaper from the Muon g–2 Theory Initiative by the end of this year, in anticipation of the final measurement from the Fermilab experiment sometime in 2025.

New directions

While the main focus of Lattice calculations is the study of QCD, lattice methods have been applied beyond that. There is a small but active community investigating systems that could be relevant to physics beyond the Standard Model, including composite Higgs models, supersymmetry and dark matter. These studies often inspire formal "theoretical" developments that are of interest beyond the lattice community. Particularly exciting directions this year were the development on emergent phases, non-invertible symmetries and their possible application to formulate chiral gauge theories, one of the outstanding theoretical issues in lattice gauge theories.

The lattice QCD community is one of the main users of high-performance computing resources, with its simulation efforts generating petabytes of Monte Carlo data. For more than 20 years, a community wide effort, the international lattice data grid (ILDG), has allowed this data to be shared. Since its inception, ILDG implemented the FAIR principles – data should be findable, accessible, interoperable and reusable – almost fully. The lattice QCD community is now discussing Open Science. Ed Bennett (Swansea) led a panel discussion that explored the benefits of ILDG embracing open science, such as higher credibility for published results, and not least the means to fulfill the expectations of funding bodies. Sustainably maintaining the infrastructure and employing the personnel required calls for national or even international community efforts to convince the funding agencies to provide corresponding funding lines, but also the researchers of the benefits of open science.

The lattice QCD community is one of the main users of high-performance computing resources

The Kenneth G. Wilson Award for Excellence in Lattice Field Theory was awarded to Michael Wagman (Fermilab) for his lattice-QCD studies of noise reduction in nuclear systems, the structure of nuclei and transverse-momentum-dependent hadronic structure functions. Fifty years on from Wilson's seminal paper, two of the field's earliest contributors, John Kogut (US Department of Energy) and Jan Smit (University of Amsterdam), reminisced about the birth of the lattice in a special session chaired by Liverpool pioneer Chris Michael. Both speakers gave fascinating insights into a time where physics was extracted from a handful of small-volume gauge configurations, compared to hundreds of thousands today.

Lattice 2025 will take place at the Tata Institute of Fundamental Research in Mumbai, India, from 3 to 8 November 2025.

Andreas Kronfeld *Fermilab*, **Anna Hasenfratz** *University of Colorado Boulder and* **Carsten Urbach** *University of Bonn.*

German community workshop

German community discusses future collider at CERN


M Schott

Bonn workshop *The German particle-physics community gathered at Bonn to discuss the opportunities of a future collider at CERN.*

More than 150 German particle physicists gathered at Bonn University for a community event on a future collider at CERN. More precisely, the focus set for this meeting was to discuss the opportunities that the FCC-ee would offer should this collider be built at CERN. The event was organised by the German committee for particle physics, KET, and took place from 22 to 24 May. Representatives from almost all German institutes and groups active in particle physics were present, an attendance that shows the large interest in the collider to be built at CERN after the successful completion of the HL-LHC programme.

The main workshop was preceded by a dedicated session with more than 80 early-career scientists, organised by the Young High Energy Physicists Association, yHEP, to bring the generation that will benefit most from a future collider at CERN up to speed on the workshop topics. It included a presentation by former ECFA chair Karl Jakobs (Freiburg University) "From Strategy Discussions to Decision-Taking for Large Projects", explaining the mechanisms and bodies involved in setting a project like the FCC-ee on track.

The opening session of the main workshop featured a fresh view on "The physics case for an e^+e^- collider at CERN" by Margarete Mühlleitner (KIT Karlsruhe), who spread excitement about the strong and comprehensive physics case from super-precise measurements of the properties of the Z boson, the W boson and the top quark to what most people associate with a future e^+e^- collider: precision measurements of the Higgs boson and insights about its connection to many of the still open questions of particle physics like dark matter or the matter–antimatter asymmetry. Markus Klute (KIT Karlsruhe) gave an in-depth review of the FCC-ee project. The midterm results of the FCC feasibility study indicate that no showstoppers were found in all the aspects studied so far and that the integrated FCC programme offers unparalleled exploration potential through precision measurements and direct searches. The picture was rounded off by a presentation from Jenny List (DESY, Hamburg) who talked about alternative options to realise an e^+e^- Higgs factory at CERN, and the perspective of the early-career researchers was highlighted by Michael Lupberger (Bonn University). While all these presentations concentrated on the science and technology of the FCC-ee or alternatives, Eckart Lilienthal, representing the German Ministry of Education and Research, BMBF, reminded the audience that a future collider project at CERN needs an affordable financial plan and that – given the large uncertainties at present – this requires the community to prepare for different scenarios including one without the FCC-ee. Lilienthal confirmed that the future of CERN remains of the highest priority to BMBF.

The workshop went on to review many aspects of the FCC-ee and possible alternatives in more detail: accelerator R&D, detector concepts and technologies, computing and software, theory challenges as well as sustainability. The workshop witnessed the first meetings of the newly established German detector R&D consortia on silicon detectors, gaseous detectors and calorimetry. They will receive BMBF funding for the next three years and will allow German groups to strongly participate in the recently formed international DRD consortia in the context of the ECFA detector roadmap.

The event was an important step in building consensus in the German community for a future collider project at CERN

The path ahead

The workshop concluded with discussion sessions on the future collider scenarios for CERN, the engagement of the German community and a path to prepare the German input to the update of the European Strategy for Particle Physics. A series of three additional community workshops will be held in Germany before this input is due in March 2025.

The Bonn event was an important step in building consensus in the German community for a future collider project at CERN. The FCC-ee project generated a lot of interest and many groups plan to embark more strongly on this project. Contributions concerning the physics case, theory challenges, detector design and development, software, computing, and accelerator development were discussed. Alternative options for a future collider project at CERN need to be kept open to address the unanswered fundamental questions of particle physics in case the FCC-ee is not built at CERN. This event was clear evidence that a bright future for CERN remains of highest priority for the German particle-physics community and funding agency.

Lutz Feld *RWTH Aachen University and KET and* **Hans-Christian Schultz-Coulon** *Heidelberg University and KET.*

Aspen Winter Conference

A new generation, a new vision

The 2024 Aspen Winter Conference, The Future of High Energy Physics: A New Generation, A New Vision, attracted 50 early-career researchers (ECRs) from across the world to the Aspen Center for Physics, 8000 feet above sea level in the Colorado Rockies, from 24 to 29 March. The conference built on the many new ideas that arose from the recent Snowmass process of the US particle physics community (*CERN Courier* January/February 2024 p7). The conference sought to highlight the role of ECRs in realising bold long-term visions for the field, covering theoretical questions, the experimental vision for the next 50 years and the technologies required to make it a reality. Students, postdocs and junior faculty are often the drivers of new ideas in science. Helping them transition new ideas to the mainstream requires enthusiasm, community support and time.


Aspen Winter Conference

Next generation *Early-career researchers converged on the Colorado Rockies to discuss the future of the field.*

Crossing frontiers

85% of the matter in the universe at most minimally interacts with the electromagnetic force but provided the gravitational seed for large-scale structure formation in the early universe. Hugh Lippincott (University of California, Santa Barbara) summarised cross-frontier searches. Pursuing all possible scenarios via direct detection will require scaling up existing technology and developing new technologies such as quantum sensors to probe lighter dark-matter candidates. On the one hand, the 60 to 80 tonne "XLZD" liquid xenon detector will merge the expertise of the XENONnT, LUX-ZEPLIN and DARWIN collaborations; on the low-mass side, Reina Maruyama (Yale) discussed the ALPHA and HAYSTAC haloscopes, which seek to convert axions into photons in highly tuned resonant cavities. Indirect detection and collider experiments will also play an important role in closing in on minimal dark-matter models.

Delegates expressed a sense of urgency to probe higher energies. Cari Cesarotti (MIT) advocated R&D towards a future muon collider, arguing that muons ▷

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offer a clean and power-efficient route to the 10 TeV scale and above. Recently, experts have estimated that challenges due to the finite muon lifetime could be overcome on a 20-year technically limited timeline. Both CERN and China have proposed building 100 km-circumference tunnels, initially hosting an electron–positron collider followed by a 100 TeV hadron machine, however, the timeline suggests that almost all of the conference attendees would be retired before hadron collisions come online. Elliot Lipeles (Pennsylvania) proposed skipping the electron–positron stage and immediately pursuing an intermediate-energy hadron collider: existing magnets in a 100 km tunnel could produce 37 TeV collisions, advancing measurements of the Higgs self-coupling and electroweak phase transition, dark matter and its mediators, and naturalness.

Neutrinos were discussed at length. Georgia Karagiorgi (Columbia University) argued that three short-baseline anomalies remain, potentially hinting at additional sterile neutrinos or dark-sector portals. Julieta Gruszko (North Carolina at Chapel Hill) presented an exciting future for experiments that seek to discern the fundamental nature of neutrinos. A new tonne-scale generation of detectors comprising LEGEND1000, nEXO and CUPID may succeed in confirming the Majorana nature of the neutrino if they observe neutrinoless double beta decay.

The energy, intensity and cosmic frontiers of particle physics target deeply connected questions

Talks on the importance of science communication and education provoked a great deal of discussion. Ethan Siegal, host of popular podcast "Starts with a Bang" spoke on public outreach, Kevin Pedro (Fermilab) on advocacy with policymakers in Washington, DC, and Roger Freedman (University of California Santa Barbara) on educating the next generation of physicists. In public programming, Nausheen Shah (Wayne State) was the guest speaker at a screening of *Hidden Figures*, the inspiring true story of the black women who helped the US win the space race, and Philip Chang (University of California San Diego) lectured on "An Invitation to Imagine Something from Nothing".

The energy, intensity and cosmic frontiers of particle physics target deeply connected questions. Dark matter, dark energy, cosmic inflation and baryogenesis have remained unexplained for decades, and the structure of the Standard Model itself provokes questions, not least in relation to the Higgs boson and neutrinos. Innovative and complementary experiments are needed across all areas of particle physics. Judging from the 2024 Aspen Winter Conference, the future of the field is in good hands.

Karri Folan Di Petrillo *University of Chicago*, **Lawrence Lee** *University of Tennessee Knoxville*, **Nausheen Shah** *Wayne State University and* **Sally Shaw** *University of Edinburgh*.

MEDICAL APPLICATIONS OF SPECTROSCOPIC X-RAY DETECTORS

Threshold moment for medical photon counting


M Cavazza/CERN-PHOTO-202404-081-4

Industry engagement *The participants of the 7th Workshop on Medical Applications of Spectroscopic X-ray Detectors at CERN.*

The seventh workshop on Medical Applications of Spectroscopic X-ray Detectors was held at CERN from 15 to 18 April. This year's workshop brought together more than 100 experts in medical imaging, radiology, physics and engineering. The workshop focused on the latest advancements in spectroscopic X-ray detectors and their applications in medical diagnostics and treatment. Such detectors, whose origins are found in detector R&D for high-energy physics, are now experiencing a breakthrough moment in medical practice.

Spectroscopic X-ray detectors represent a significant advancement in medical imaging. Unlike traditional X-ray detectors that measure only the intensity of X-rays, these advanced detectors can differentiate the energies of X-ray photons. This enables enhanced tissue differentiation, improved tumour detection and advanced material characterisation, which may lead in certain cases to functional imaging without the need for radioactive tracers.

The technology has its roots in the 1980s and 1990s when the high-energy-physics community centred around CERN developed a combination of segmented silicon sensors and very large-scale integration (VLSI) readout circuits to enable precision measurements at unprecedented event rates, leading to the development of hybrid pixel detectors (see p37). In the context of the Medipix Collaborations, CERN has coordinated research on spectroscopic X-ray detectors including the development of photon-counting detectors and new semiconductor materials that offer higher sensitivity and energy resolution. By the late 1990s, several groups had proofs of concept, and by 2008, pre-clinical spectral photon-counting computed-tomography (CT) systems were under investigation.

In 2011, leading researchers in the field decided to bring together engineers, physicists and clinicians to help address the scientific, medical and engineering challenges associated with guiding the technology toward clinical adoption. In 2021, the FDA

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approval of Siemens Healthineers' photon-counting CT scanner marked a significant milestone in the field of medical imaging, validating the clinical benefits of spectroscopic X-ray detectors. The mobile CT scanner, OmniTom Elite from NeuroLogica, approved in March 2022, also integrates photon counting detector (PCD) technology. The 3D colour X-ray scanner developed by MARS Bioimaging, in collaboration with CERN based on Medipix3 technology, has already shown significant promise in pre-clinical and clinical trials. Clinical trials of MARS scanners demonstrated its applications for detecting acute fractures, evaluation of fracture healing and assessment of osseous integration at the bone–metal interface for fracture fixations and joint replacements. With more than 300 million CT scans being performed annually around the world, the potential impact for spectroscopic X-ray imaging is enormous, but technical and medical challenges remain, and the need for this highly specialised workshop continues.

Spectroscopic X-ray detectors offer unparalleled diagnostic capabilities, enabling more detailed imaging and earlier and precise disease detection

The scientific presentations in the 2024 workshop covered the integration of spectroscopic CT in clinical workflows, addressed technical challenges in photon counting detector technology and explored new semiconductor materials for X-ray detectors. The technical sessions on detector physics and technology discussed new methodologies for manufacturing high-purity cadmium–zinc–tellurium semiconductor crystals and techniques to enhance the quantum efficiency of current detectors. Sessions on clinical applications and imaging techniques included case studies demonstrating the benefits of multi-energy CT in cardiology and neurology, and advances in using spectroscopic detectors for enhanced contrast agent differentiation. The sessions on computational methods and data processing covered the implementation of AI algorithms to improve image reconstruction and analysis, and efficient storage and retrieval systems for large-scale spectral imaging datasets. The sessions on regulatory and safety aspects focused on the regulatory pathway for new spectroscopic X-ray detectors, ensuring patient and operator safety with high-energy X-ray systems.

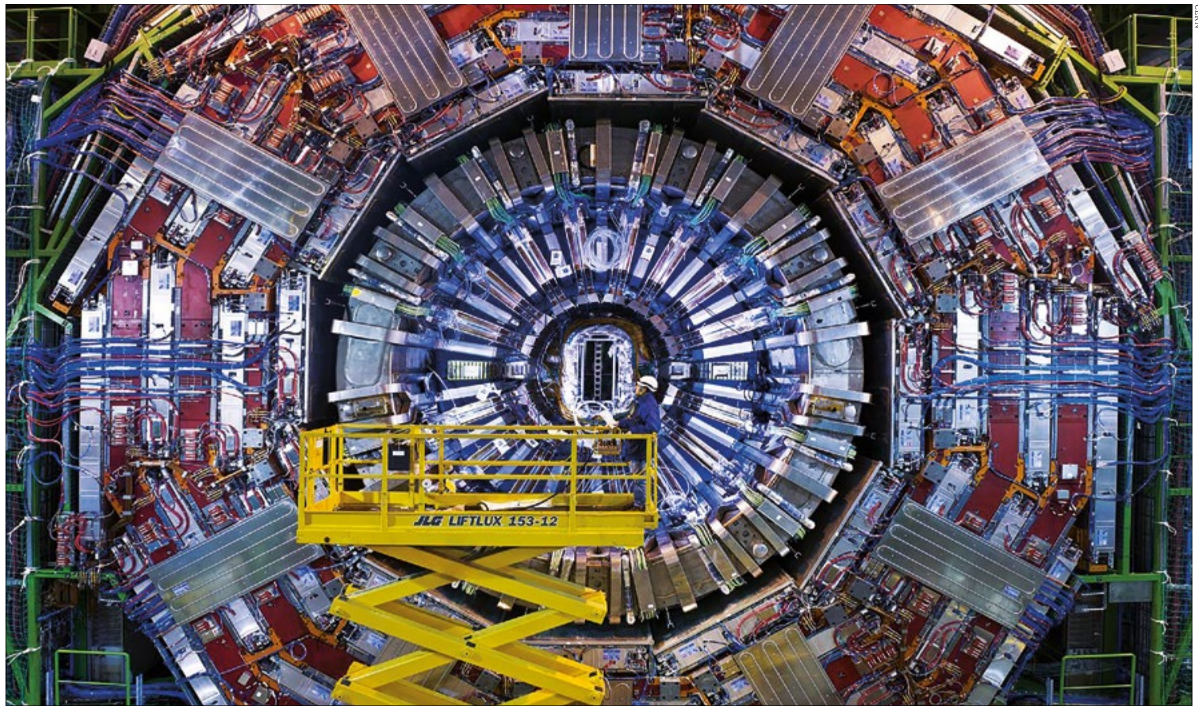
Enhancing patient outcomes

The field of spectroscopic X-ray detectors is rapidly evolving. Continued research, collaboration and innovation to enhance medical diagnostics and treatment outcomes will be essential. Spectroscopic X-ray detectors offer unparalleled diagnostic capabilities, enabling more detailed imaging and earlier and precise disease detection, which improves patient outcomes. To stay competitive and meet the demand for precision medicine, medical institutions are increasingly adopting advanced imaging technologies. Continued collaboration among researchers, physicists and industry leaders will drive innovation, benefiting patients, healthcare providers and research institutions.

Anthony Butler *and* **Maya Rajeswari**
MARS Bioimaging Ltd.

ELECTROWEAK PRECISION AT THE LHC

Geared for discovery more so than delicacy, the LHC is defying expectations by rivalling lepton colliders for precision. Guillelmo Gomez-Ceballos and Jan Kretzschmar identify five measurements of the electroweak interaction where the LHC experiments are pushing the boundaries of our knowledge.



CERN

Precision rising *The CMS detector.*

The Standard Model – an inconspicuous name for one of the great human inventions. It describes all known elementary particles and their interactions, except for gravity. About 19 free parameters tune its behaviour. To the best of our knowledge, they could in principle take any value, and no underlying theory yet conceived can predict their values. They include particle masses, interaction strengths, important technical numbers such as mixing angles and phases, and the vacuum strength of the Higgs field, which theorists believe has alone among fundamental fields permeated every cubic attometre of the universe, since almost the beginning of time. Measuring these parameters is the most fundamental experimental task available to modern science.

The basic constituents of matter interact through forces which are mediated by virtual particles that ping back and forth, delivering momentum and quantum numbers. The gluon mediates the strong interaction, the photon mediates the electromagnetic interaction, and the W and Z bosons mediate the weak interaction. Although the electromagnetic and weak forces operate very differently to each other in everyday life, in the Standard Model they are two manifestations of the broken electroweak interaction – an interaction that broke when the Higgs field switched on throughout the universe, giving mass to matter particles, the W and Z bosons, and the Higgs boson itself, via the Brout–Englert–Higgs (BEH) mechanism. The electroweak theory has been extraordinarily successful in describing experimental results, but it remains mysterious – and the BEH mechanism is the origin of some of those free param-

THE AUTHORS

Guillelmo Gomez-Ceballos *MIT and*
Jan Kretzschmar *University of Liverpool.*

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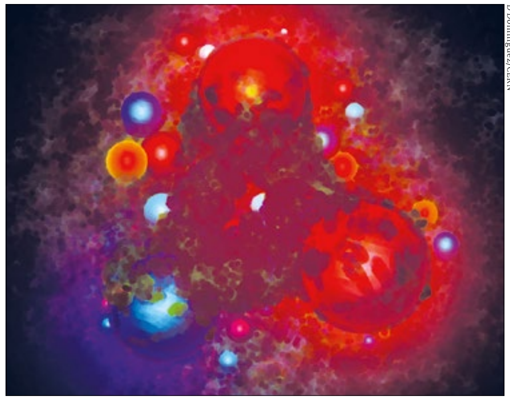
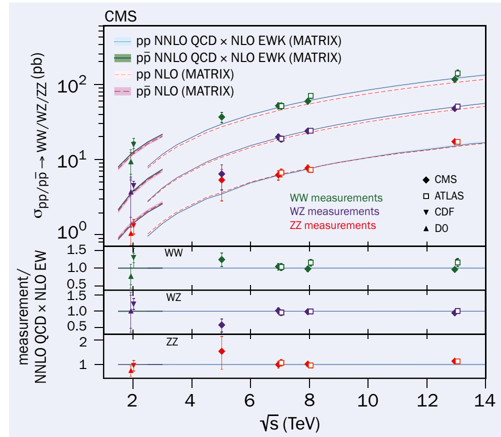
The capabilities of the LHC experiments and the ingenuity of analysts have enabled many of the world's most precise measurements of the electroweak interaction



D Dominguez/CERN

Quantum complexity *An artist's visualisation of a proton.*



CMS Collab. 2021 arXiv:2107.01137

Diboson production *Total WW, WZ and ZZ cross sections as a function of centre-of-mass energy. ATLAS and CMS measurements are shown together with those by the CDF and D0 experiments at the Tevatron, which made the first observation of the production of pairs of weak bosons in hadron collisions by colliding proton and antiproton beams.*

eters. The best way to test the electroweak model is to over-constrain its free parameters using precision measurements and try to find a breaking point.

Ever since the late 1960s, when Steven Weinberg, Sheldon Glashow and Abdus Salam unified the electromagnetic and weak forces using the BEH mechanism, CERN has had an intimate experimental relationship with the electroweak theory. In 1973 the Z boson was indirectly discovered by observing "neutral current" events in the Gargamelle bubble chamber, using a neutrino beam from the Proton Synchrotron. The W boson was discovered in 1983 at the Super Proton Synchrotron collider, followed by the direct observation of the Z boson in the same machine soon after. The 1990s witnessed a decade of exquisite electroweak precision measurements at the Large Electron Positron (LEP) collider at CERN and the Stanford Linear Collider (SLC) at SLAC National Accelerator Laboratory in the US, before the crown jewel of the electroweak sector, the Higgs boson, was discovered by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) in 2012 – a remarkable success that delivered the last to be observed, and arguably most mysterious, missing piece of the Standard Model.

What was not expected, was that the ATLAS, CMS and LHCb experiments at the LHC would go on to make electroweak measurements that rival in precision those made at lepton colliders.

Discovery or precision?

Studying the electroweak interaction requires a supply of W and Z bosons. For that, you need a collider. Electrons and positrons are ideally suited for the task as they interact exclusively via the electroweak interaction. By precisely tuning the energy of electron–positron collisions, experiments at LEP and the SLC tested the electroweak sector with an unprecedented 0.1% accuracy at the energy scale of the Z-boson mass (m_Z).

Hadron colliders like the LHC have different strengths and weaknesses. Equipped to copiously produce all known Standard Model particles – and perhaps also hypothetical new ones – they are the ultimate instruments for probing the high-energy frontier of our understanding of the microscopic world. The protons they collide are not elementary, but a haze of constituent quarks and gluons that bubble and fizz with quantum fluctuations. Each constituent "parton" carries an unpredictable fraction of the proton's energy. This injects unavoidable uncertainty into studies of hadron collisions that physicists attempt to encode in probabilistic parton distribution functions. What's more, when a pair of partons from the two opposing protons interact in an interesting way, the result is overlaid by numerous background particles originating from the remaining partons that were untouched by the original collision – a complexity that is exacerbated by the difficult-to-model strong force which governs the behaviour of quarks and gluons. As a result, hadron colliders have a reputation for being discovery machines with limited precision.

The LHC has collided protons at the energy frontier since 2010, delivering far more collisions than comparable previous machines such as the Tevatron at Fermilab in the US. This has enabled a comprehensive search and measurement programme. Following the discovery of the Higgs boson in 2012, measurements have so far verified its place in the electroweak sector of the Standard Model, although the relative precisions of many measurements are currently far lower than those achieved for the W and Z bosons at LEP. But in defiance of expectations, the capabilities of the LHC experiments and the ingenuity of analysts have also enabled many of the world's most precise measurements of the electroweak interaction. Here, we highlight five.

1. Producing W and Z bosons

When two streams of objects meet, how many strike each other depends on their cross-sectional area. Though quarks and other partons are thought to be fundamental objects with zero extent, particle physicists borrow this logic for particle beams, and extend it by subdividing the metaphorical cross section according to the resulting interactions. The range

ATLAS-PHOTO-2024-002-1

Perspectives on parameters *The ATLAS detector.*

of processes used to study W and Z bosons at the LHC spans a remarkable eight orders of magnitude in cross section.

The most common interaction is the production of single W and Z bosons through the annihilation of a quark and an antiquark in the colliding protons. Measurements with single W and Z boson events have now reached a precision well below 1% thanks to the excellent calibration of the detector performance. They are a prodigious tool for testing and improving the modelling of the underlying process, for example using parton distribution functions.

The second most common interaction is the simultaneous production of two bosons. Measurements of "diboson" processes now routinely reach a precision better than 5%. Since the start of the LHC operation, the accelerator has operated at several collision energies, allowing the experiments to map diboson cross sections as a function of energy. Measurements of the cross sections for creating WW, WZ and ZZ pairs exhibit remarkable agreement with state-of-the art Standard Model predictions (see "Diboson production" figure).

The large amount of collected data at the LHC has recently allowed us to move the frontier to the observation of extremely infrequent "triboson" processes with three W or Z bosons, or photons, produced simultaneously – the first step towards confirming the existence of the quartic self-interaction between the electroweak bosons.

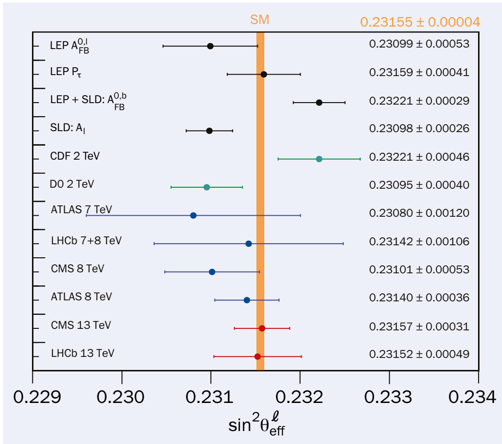
2. The weak mixing angle

The Higgs potential is famously thought to resemble a Mexican hat. The Higgs field that permeates space could in principle exist with a strength corresponding to any point on its surface. Theorists believe it settled somewhere in the brim a picosecond or so after the Big Bang, breaking the perfect symmetry of the hat's apex, where its value was zero. This switched the Higgs field on throughout the universe – and the massless gauge bosons of the unified electroweak theory mixed to form the photon and W and Z boson mass eigenstates that mediate the broken electroweak interaction today. The weak mixing angle θ_W is the free parameter of the Standard Model which defines that mixing.

The θ_W angle can be studied using a beautifully simple interaction: the annihilation of a quark and its antiquark to create an electron and a positron or a muon and an antimuon. When the pair has an invariant mass in the vicinity of m_Z, there is a small preference for the negatively charged lepton to be produced in the same direction as the initial quark. This arises due to quantum interference between the Z boson's vector and axial-vector couplings, whose relative strengths depend on θ_W.

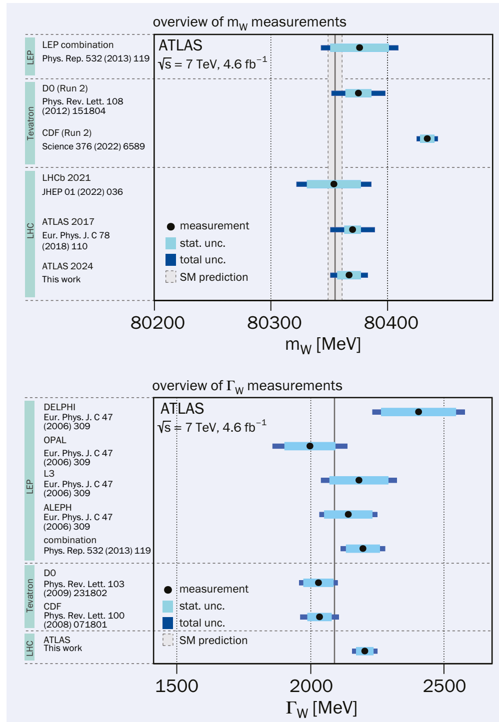
The unique challenge at a proton–proton collider like the LHC is that the initial directions of the quark and the antiquark can only be inferred using our limited knowledge of parton distribution functions. These systematic uncertainties currently dominate the total uncertainty, although they can be reduced somewhat by using information on lepton pairs produced away from the Z resonance. The CMS and LHCb collaborations have recently released new measurements consistent with the Standard Model prediction with a precision comparable to that of the LEP and SLC experiments (see "Weak mixing angle" figure).

Quantum physics effects play an interesting role here. In practice, it is not possible to experimentally isolate "tree level" properties like θ_W, which describe the simplest



G Gomez-Ceballos

Weak mixing angle *The recent CMS and LHCb measurements of the effective weak mixing angle (red) compared with previous results and with the Standard Model prediction (vertical orange band).*



ATLAS Collaboration 2024 arXiv:2403.15085

Mass and width *The latest measurement of the W boson's mass (top) and width (bottom) by the ATLAS collaboration, compared with previous results from the LHCb, LEP and Tevatron experiments, and the Standard Model prediction (vertical grey band).*

interactions that can be drawn on a Feynman diagram. Measurements are in fact sensitive to the effective weak mixing angle, which includes the effect of quantum interference from higher-order diagrams.

A crucial prediction of electroweak theory is that the masses of the W and Z bosons are, at leading order, related by the electroweak mixing angle: $\sin^2\theta_W = 1 - m_W^2/m_Z^2$, where m_W and m_Z are the masses of the W and Z bosons. This relationship is modified by quantum loops involving the Higgs boson, the top quark and possibly new particles. Measuring the parameters of the electroweak theory precisely, therefore, allows us to test for any gaps in our understanding of nature.

Surprisingly, combining this relationship with the m_Z measurement from LEP and the CMS measurement of θ_W also allows a competitive measurement of m_W. A measurement of $\sin^2\theta_W$ with a precision of 0.0003 translates into a prediction of m_W with 15 MeV precision, which is comparable to the best direct measurements.

3. The mass and width of the W boson

Precisely measuring the mass of the W boson is of paramount importance to efforts to further constrain the relationships between the parameters of the electroweak theory, and probe possible beyond-the-Standard Model contributions. Particle lifetimes also offer a sensitive test of the electroweak theory. Because of their large masses and numerous decay channels, the W and Z bosons have mean lifetimes of less than 10^{-24} s. Though this is an impossibly brief time interval to measure directly, Heisenberg's uncertainty principle smudges a particle's observed mass by a certain "width" when it is produced in a collider. This width can be measured by fitting the mass distribution of many virtual particles. It is reciprocally related to the particle's lifetime.

While lepton-collider measurements of the properties of the Z boson were extensive and achieved remarkable precision, the same is not quite true for the W boson. The mass of the Z boson was measured with a precision of 0.002%, but the mass of the W boson was measured with a precision of only 0.04% – a factor 20 worse. The reason is that while single Z bosons were copiously produced at LEP and SLC, W bosons could not be produced singly, due to charge conservation. W^+W^- pairs were produced, though only at low rates at LEP energies.

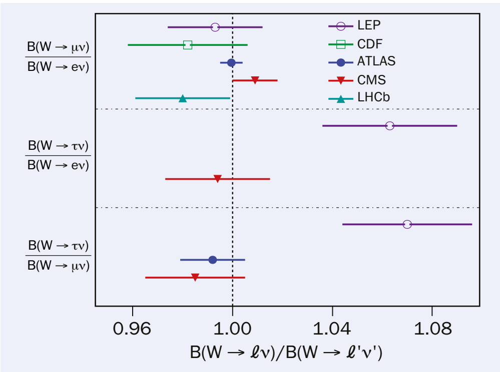
In contrast to LEP, hadron colliders produce large quantities of single W bosons through quark–antiquark annihilation. The LHC produces more single W bosons in a minute than all the W-boson pairs produced in the entire lifetime of LEP. Even when only considering decays to electrons or muons and their respective neutrinos – the most precise measurements – the LHC experiments have recorded billions of W-boson events.

But there are obstacles to overcome. The neutrino in the final state escapes undetected. Its transverse momentum with respect to the beam direction can only be measured indirectly, by measuring all other products of the collision – a major experimental challenge in an environment with not just one, but up to 60 simultaneous proton–proton collisions. Its longitudinal momentum cannot be measured at all. And as the W bosons are not produced at rest, extensive theoretical calculations and ancillary measurements are needed to model their momenta, incurring uncertainties from parton distribution functions.

Despite these challenges, the latest measurement of the W boson's mass by the ATLAS collaboration achieved a

P Ginter

Complementary coverage *The LHCb detector.*



J Kretzschmar

Couplings to leptons *Ratios of branching fractions for the W boson to decay to each possible pairing of lepton flavours. Any statistically significant deviation from unity would indicate physics beyond the Standard Model.*

If the W boson decays into any hitherto undiscovered particles, its lifetime should be shorter than predicted, and its width greater, potentially indicating the presence of new physics

precision of roughly 0.02% (see "Mass and width" figure, top). The LHCb collaboration also recently produced its first measurement of the W-boson mass using W bosons produced close to the beam line with a precision at the 0.04% level, dominated for now by the size of the data sample. Owing to the complementary detector coverage of the LHCb experiment with respect to the ATLAS and CMS experiments, several uncertainties are reduced when these measurements are combined.

The Tevatron experiments CDF and D0 also made precise W-boson measurements using proton–antiproton collisions at a lower centre-of-mass energy. The single most precise mass measurement, at the 0.01% level, comes from CDF. It is in stark disagreement with the Standard Model prediction and disagrees with the combination of other measurements.

A highly anticipated measurement by the CMS collaboration may soon weigh in decisively in favour either of the CDF measurement or the Standard Model. The CMS measurement will combine innovative analysis techniques using the Z boson with a larger 13 TeV data set than the 7 TeV data used by the recent ATLAS measurement, enabling more powerful validation samples and thereby greater power to reduce systematic uncertainties.

Measurements of the W boson's width are not yet sufficiently precise to constrain the Standard Model significantly, though the strongest constraint so far comes from the ATLAS collaboration (see "Mass and width" figure, bottom). Further measurements are a promising avenue to test the Standard Model. If the W boson decays into any hitherto undiscovered particles, its lifetime should be shorter than predicted, and its width greater, potentially indicating the presence of new physics.

4. Couplings of the W boson to leptons

Within the Standard Model, the W and Z bosons have equal couplings to leptons of each of the three generations – a property known as lepton flavour universality (LFU). Any experimental deviation from LFU would indicate new physics.

As with mass and width, lepton colliders' precision was superior for the Z boson than the W boson. LEP confirmed LFU in leptonic Z-boson decays to about 0.3%. Comparing the three branching fractions of the W boson in the electron, muon and tau-lepton decay channels, the combination of the four LEP experiments reached a precision of only about 2%.

At the LHC, the large cross section for producing top quark–antiquark pairs that both decay into a W boson and a bottom quark offers a unique sample of W-boson pairs for high-precision studies of their decays. The resulting measurements are the most precise tests of LFU for all three possible comparisons of the coupling of the lepton flavours to the W boson (see "Couplings to leptons" figure).

Regarding the tau lepton to muon ratio, the ATLAS collaboration observed 0.992 ± 0.013 decays to a tau for every one decay to a muon. This result favours LFU and is twice as precise than the corresponding LEP result of 1.066 ± 0.025, which exhibits a deviation of 2.6 standard deviations from unity. Because of the relatively long tau lifetime, ATLAS was able to separate muons produced in the decay of tau leptons from those produced promptly by observing the tau decay length of the order of 2 mm.

The best tau to electron measurement is provided by a simultaneous CMS measurement of all the leptonic and hadronic decay branching fractions of the W boson. The analysis splits the top quark–antiquark pair events based on the multiplicity and flavour of reconstructed leptons, the number of jets, and the number of jets identified as originating from the hadronisation of b quarks. All CMS ratios are consistent with the LFU hypothesis and reduce tension with the Standard Model prediction.

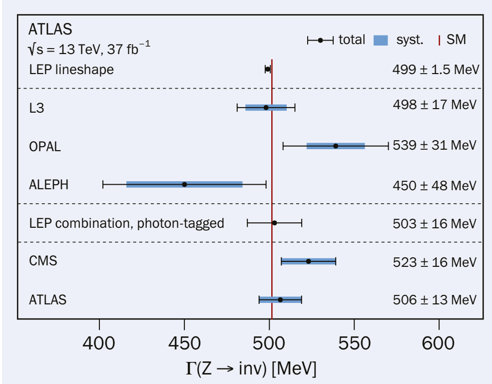
Regarding the muon to electron ratio, measurements have been performed by several LHC and Tevatron experiments. The observed results are consistent with LFU, with the most precise measurement from the ATLAS experiment boasting a precision better than 0.5%.

5. The invisible width of the Z boson

A groundbreaking measurement at LEP deduced how often a particle that cannot be directly observed decays to particles that cannot be detected. The particle in question is the Z boson. By scanning the energy of electron–positron collisions and measuring the broadness of the "lineshape" of the smudged bump in interactions around the mass of the Z, LEP physicists precisely measured its width. As pre-

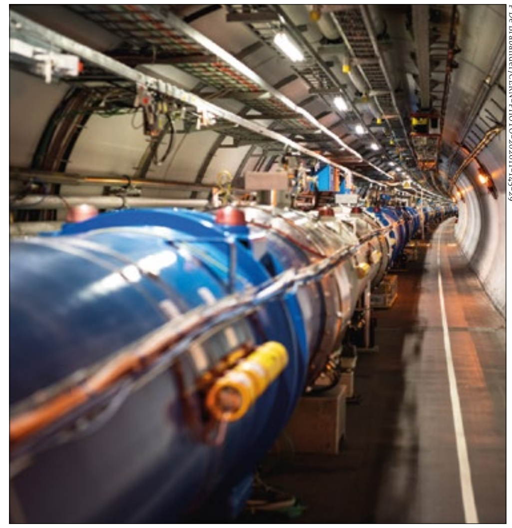
CERNCOURIER
Volume 64 Number 5 September/October 2024
IOP Publishing

The LHC collaborations have made remarkable strides forward in probing the electroweak theory



ATLAS Collaboration 2023 arXiv:2312.02789

Invisible width *Invisible width measurements by the LEP experiments L3, OPAL and ALEPH, and by the ATLAS and CMS experiments at the LHC. All measurements use the "recoil" method, except the more precise LEP combination (top), which uses the "lineshape" method. The Standard Model prediction is shown by the solid red line.*



P De Brabander/CERN-PHOTO-202011-145-29

Precision instrument *The Large Hadron Collider powers on.*

viously noted, a particle's width is reciprocal to its lifetime and therefore proportional to its decay rate – something that can also be measured by directly accounting for the observed rate of decays to visible particles of all types. The difference between the two numbers is due to Z-boson decays to so-called invisible particles that cannot be reconstructed in the detector. A seminal measurement concluded that exactly three species of light neutrino couple to the Z boson.

The LEP experiments also measured the invisible width of the Z boson using an ingenious method that searched for solitary "recoils". Here, the trick was to look for the rare occasion when the colliding electron or positron emitted a photon just before creating a virtual Z boson that decayed invisibly. Such events would yield nothing more than a single photon recoiling from an otherwise invisible Z-boson decay.

The ATLAS and CMS collaborations recently performed similar measurements, requiring the invisibly decaying Z boson to be produced alongside a highly energetic jet in place of a recoil photon. By taking the ratio with equivalent recoil decays to electrons and muons, they achieved remarkable uncertainties of around 2%, equivalent to LEP, despite the much more challenging environment (see "Invisible width" figure). The results are consistent with the Standard Model's three generations of light neutrinos.

Future outlook

Building on these achievements, the LHC experiments are now readying themselves for a more than comparable experimental programme, which is yet to begin. Following the ongoing run of the LHC, a high-luminosity upgrade (HL-LHC) is scheduled to operate throughout the 2030s, delivering a total integrated luminosity of 3 ab^{-1} to both ATLAS and CMS. The LHCb experiment also foresees a major upgrade to collect an integrated luminosity of more than 300 fb^{-1} by the end of the LHC operations. A tenfold data set, upgraded detectors and experimental methods, and improvements to theoretical modelling will greatly extend both experimental precision and the reach of direct and indirect searches for new physics. Unprecedented energy scales will be probed and anomalies with respect to the Standard Model may become apparent.

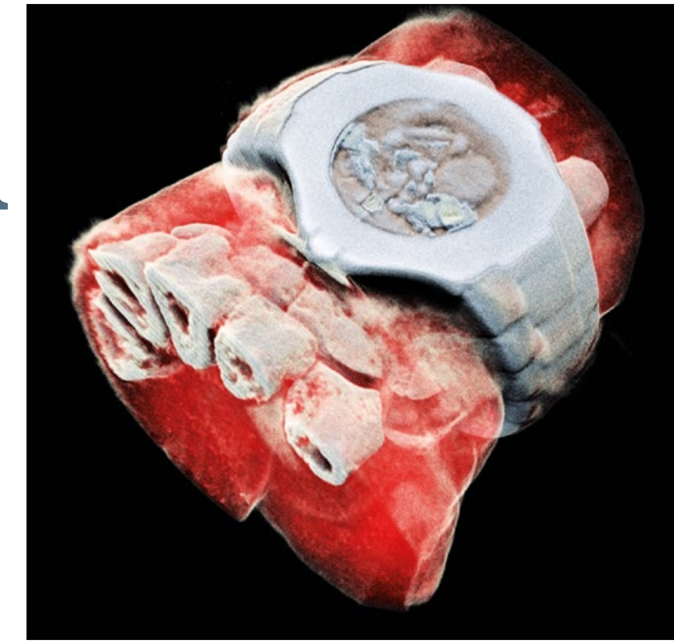
Despite the significant challenges posed by systematic uncertainties, there are good prospects to further improve uncertainties in precision electroweak observables such as the mass of the W boson and the effective weak mixing angle, thanks to the larger angular acceptances of the new inner tracking devices currently under production by ATLAS and CMS. A possible programme of high-precision measurements in electron–proton collisions, the LHeC, could deliver crucial input to reduce uncertainties such as from parton distribution functions. The LHeC has been proposed to run concurrently with the HL-LHC by adding an electron beam to the LHC.

Beyond the HL-LHC programme, several proposals for future particle colliders have captured the imagination of the global particle-physics community – and not least the two phases of the Future Circular Collider (FCC) being studied at CERN. With a circumference three to four times greater than that of the LEP/LHC tunnel, electron–positron collisions could be delivered with very high luminosity and centre-of-mass energies from 90 to 365 GeV in the initial FCC-ee phase. The FCC-ee would facilitate an impressive leap in the precision of most electroweak observables. Projections estimate a factor of 10 improvement for Z-boson measurements and up to 100 for W-boson measurements. For the first time, the top quark could be produced in an environment where it is not colour-connected to initial hadrons, in some cases reducing uncertainties by a factor of 10 or more.

The LHC collaborations have made remarkable strides forward in probing the electroweak theory – a theory of great beauty and consequence for the universe. But its most fundamental workings are subtle and elusive. Our exploration is only just beginning. ●

WATCH OUT FOR HYBRID PIXELS

First developed for the Large Hadron Collider, hybrid pixel detectors are now changing the face of X-ray imaging in medical practice. The next challenge is for a diverse range of societal applications to exploit precise timing at the pixel level, say Rafael Ballabriga, Michael Campbell and Xavier Llopart.



MARS Bioimaging

Time for timing *A spectroscopic X-ray image taken using the Medipix3 chip, in which materials are differentiated using information on the energy of individual photons. Timepix chips also provide the photons' times of arrival, opening up myriad detector applications that are just beginning to be explored.*

In 1885, in a darkened lab in Würzburg, Bavaria, Wilhelm Röntgen noticed that a screen coated with barium platinocyanide fluoresced, despite being shielded from the electron beam of his cathode-ray tube. Hitherto undiscovered "X"-rays were being emitted as the electrons braked sharply in the tube's anode and glass casing. A week later, Röntgen imaged his wife's hand using a photographic plate, and medicine was changed forever. X-rays would be used for non-invasive diagnosis and treatment, and would inspire countless innovations in medical imaging. Röntgen declined to patent the discovery of X-ray imaging, believing that scientific advancements should benefit all of humanity, and donated the proceeds of the first Nobel Prize for Physics to his university.

One hundred years later, medical imaging would once again be disrupted – not in a darkened lab in Bavaria, but in the heart of the Large Hadron Collider (LHC) at CERN. The innovation in question is the hybrid pixel detector, which allows remarkably clean track reconstruction. When the technology is adapted for use in a medical context, by modifying the electronics at the pixel level, X-rays can be individually detected and their energy measured, leading to spectroscopic X-ray images that distinguish between different materials in the body. In this way, black and white medical imaging is being reinvented in full colour, allowing more precise diagnoses with lower radiation doses.

The next step is to exploit precise timing in each pixel. The benefits will be broadly felt. Electron microscopy of biological samples can be clearer and more detailed. Biomolecules can be more precisely identified and quantified by imaging time-of-flight mass spectrometry. Radiation doses can be better controlled in hadron therapy, reducing damage to healthy tissue. Ultra-fast changes can be captured in detail at synchrotron light sources. Hybrid pixel detectors with fast time readout are even being used to monitor quantum-mechanical processes.

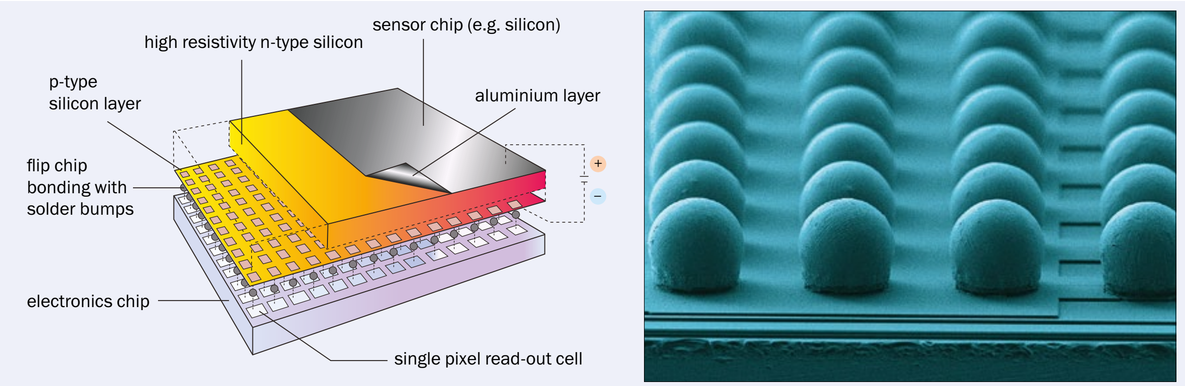
Digital-camera drawbacks

X-ray imaging has come a long way since the photographic plate. Most often, the electronics work in the same way as a cell-phone camera. A scintillating material converts X-rays into visible photons that are detected by light-sensitive diodes connected to charge-integrating electronics. The charge from high-energy and low-energy photons is simply added up within the pixel in the same way a photographic film is darkened by X-rays.

Charge integration is the technique of choice in the flat-panel detectors used in radiology as large surfaces can be covered relatively cheaply, but there are several drawbacks. It's difficult to collect the scintillation light from an X-ray on a single pixel, as it spreads out. And

THE AUTHORS
Rafael Ballabriga, **Michael Campbell** *and* **Xavier Llopart** *CERN.*

CERNCOURIER
VOLUME 64 NUMBER 5 SEPTEMBER/OCTOBER 2024
IOP Publishing



Hybrid pixels *The construction of a hybrid pixel detector (left) and a scanning electron microscope image of a Medipix3 chip with 30 μm-diameter bump bonds deposited (right).*

information about the energy of the X-rays is lost.

By the 1990s, however, LHC detector R&D was driving the development of the hybrid pixel detector, which could solve both problems by detecting individual photons. It soon became clear that "photon counting" could be as useful in a hospital ward as it would prove to be in a high-energy-physics particle detector. In 1997 the Medipix collaboration first paired semiconductor sensors with readout chips capable of counting individual X-rays.

Nearly three decades later, hybrid pixel detectors are making their mark in hospital wards. Parallel to the meticulous process of preparing a technology for medical applications in partnership with industry, researchers have continued to push the limits of the technology, in pursuit of new innovations and applications.

Photon counting

In a hybrid pixel detector, semiconductor sensor pixels are individually fixed to readout chips by an array of bump bonds – tiny balls of solder that permit the charge signal in each sensor pixel to be passed to each readout pixel (see "Hybrid pixels" figure). In these detectors, low-noise pulse-processing electronics take advantage of the intrinsic properties of semiconductors to provide clean track reconstruction even at high rates (see "Semiconductor subtlety" panel).

Since silicon detectors are relatively transparent to the X-ray energies used in medical imaging (approximately 20 to 140 keV), denser sensor materials with higher stopping power are required to capture every photon passing through the patient. This is where hybrid pixel detectors really come into their own. For X-ray photons with an energy above about 20 keV, a highly absorbing material such as cadmium telluride can be used in place of the silicon used in the LHC experiments. Provided precautions are taken to deal with charge sharing between pixels, the number of X-rays in every energy bin can be recorded, allowing each pixel to measure the spectrum of the interacting X-rays.

Protocols regarding the treatment of patients are strictly regulated in the interest of safety, making it challenging to introduce new technologies. Therefore, in parallel with the development of successive generations of Medipix readout chips, a workshop series on the medical applications of spectroscopic X-ray detectors has been hosted at CERN. Now in its seventh edition (see p25), the workshop gathers representatives of cross-disciplinary specialists ranging from the designers of readout chips to specialists in the large equipment suppliers, and from medical physicists all the way up to opinion-leading radiologists. The role of the workshop is the formation and development of a community of practitioners from diverse fields willing to share knowledge – and, of course, reasonable doubts – in order to encourage the transition of spectroscopic photon counting from the lab to the clinic. CERN and the Medipix collaborations have played a pathfinding role in this community, exploring avenues well in advance of their introduction to medical practice.

The Medipix2 (1999–present), Medipix3 (2005–present) and Medipix4 (2016–present) collaborations are composed only of publicly funded research institutes and universities, which helps keep the development programmes driven by science. There have been hundreds of peer-reviewed publications and dozens of PhD theses written by the designers and users of the various chips. With the help of CERN's Knowledge Transfer Office, several start-up companies have been created and commercial licences signed. This has led to many unforeseen applications and helped enormously with the dissemination of the technology. The publications of the clients of the industrial partners now represent a large share of the scientific outcome from these efforts, totalling hundreds of papers.

Spectroscopic X-ray imaging is now arriving in clinical practice. Siemens Healthineers were first to market in 2022 with the Naeotom Alpha photon counting CT scanner, and many of the first users have been making ground-breaking studies exploiting the newly available spectroscopic information in the clinical domain. CERN's Medipix3 chip is at the heart of the MARS Bioimaging scanner, which brings unprecedented imaging performance to the point of patient care, opening up new patient pathways and saving time and money.

ASIC (application-specific integrated circuit) development

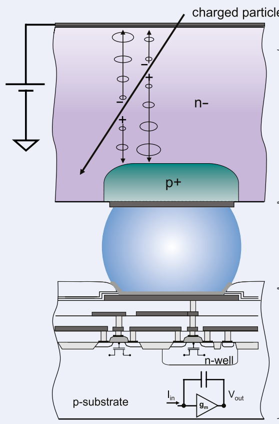
Spectroscopic X-ray imaging is now arriving in clinical practice

Semiconductor subtlety

In insulators, the conduction band is far above the energy of electrons in the valence band, making it difficult for current to flow. In conductors, the two bands overlap and current flows with little resistance. In semiconductors, the gap is a just a couple of electron-volts. Passing charged particles, such as those created in the LHC experiments, promotes thousands of valence electrons into the conduction band, creating positively charged "holes" in the valence band, allowing current to flow.

Silicon has four valence electrons and therefore forms four covalent bonds with neighbouring atoms to fill up its outermost shell in silicon crystals. These crystals can be doped with impurities that either add additional electrons to the conduction band (n-type doping) or additional holes to the valence band (p-type doping). The silicon pixel sensors used at the LHC are made up of rectangular pixels doped with additional holes on one side coupled to a single large electrode doped with additional electrons on the rear (see "Pixel picture" figure).

In p-n junctions such as these, "depletion zones" develop at the pixel boundaries, where neighbouring electrons and holes recombine, generating a natural electric field. The depletion zones can be extended throughout the whole sensor by applying a strong



Pixel picture *In hybrid pixel detectors at the LHC, p-type sensor pixels are embedded in an n-type electrode with a reverse-bias and individually fixed to individual readout chips by an array of bump bonds. (Credit: CERN)*

"reverse-bias" field in the opposite direction. When a charged particle passes, electrons and holes are created as before, but thanks to the field a directed pulse of charge now flows across the bump bond into the readout chip. Charge collection is prompt, permitting the pixel to be ready for the next particle.

In each readout pixel the detected charge pulse is compared with an externally adjustable threshold. If the pulse exceeds the threshold, its amplitude and timing can be measured. The threshold level is typically set to be many times higher than the electronic noise of the detection circuit, permitting noise-free images. Because of the intimate contact between the sensor and the readout circuit, the noise is typically less than a root-mean-square value of 100 electrons, and any signal higher than a threshold of about 500 electrons can be unambiguously detected. Pixels that are not hit remain silent.

In the LHC, each passing particle liberates thousands of electrons, allowing clean images of the collisions to be taken even at very high rates. Hybrid pixels have therefore become the detector of choice in many large experiments where fast and clean images are needed, and are the heart of the ATLAS, CMS and LHCb experiments. In cases where the event rates are lower, such as the ALICE experiment at the LHC and the Belle II experiment at SuperKEKB at KEK in Japan, it has now become possible to use "monolithic" active pixel detectors, where the sensor and readout electronics are implemented in the same substrate. In the future, as the semiconductor industry shifts to three-dimensional chip and wafer stacking, the distinction between hybrid and monolithic pixel detectors will be blurred.

is still moving forwards rapidly in the Medipix collaborations. For example, in the Medipix3 and Medipix4 chips, on-pixel circuitry mitigates the impact of X-ray fluorescence and charge diffusion in the semiconductor by summing up the charge in a localised region and allocating the hit to one pixel. The fine segmentation of the detector not only leads to unprecedented spatial resolution but also mitigates "hole trapping" – a common bugbear of the high-density sensor materials used in medical imaging, whereby photons of the same energy induce different charges according to their interaction depth in the sensor. Where the pixel size is significantly smaller than the perpendicular sensor thickness – as in the Medipix case – only one of the charge species (usually electrons) contributes to the measured charge, and no matter where the X-ray is deposited in the sensor thickness, the total charge detected is the same.

But photon counting is only half the story. Another parameter that has not yet been exploited in high-spatial-resolution medical imaging systems can also be measured at the pixel level.

A new dimension

In 2005, Dutch physicists working with gas detectors requested a modification that would permit each pixel to measure arrival times instead of counting photons. The Medipix2 collaboration agreed and designed a chip with three acquisition modes: photon counting, arrival time and time over threshold, which provides a measure of energy. The Timepix family of pixel-detector readout chips was born.

The most recent generations of Timepix chips, such as Timepix3 (released in 2016) and Timepix4 (released in 2022) stream hit information off chip as soon as it is generated – a significant departure from Medipix chips, which process hits locally, assuming them to be photons, sending only a spectroscopic image off chip. With Timepix, each time a charge exceeds the threshold, a packet of information is sent off chip that contains the coordinates of the hit pixel, the particle's arrival time and the time over threshold (66 bits in total per hit). This allows offline reconstruction of individual clusters of hits, opening up a myriad of potential new applications.

One advantage of Timepix is that particle event reconstruction is not limited to photons. Cosmic muons leave a straight track. Low-energy X-rays interact in a point-like fashion, lighting up only a small number of pixels. Electrons interact with atomic electrons in the sensor material, leaving a curly track. Alpha particles deposit a large quantity of charge in a characteristic blob. To spark the imagination of young people, Timepix chips have been

incorporated on a USB thumb drive that can be read out on a laptop computer (see "Thumb-drive detector" figure). The CERN & Society Foundation is raising funds to make these devices widely available in schools.

Timepix chips have also been adapted to dose monitoring for astronauts. Following a calibration effort by the University of Houston, NASA and the Institute for Experimental and Applied Physics in Prague, a USB device identical to that used in classrooms precisely measures the doses experienced by flight crews in space. Timepix is now deployed on the International Space Station (see "Radiation monitoring" figure), the Artemis programme and several European space-weather studies, and will be deployed on the Lunar Gateway programme.

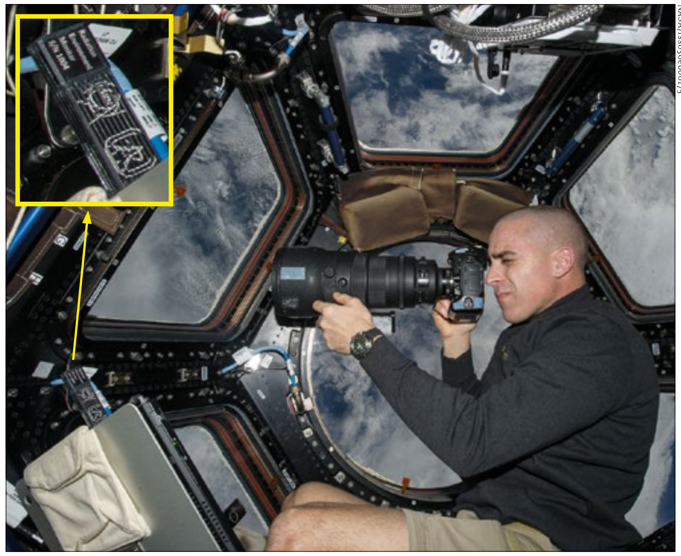
Stimulating innovation

Applications in science, industry and medicine are too numerous to mention in detail. In time-of-flight mass spectrometry, the vast number of channels allowed by Timepix promises new insights into biomolecules. Large-area time-resolved X-ray cameras are valuable at synchrotrons, where they have applications in structural biology, materials science, chemistry and environmental science. In the aerospace, manufacturing and construction industries, non-destructive X-ray testing using backscattering can probe the integrity of materials and structures while requiring access from one side only. Timepix chips also play a crucial role in X-ray diffraction for materials analysis and medical applications such as single-photon-emission computed tomography (SPECT), and beam tracking and dose-deposition monitoring in hadron therapy (see "Carbon therapy" figure). The introduction of noise-free hit streaming with timestamp precision down to 200 picoseconds has also opened up entirely new possibilities in quantum science, and early applications of Timepix3 in experiments exploring the quantum behaviour of particles are already being reported. We are just beginning to uncover the potential of these innovations.

It's also important to note that applications of the Timepix chips are not limited to the readout of semiconductor pixels made of silicon or cadmium telluride. A defining feature of hybrid pixel detectors is that the same readout chip can be used with a variety of sensor materials and structures. In cases where visible photons are to be detected, an electron can be generated in a photocathode and then amplified using a micro-channel plate. The charge cloud from the micro-channel plate is then detected on a bare readout chip in much the same way as the charge cloud in a semiconductor sensor. Some gas-filled detectors are constructed using gas electron multipliers and micromegas foils, which amplify charge passing through holes in the foils. Timepix chips can be used for readout in place of the conventional pad arrays, providing much higher spatial and time resolution than would otherwise be available.

Successive generations of Timepix and Medipix chips have followed Moore's law, permitting more and more circuitry to be fitted into a single pixel as the minimum feature size of transistors has shrunk. In the Timepix3 and

Thumb-drive detector *Timepix has been adapted for physics education. Here, Xènia Turró, a student from INS Vilafant near Barcelona, uses a Timepix-based thumb-drive detector to observe radiation in the environment.*



Radiation monitoring *Astronaut Chris Cassidy working near the Timepix USB (see inset) on the International Space Station (ISS). Timepix devices have been running continuously on the ISS since 2012.*

Timepix4 chips, data-driven architecture and on-pixel time stamping are the unique features. The digital circuitry of the pixel has become so complex that an entirely new approach to chip design – "digital-on-top" – was employed. These techniques were subsequently deployed in ASIC developments for the LHC upgrades.

Just as hybrid-pixel R&D at the LHC has benefitted societal applications, R&D for these applications now benefits fundamental research. Making highly optimised chips available to industry "off the shelf" can also save substantial time and effort in many applications in fundamental research, and the highly integrated R&D model whereby detector designers keep one foot in both camps

CERNCOURIER
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We have a duty to make our advancements available to a larger community than our own


Heidelberg University Hospital/H Schroeder

Carbon therapy *Medical physicists Maria Martišíková and Laurent Kelleter prepare to monitor dose delivery by tracking secondary particles using a Timepix3-based camera visible behind the patient.*

generates creativity and the reciprocal sparking of ideas and sharing of expertise. Timepix3 is used as readout of the beam–gas-interaction monitors at CERN's Proton Synchrotron and Super Proton Synchrotron, providing non-destructive images of the beams in real time for the first time. The chips are also deployed in the ATLAS and MoEDAL experiments at the LHC, and in numerous small-scale experiments, and Timepix3 know-how helped develop the VeloPix chip used in the upgraded tracking system for the LHCb experiment. Timepix4 R&D is now being applied to the development of a new generation of readout chips for future use at CERN, in applications where a time bin of 50 ps or less is desired.

All these developments have relied on collaborating research organisations being willing to pool the resources needed to take strides into unexplored territory. The effort has been based on the solid technical and administrative infrastructure provided by CERN's experimental physics department and its knowledge transfer, finance and procurement groups, and many applications have been made possible by hardware provided by the innovative companies that license the Medipix and Timepix chips.

With each new generation of chips, we have pushed the boundaries of what is possible by taking calculated risks ahead of industry. But the high-energy-physics community is under intense pressure, with overstretched resources. Can blue-sky R&D such as this be justified? We believe, in the spirit of Röntgen before us, that we have a duty to make our advancements available to a larger community than our own. Experience shows that when we collaborate across scientific disciplines and with the best in industry, the fruits lead directly back into advancements in our own community. ●

15th Anniversary of CIVIDEC Instrumentation

by Erich Griesmayer

15 years of CIVIDEC Instrumentation is a good time to look back and take stock!

CIVIDEC Instrumentation was founded in 2009 in Vienna, Austria. We had the aim of designing beam diagnostics devices based on diamond detectors with dedicated electronics and readout systems.

After the incident of the LHC during its start-up phase, when the machine suffered severe damage due to a quench of a superconducting magnet, the Beam Instrumentation Group, headed by the late Bernd Dehning, asked for our help.

A super fast beam diagnostic system was requested for bunch-to-bunch beam loss analysis. The beam bunch spacing of 25 ns meant that diamond was the only candidate for this innovative type of beam loss detectors.

Its response time of 1-2 ns, sensitivity to single MIP particles and its vast dynamic range of nine decades, made it the ideal detector material.

During this period we also created RF-tight packaging against EMI and learned how to apply the internal circuit with charging capacitors for the fast readout and filters for the bias supply of 500 V. The design of our C2 Diamond Broadband Amplifier had to be based on 2 GHz technology and radiation-hard components. Our prototype readout system **ROSY®** was developed for the real-time diagnostics of bunched beam losses. The detectors were initially tested at the SPS, before they were mounted in the collimation area at point 7. Results were successful and led to our first product, the Diamond Beam Loss Monitor. These were mounted in the LHC and in all its pre-accelerators.

The CIVIDEC Broadband Amplifier as used for the LHC Diamond Beam Loss Detectors.

Five years later, in 2014, we were invited by Günther Rehm, the former head of the Diagnostics Group of the Diamond Light Source, to develop a diamond-based beam position monitor for the experimental X-ray beams of synchrotron light sources.

Working with X-rays was completely new to us. After completing a steep learning curve, we were able to produce diamond membranes with 20 µm thickness and transparent four-quadrant electrodes separated by a gap of only 1 µm for low absorption at low X-ray energies.

The highest precision was attained with our Diamond XBPM® and we were the first to publish a position resolution of 0.37 nm.

In parallel, **CIVIDEC Instrumentation** started to work on the diagnostics of neutrons. We supported the work of Christina Weiss in developing the Diamond Mosaic Detector and the famous Cx-L Spectroscopic Amplifier for her experimental work at the n_TOF facility at CERN. The campaign was extremely successful, and the cross section of $^{59}Ni(n,\alpha)^{56}Fe$ was experimentally validated.

At present **CIVIDEC Instrumentation** is specialising in neutron diagnostics for nuclear fusion facilities and provides solutions for DD and DT fusion diagnostics.

The measurement of the fusion plasma temperature of 100 million centigrade has become our specialty. We provide the Neutron Diagnostics Systems, composed of detectors, amplifiers and real-time readout systems.

We are proud to present our innovations in the fields of beam loss diagnostics for HEP and medical machines, X-ray diagnostics for experimental beamlines and neutron diagnostics for fusion applications.

Today CIVIDEC is the worldwide leader in these domains.

CIVIDEC Instrumentation specialises in beam diagnostics in the fields of:

- beam loss diagnostics for HEP and medical machines
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Erich Griesmayer is CEO of CIVIDEC Instrumentation and has been working at CERN for more than 30 years. He is associated professor at the Vienna University of Technology and Member of n_TOF at CERN.

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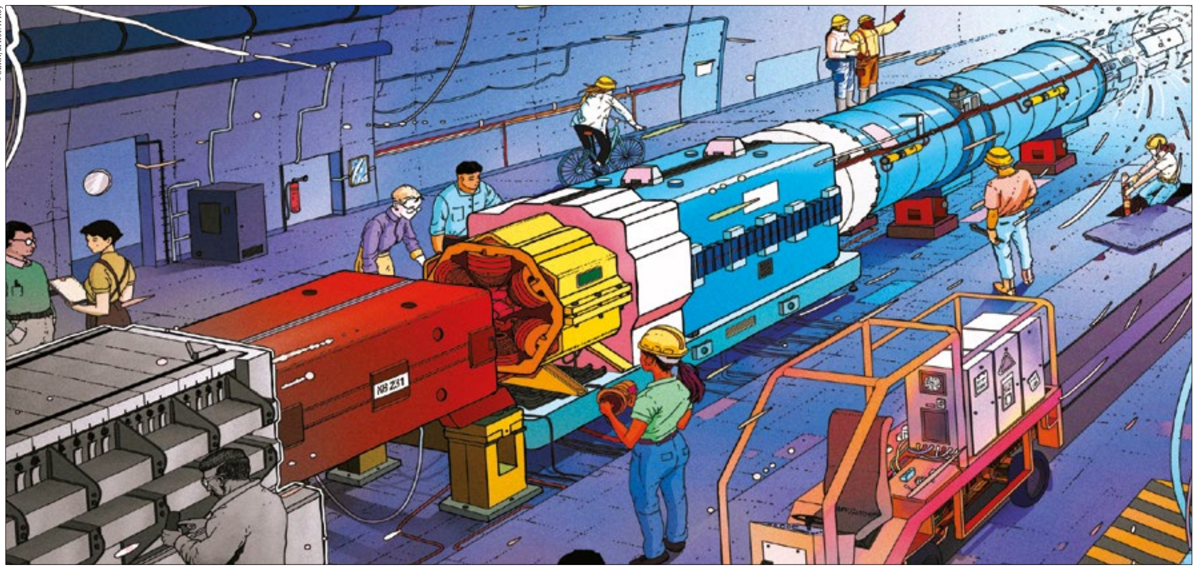
VOICES FROM A NEW GENERATION

Early-career researchers tell the *Courier* what they think is the key strategic issue for the future of high-energy physics.



Accelerating into the future *Seventy years after construction began on CERN's still-operational Proton Synchrotron (above, left), a new generation of researchers is being called upon to help conceive a programme for the next 70 years of high-energy physics.*

In January 1962, CERN was for the first time moving from machine construction to scientific research with the machines. Director-General Victor Weisskopf took up the pen in the first *CERN Courier* after a brief hiatus. "This institution is remarkable in two ways," he wrote. "It is a place where the most fantastic experiments are carried out. It is a place where international co-operation actually exists."

A new generation of early-career researchers (ECRs) shares his convictions. Now, as then, they do much of the heavy lifting that builds the future of the field. Now, as then, they need resilience and vision. As Weisskopf wrote in these pages, the everyday work of high-energy physics (HEP) can hide its real importance – its romantic glory, as the renowned theorist put it. "All our work is for an idealistic aim, for pure science without commercial or any other interests. Our effort is a symbol of what science really means."

As CERN turns 70, the *Courier* now hands the pen to the field's next generation of leaders. All are new post-docs. Each has already made a tangible contribution and earned recognition from their colleagues. All, in short, are among the most recent winners of the four big LHC collaborations' thesis prizes. Each was offered carte blanche to write about a subject of their choosing, which they believe will be strategically crucial to the future of the field. Almost all responded. These are their viewpoints.

Invest in accelerator innovation

M Montella

I come from Dallas, Texas, so the Superconducting Super Collider should have been in my backyard as I was growing up. By the late 1990s, its 87 km ring could have delivered 20 TeV per proton beam. The Future Circular Collider could deliver 50 TeV per proton beam in a 91 km ring by the 2070s. I'd be retired before first collisions. Clearly, we need an intermediate-term project to keep expertise in our community. Among the options proposed so far, I'm most excited by linear electron–positron colliders, as they would offer sufficient energy to study the Higgs self-coupling via di-Higgs production. This could be decisive in understanding electroweak symmetry breaking and unveiling possible Higgs portals.

A paradigm shift for accelerators might achieve our physics goals without a collider's cost scaling with its energy. A strong investment in collider R&D could therefore offer hope for my generation of scientists to push back the energy frontier. Muon colliders avoid synchrotron radiation. Plasma wakefields offer a 100-fold increase in electric field gradient. Though both represent enormous challenges, psychologists have noted an "end of history" phenomenon, whereby as humans we appreciate how much we have changed in the past, but underestimate how much we will change in the future. Reflecting on the past physics breakthroughs galvanises me to optimism: unlocking the next chapter of physics has always been within the reach of technological innovation. CERN has been a mecca for accelerator applications in the last 70 years. I'd argue that a strong increase in support for novel collider R&D is the best way to carry this legacy forwards.

Nicole Hartman *is a post-doc at the Technical University of Munich and Origins Data Science Lab. She was awarded a PhD by Stanford University for her thesis "A search for non-resonant HH → 4b at $\sqrt{s}$ = 13 TeV with the ATLAS detector – or – 2b, and then another 2b… now that's the thesis question".*

Reward technical work with career opportunities

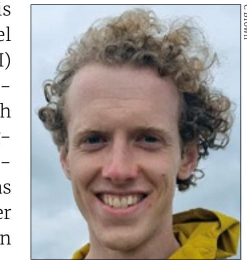
A Scarabotto

This job is a passion and a privilege, and ECRs devote nights and weekends to our research. But this energy should be handled in a more productive way. In particular, technical work on hardware and software is not valued and rewarded as it should be. ECRs who focus on technical aspects are often forced to divide their focus with theoretical work and data analysis, or suffer reduced opportunities to pursue an academic career. Is this correct? Why shouldn't technical and scientific work be valued in the same way?

I am very hopeful for the future. In recent years, I have seen improvements in this direction, with many supervisors increasingly pushing their students towards technical work. I expect senior leadership to make organisational adjustments to reward and value these two aspects of research in exactly the same way. This cultural shift would greatly benefit our physics community by more efficiently transforming the enthusiasm and hard work of ECRs into skilled contributions to the field that are sustained over the decades.

Alessandro Scarabotto *is a postdoctoral researcher at Technische Universität Dortmund. He was awarded a PhD by Sorbonne Université, Paris, for his thesis "Search for rare four-body charm decays with electrons in the final state and long track reconstruction for the LHCb trigger".*

A revolving door to industry



C Brown

Big companies' energy usage is currently skyrocketing to fuel their artificial intelligence (AI) systems. There is a clear business adaptation of my research on fast, energy-saving AI triggers, but I feel completely unable to make this happen. Why, as a field, are we unable to transfer our research to industry in an effective way?

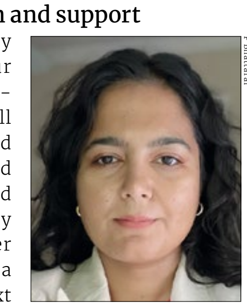
While there are obvious milestones for taking data to publication, there is no equivalent for starting a business or getting our research into major industry players. Our collaborations are incubators for ideas and people. They should implement dedicated strategies to help ECRs obtain the funding, professional connections and business skills they need to get their ideas into the wider world. We should be presenting at industry conferences – both to offer solutions to industry and to obtain them for our own research – and industry sessions within our own conferences could bring links to every part of our field.

Most importantly, the field should encourage a revolving door between academia and industry to optimise the transfer of knowledge and skills. Unfortunately, when physicists leave for industry, slow, single-track physics career progressions and our focus on publication count rather than skills make a return unrealistic. There also needs to be a way of attracting talent from industry into physics without the requirement of a PhD so that experienced people can start or return to research in high-profile positions suitable for their level of work and life experience.

The field should encourage a revolving door between academia and industry to optimise the transfer of knowledge and skills

Christopher Brown *is a CERN fellow working on next-generation triggers. He was awarded a PhD by Imperial College London for his thesis "Fast machine learning in the CMS Level-1 trigger for the High-Luminosity LHC".*

Collaboration, retention and support



P Bhattarai

I feel a strong sense of agency regarding the future of our field. The upcoming High-Luminosity LHC (HL-LHC) will provide a wealth of data beyond what the LHC has offered, and we should be extremely excited about the increased discovery potential. Looking further ahead, I share the vision of a future Higgs factory as the next

If future experiments want to attract diverse talent, they should consider new collaborative models that allow participation irrespective of a person's institution or country of origin

logical step for the field. The proposed Future Circular Collider is currently the most feasible option. However, the high cost and evolving geopolitical landscape are causes for concern. One of the greatest challenges we face is retaining talent and expertise. In the US, it has become increasingly difficult for researchers to find permanent positions after completing postdocs, leading to a loss of valuable technical and operational expertise. On a positive note, our field has made significant strides in providing opportunities for students from underrepresented nationalities and socioeconomic backgrounds – I am a beneficiary of these efforts. Still, I believe we should intensify our focus on supporting individuals as they transition through different career stages to ensure a vibrant and diverse future workforce.

Prajita Bhattarai *is a research associate at SLAC National Accelerator Laboratory in the US. She was awarded her PhD by Brandeis University in the US for her thesis "Standard Model electroweak precision measurements with two Z bosons and two jets in ATLAS".*

Redesign collaborations for equitable opportunity

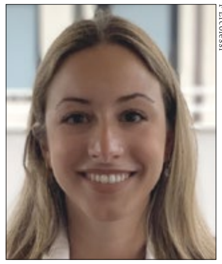
S Mondal

Particle physics and cosmology capture the attention of nearly every inquisitive child. Though large collaborations and expensive machines have produced some of humankind's most spectacular achievements, they have also made the field inaccessible to many young students. Making a meaningful contribution is contingent upon being associated with an institution or university that is a member of an experimental collaboration. One typically also has to study in a country that has a cooperation agreement with an international organisation like CERN.

If future experiments want to attract diverse talent, they should consider new collaborative models that allow participation irrespective of a person's institution or country of origin. Scientific and financial responsibilities could be defined based on expertise and the research grants of individual research groups. Remote operations centres across the globe, such as those trialled by CERN experiments, could enable participants to fulfil their responsibilities without being constrained by international borders and travel budgets; the worldwide revolution in connectivity infrastructure could provide an opportunity to make this the norm rather than the exception. These measures could provide equitable opportunities to everyone while simultaneously maximising the scientific output of our field.

Spandan Mondal *is a postdoctoral fellow at Brown University in the US. He was awarded a PhD by RWTH Aachen in Germany for his thesis on the CMS experiment "Charming decays of the Higgs, Z, and W bosons: development and deployment of a new calibration method for charm jet identification".*

Reward risk taking



F Ercolessi

Young scientists often navigate complex career paths, where the pressure to produce consistent publishable results can stifle creativity and discourage risk taking. Traditionally, young researchers are evaluated almost solely on achieved results, often leading to a culture of risk aversion. To foster a culture of innovation we must shift our approach to research and evaluation. To encourage bold and innovative thinking among ECRs, the fuel of scientific progress, we need to broaden our definition of success. European funding and grants have made strides in recognising innovative ideas, but more is needed. Mentorship and peer-review systems must also evolve, creating an environment open to innovative thinking, with a calculated approach to risk, guided by experienced scientists. Concrete actions include establishing mentorship programmes during scientific events, such as workshops and conferences. To maximise the impact, these programmes should prioritise diversity among mentors and mentees, ensuring that a wide range of perspectives and experiences are shared. Equally important is recognising and rewarding innovation. This can be achieved by dedicated awards that value originality and potential impact over guaranteed success. Celebrating attempts, even failed ones, can shift the focus from the outcome to the process of discovery, inspiring a new generation of scientists to push the boundaries of knowledge.

Francesca Ercolessi *is a post-doc at the University of Bologna. She was awarded a PhD by the University of Bologna for her thesis "The interplay of multiplicity and effective energy for (multi) strange hadron production in pp collisions at the LHC".*

Our employment model stifles creativity

F Jonas

ECR colleagues are deeply passionate about the science they do and wish to pursue a career in our field – "if possible". Is there anything one can do to better support this new generation of physicists? In my opinion, we have to address the scarcity of permanent positions in our field. Short-term contracts lead to risk aversion, and short-term projects with a high chance of publication increase your employment prospects. This is in direct contrast to what is needed to successfully complete ambitious future projects this century – projects that require innovation and out-of-the-box thinking by bright young minds.

In addition, employment in fundamental science is more than ever in direct competition with permanent jobs in industry. For example, machine learning and computing experts innovate our field with novel analysis techniques, but end up ultimately leaving our field to apply their skills in permanent employment elsewhere. If we want to keep talent in our field we must create a funding structure that allows realistic prospects for long-term employment and commitment to future projects.

Florian Jonas *is a postdoctoral scholar at UC Berkeley and LBNL. He was awarded a PhD by the University of Münster for his thesis on the ALICE experiment "Probing the initial state of heavy-ion collisions with isolated prompt photons".*

Embrace private expertise and investment

J Motta

The two great challenges of our time are data taking and data analysis. Rare processes like the production of Higgs-boson pairs have cross sections 10 orders of magnitude smaller than their backgrounds – and during HL-LHC operation the CMS trigger will have to analyse about 50 TB/s and take decisions with a latency of 12.5 µs. In recent years, we have made big steps forward with machine learning, but our techniques are not always up to speed with the current state-of-the-art in the private sector.

To sustain and accelerate our progress, the HEP community must be more open to new sources of funding, particularly from private investments. Collaborations with tech companies and private investors can provide not only financial support but also access to advanced technologies and expertise. Encouraging CERN-private partnerships can lead to the development of innovative tools and infrastructure, driving the field forward.

The recent establishment of the Next Generation Trigger Project, funded by the Eric and Wendy Schmidt Fund for Strategic Innovation, represents the first step toward this kind of collaboration. Thanks to overlapping R&D interests, this could be scaled up to direct partnerships with companies to introduce large and sustained streams of funds. This would not only push the boundaries of our knowledge but also inspire and support the next generation of physicists, opening new tenured positions thanks to private funding.

Jona Motta *is a post-doc at Universität Zürich. He was awarded a PhD by Institut Polytechnique de Paris for his thesis "Development of machine learning based τ trigger algorithms and search for Higgs boson pair production in the bbττ decay channel with the CMS detector at the LHC".*

Stability would stop the brain drain

H El Jarrari

The proposed Future Circular Collider presents a formidable challenge. Every aspect of its design, construction, commissioning and operations would require extensive R&D to achieve the needed performance and stability, and fully exploit the machine's potential. The vast experience acquired at the LHC will play a significant role. Knowledge must be preserved and transmitted between generations. But the loss of expertise is already a significant problem at the LHC.

The main reason for young scientists to leave the field is the lack of institutional support: it's hard to count on a stable working environment, regardless of our expertise and performance. The difficulty in finding permanent academic or research positions and the lack of recognition and advancement are all viewed as serious obstacles to pursuing a career in HEP. In these conditions, a young physicist might find competitive sectors such as industry or finance more appealing given the highly stable future they offer.

It is crucial to address this problem now for the HL-LHC. Large HEP collaborations should be more supportive to ensure better recognition and career advancement towards permanent positions. This kind of policy could help to retain young physicists and ensure they continue to be involved in the current HEP projects that would then define the success of the FCC.

Hassnae El Jarrari *is a CERN research fellow in experimental physics. She was awarded a PhD by Université Mohammed-V De Rabat for her thesis "Dark photon searches from Higgs boson and heavy boson decays using pp collisions recorded at $\sqrt{s}$ = 13 TeV with the ATLAS detector at the LHC and performance evaluation of the low gain avalanche detectors for the HL-LHC ATLAS high-granularity timing detector".*

Reduce environmental impacts

L Quaglia

The main challenge for the future of large-scale HEP experiments is reducing our environmental impact, and raising awareness is key to this. For example, before running a job, the ALICE computing grid provides an estimate of its CO_2-equivalent carbon footprint, to encourage code optimisation and save power.

I believe that if we want to thrive in the future, we should adopt a new way of doing physics where we think critically about the environment. We should participate in more collaboration meetings and conferences remotely, and promote local conferences that are reachable by train.

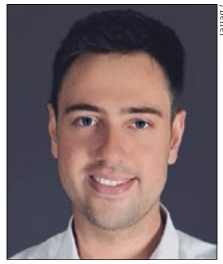
I'm not saying that we should ban air travel *tout court*. It's especially important for early-career scientists to get their name out there and to establish connections. But by attending just one major international conference in person every two years, and publicising alternative means of communication, we can save resources and travel time, which can be invested in our home institutions. This would also enable scientists from smaller groups with reduced travel budgets to attend more conferences and disseminate their findings.

Luca Quaglia *is a postdoctoral fellow at the Istituto Nazionale di Fisica Nucleare, Sezione di Torino. He was awarded his PhD by the University of Torino for his thesis "Development of eco-friendly gas mixtures for resistive plate chambers".*

To sustain and accelerate our progress, the HEP community must be more open to new sources of funding, particularly from private investments

It is in the interest of the community to retain top talent by creating more attractive and secure career paths

Invest in software and computing talent


J Beirer

With both computing and human resources in short supply, funds must be invested wisely. While scaling up infrastructure is critical and often seems like the simplest remedy, the human factor is often overlooked. Innovative ideas and efficient software solutions require investment in training and the recruitment of skilled researchers.

This investment must start with a stronger integration of software education into physics degrees. As the boundaries between physics and computer science blur, universities must provide a solid foundation, raise awareness of the importance of software in HEP and physics in general, and promote best practices to equip the next generation for the challenges of the future. Continuous learning must be actively supported, and young researchers must be provided with sufficient resources and appropriate mentoring from experienced colleagues.

Software skills remain in high demand in industry, where financial incentives and better prospects often attract skilled people from academia. It is in the interest of the community to retain top talent by creating more attractive and secure career paths. After all, a continuous drain of talent and knowledge is detrimental to the field, hinders the development of efficient software and computing solutions, and is likely to prove more costly in the long run.

Joshua Beirer *is a CERN research fellow in the offline software group of the ATLAS experiment and part of the lab's strategic R&D programme on technologies for future experiments. He was awarded his PhD by the University of Göttingen for his thesis "Novel approaches to the fast simulation of the ATLAS calorimeter and performance studies of track-assisted reclustered jets for searches for resonant* $X \to SH \to bbWW^*$ *production with the ATLAS detector".*

Strengthen international science


E.D. Lesser

HEP is at an exciting yet critical inflection point. The coming years hold both unparalleled opportunities and growing challenges, including an expanding arena of international competition and the persistent issue of funding and resource allocation. In a swiftly evolving digital age, scientists must rededicate themselves to public service, engagement and education, informing diverse communities about the possible technological advancements of HEP research, and sharing with the world the excitement of discovering fundamental knowledge of the universe. Collaborations must be strengthened across international borders and political lines, pooling resources from multiple countries to traverse cultural gaps and open the doors of scientific diplomacy. With ever-increasing expenses and an uncertain political future, scientists must insist upon the importance of public research irrespective of any national agenda, and reinforce scientific veracity in a rapidly evolving world that is challenged by growing misinformation. Most importantly, the community must establish global priorities in a maturing age of precision, elevating not only new discoveries but the necessary scientific repetition to better understand what we discover.

The most difficult issues facing HEP research today are addressable and furthermore offer excellent opportunities to develop the scientific approach for the next several decades. By tackling these issues now, scientists can continue to focus on the mysteries of the universe, driving scientific and technological advancements for the betterment of all.

Ezra D. Lesser *is a CERN research fellow working with the LHCb collaboration. He was awarded his PhD in physics by the University of California, Berkeley for his thesis: Measurements of jet substructure in pp and Pb–Pb collisions at* $\sqrt{s_{NN}} = 5.02$ *TeV with ALICE".*

Recognise R&D


S Clawson

ECRs must drive the field's direction by engaging in prospect studies for future experiments, but dedicating time to this essential work comes at the expense of analysing existing data – a trade-off that can jeopardise our careers. With most ECRs employed on precarious two-to-four year contracts, time spent on these studies can result in fewer high-profile publications, making it harder to secure our next academic position. Another important factor is the unprecedented timescales associated with many prospective futures. Those working on R&D today may never see the fruits of their labour.

Anxieties surrounding these issues are often misinterpreted as disengagement, but nothing could be further from the truth. In my experience, ECRs are passionate about research, bringing fresh perspectives and ideas that are crucial for advancing the field. However, we often struggle with institutional structures that fail to recognise the breadth of our contributions. By addressing longstanding issues surrounding attitudes toward work–life balance and long-term job stability – through measures such as establishing enforced minimum contract durations, as well as providing more transparent and diverse sets of criteria for transitioning to permanent positions – we can create a more supportive environment where HEP thrives, driven by the creativity and innovation of its next generation of leaders.

Savannah Clawson *is a postdoctoral fellow at DESY Hamburg. She was awarded her PhD by the University of Manchester for her thesis "The light at the end of the tunnel gets weaker: observation and measurement of photon-induced* W^+W^- *production at the ATLAS experiment".*

High-Voltage Pulse Stability Measurement of Klystron Modulators

Klystron modulators are key elements in free electron lasers. They provide high-voltage pulses to bias klystron tubes with energies of several hundred joules. Amplitude variations directly affect the gain and phase of amplified RF pulses and therefore the accelerating fields created by RF cavities. A huge effort is put into minimising these variations with both klystron modulators and RF pulse regulation.

For machines such as the SwissFEL (Swiss Free Electron Laser), the required HV pulse stability is 15 ppm (parts per million). Stability is calculated from measurements of 100 consecutive pulses taken at a repetition rate of 100 Hz as the relative standard deviation of gated averages with respect to a mean pulse amplitude. The measurement gate is located around the maximum plateau of the pulse, the so-called flat-top region, during which the RF pulse is fired.

A common technique for measuring such small variations involves pulse offsetting and magnification of the flat-top region in order to achieve a sufficient quantisation resolution. However, signal conditioning requires low-noise analogue electronics in the form of summing amplifiers and clippers with sufficient bandwidth and settling time. Such a set-up has so far involved the use of an external differential amplifier for signal conditioning and a high-end scope with statistical analysis functionality. The resolution of this set-up makes it possible to measure stability down to around 7 ppm, and it is mounted on a trolley so that it can be shared between RF stations.

Starting as an apprentice project, the aim was to consolidate such a bulky and extensive set-up into an embedded unit that could be integrated into any pulse modulator cabinet, allowing permanent live monitoring of pulse stability. As a versatile data-acquisition system with open source firmware / software and small size, the Red Pitaya device is a perfect fit for this application. Figure 1 shows the block diagram of how a Red Pitaya STEMlab 125-14 4-input board, connected to a signal conditioning board developed at PSI, is used to measure the pulse stability of klystron modulators.

Pulse current and voltage are measured simultaneously, while only the voltage signal is used for the stability statistics. The required pulse offset voltage is automatically set by a precision 16-bit DAC before the statistics are calculated. There is a gain factor of 20 (26 dB) between the full range pulse voltage on channel 3 and the flat-top voltage on channel 4, giving a theoretical increase in resolution of 4.3 bits. In principle, this gain can be increased further to give an even higher resolution, but in practice the pulse is not purely rectangular but has a dynamic range due to pulse droop and non-flatness. Figure 2 shows how real waveforms might look in operation. The yellow trace shows the pulse current, while the red and blue traces show the full-range and magnified flat-top pulse voltages, respectively.
The set-up presented here was able to measure pulse stability of 7–8 ppm in operation, with a resolution limit of 5–6 ppm at a 1 µs gate length and 67% of ADC full scale.

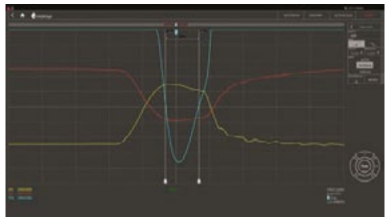


Figure 2: Waveforms after automatic CVD offset adjustment with a 1 µs measurement gate.

The software running on the Red Pitaya is built around the standard C API and includes the OPC-UA stack from open62541.org to allow communication and data transfer via the server and client approach. The integration into our control system environment (EPICS) is currently on-going.

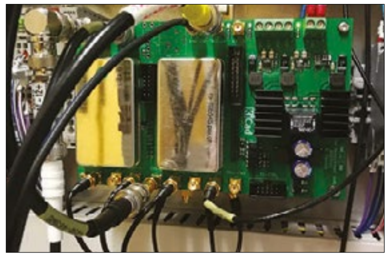


Figure 3: Pulse Measurement Unit.

The complete assembly is called a Pulse Measurement Unit (PMU), and it offers many additional features such as the regulation of a high-voltage charging power supply, interfacing with opto-isolated IOs and a low-jitter PLL in order to lock external synchronisation frequencies to generate a synchronised ADC clock. With an overall size of 160 x 100 mm, the unit fits easily in a Eurocard rack or can be mounted on a DIN rail, as shown in Figure 3.

Authors: Alexander Dietrich, Jürgen Alex, Paul Scherrer – Institut, 5232 Villigen PSI, Switzerland

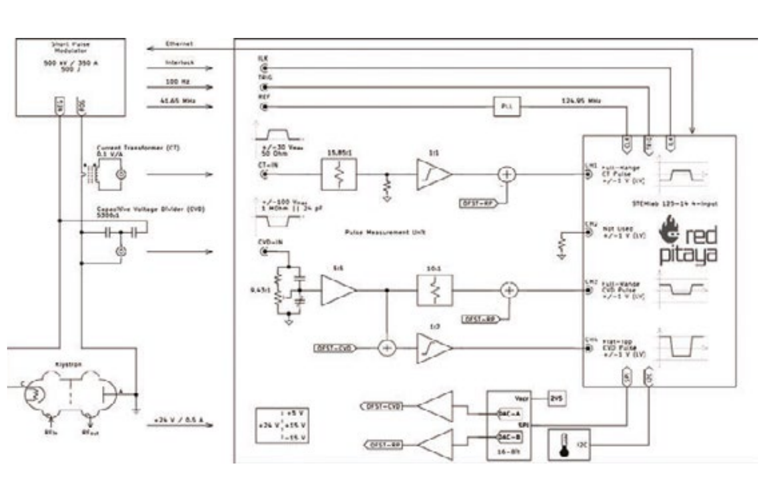


Figure 1: Block schematic of the measurement setup.

BACK TO THE FUTURE

The *Courier* matched photos from CERN's first 25 years to current experts and asked them to reflect on how much has changed across 70 years of science.

The past seven decades have seen remarkable cultural and technological changes. And CERN has been no passive observer. From modelling European cooperation in the aftermath of World War II to democratising information via the web and discovering a field that pervades the universe, CERN has nudged the zeitgeist more than once since its foundation in 1954.

It's undeniable, though, that much has stayed the same. A high-energy physics lab still needs to be fast, cool, collaborative, precise, practically useful, deep, diplomatic, creative and crystal clear. *Plus ça change, plus c'est la même chose*.

This selection of (lightly colourised) snapshots from CERN's first 25 years, accompanied by expert reflections from across the lab, show how things have changed in the intervening years – and what has stayed the same.

1960

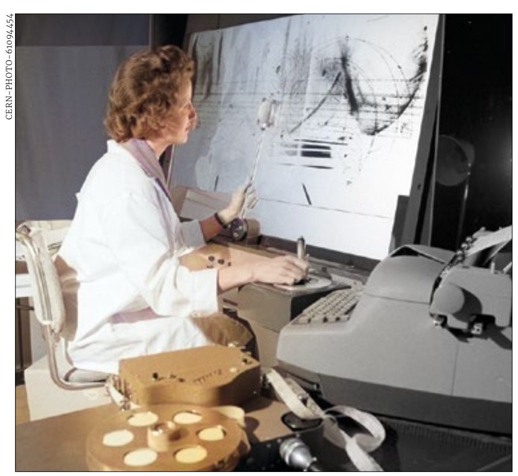
The discovery that electrons and muons possess spin that precesses in a magnetic field has inspired generations of experimentalists and theorists to push the boundaries of precision. The key insight is that quantum effects modify the magnetic moment associated with the particles' spins, making their gyromagnetic ratios (g) slightly larger than two, the value predicted by Dirac's equation. For electrons, these quantum effects are primarily due to the electromagnetic force. For muons, the weak and strong forces also contribute measurably – as well, perhaps, as unknown forces. These measurements stand with the most beautiful and precise of all time, and their history is deeply intertwined with that of the Standard Model.

CERN physicists Francis Farley and Emilio Picasso were pioneers and driving forces behind the muon g–2 experimental programme. The second CERN experiment (pictured on the next page) introduced the use of a 5 m diameter magnetic storage ring. Positive muons with 1.3 GeV momentum travelled around the ring until they decayed into positrons whose directions were correlated with the spin of the parent muons. The experiment tested the muon's anomalous magnetic moment (g–2) with a precision of 270 parts per million. A brilliant concept, the "magic gamma", was then introduced in the third CERN experiment in the late 1970s: by using muons at a momentum of 3.1 GeV, the effect of electric fields on the precession frequency cancelled out, eliminating a major source of systematic error. All subsequent experiments have relied on this principle, with the exception of an experiment using ultra-cold muons that is currently under

construction in Japan. A friendly rivalry for precision between experimentalists and theorists continues today (p21), with the latest measurement at Fermilab achieving a precision of 190 parts per *billion*.
Andreas Hoecker *is spokesperson for the ATLAS collaboration.*

1961

The excitement of discovering new fundamental particles and forces made the 1950s and 1960s a golden era for particle physicists. A lot of creative energy was channelled into making new particle detectors, such as the liquid hydrogen (or heavier liquid) bubble chambers that paved the way to discoveries such as neutral currents, and seminal studies of neutrinos and strange and charmed baryons. As particles pass through, they make the liquid boil, producing bubbles that are captured to form images. In 1961, each had to be painstakingly inspected by hand, as depicted here, to determine the properties of each particle. Fortunately, in the decades since, physicists have found ways to preserve the level of detail they offer and build on this inspiration to prepare new technologies. Liquid–argon time-projection chambers such as CERN's DUNE prototypes, which are currently the largest of their kind in the world, effectively give us access to bubble-chamber images in full colour, with



the colour representing energy deposition (*CERN Courier* July/August 2024 p41). Millions of these images are now analysed algorithmically – essential, as DUNE is expected to generate one of the highest data rates in the world.
Laura Munteanu *is a CERN staff scientist working on the T2K and DUNE experiments.*

1965

The photograph on the first page of this article shows the first experiment at CERN to use a superconducting magnet. The pictured physicist is adjusting a cryostat containing a stack of nuclear emulsions surrounded by a liquid–helium-cooled superconducting niobium–zirconium electromagnet. A pion beam from CERN's synchrocyclotron passes through the quadrupole magnet at the right, collimated by the pile of lead bricks and detected by a small plastic scintillation counter before entering the cryostat. In this study of double charge exchange from π^+ to π^- in nuclear emulsions, the experiment consumed between one and two litres of liquid helium per hour from the container in the left foreground, with the vapour being collected for reuse (*CERN Courier* August 1965 p116).

Today, the LHC is the world's largest scientific instrument, with more than 24 km of the machine operating at 1.9 K – and yet only one project among many at CERN requiring advanced cryogenics. As presented at the latest international cryogenic engineering conference organised here in July, there have never been so many cryogenics projects either implemented or foreseen. They include accelerators for basic research, light sources, medical accelerators, detectors, energy production and transmission, trains, planes, rockets and ships. The need for energy efficiency and long-term sustainability will necessitate cryogenic technology with an enlarged temperature range for decades to come. CERN's experience provides a solid foundation for a new generation of engineers to contribute to society.
Serge Claudet *is a former deputy group leader of CERN's cryogenics group.*

1966

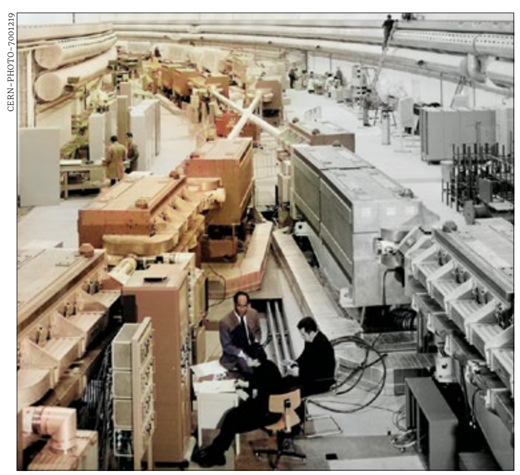
Polishing a mirror at CERN in 1966. Are physicists that narcissistic? Perhaps some are, but not in this case. Ultra-polished mirrors are still a crucial part of a class of particle detectors based on the Cherenkov effect. Just as a shock wave of sound is created when an object flies through the sky at a speed greater than the speed of sound in air, so charged particles create a shock wave of light when they pass through a medium at a speed greater than the speed of light in that medium. This effect is extremely useful for measuring the velocity of a charged particle, because the emission angle of light packets relative to the trajectory of the particle is related to the velocity of the particle itself. By measuring the emission angle of Cherenkov light for an ultra-relativistic charged particle travelling through a transparent medium, such as a gas, the velocity of the particle can be determined. Together with the measurement of the particle's momentum, it is then possible to obtain its identity card, i.e. its mass. Mirrors are used to reflect Cherenkov light to the photosensors. The LHCb experiment at CERN has the most advanced Cherenkov detector ever

built. Years go by and technology evolves, but fundamental physics is about reality, and that's unchangeable!
Vincenzo Vagnoni *is spokesperson of the LHCb collaboration.*

1970

In 1911, Heinke Kamerlingh Onnes made a groundbreaking discovery by measuring zero resistance in a mercury wire at 4.2 K, revealing the phenomenon of superconductivity. This earned him the 1913 Nobel Prize, decades in advance of Bardeen, Cooper and Schrieffer's full theoretical explanation of 1957. It wasn't until the 1960s that the first superconducting magnets exceeding 1 T were built. This delay stemmed from the difficulty in enabling bulk superconductors to carry large currents in strong magnetic fields – a challenge requiring significant research.

The world's first proton–proton collider, CERN's pioneering Intersecting Storage Rings (ISR, pictured below left), began operation in 1971, a year after this photograph was taken. One of its characteristic "X"-shaped vacuum chambers is visible, flanked by combined-function bending magnets on either side. In 1980, to boost its luminosity, eight superconducting quadrupole magnets based



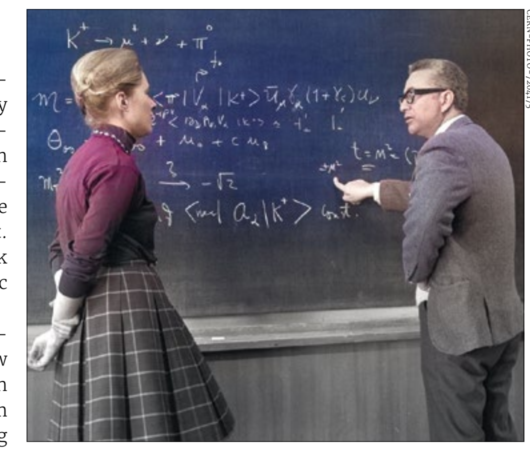
on niobium-titanium alloy were installed, each with a 173 mm bore and a peak field of 5.8 T, making the ISR the first collider to use superconducting magnets. Today, we continue to advance superconductivity. For the LHC's high-luminosity upgrade, we are preparing to install the first magnets based on niobium-tin technology: 24 quadrupoles with a 150 mm aperture and a peak field of 11.3 T.
Susana Izquierdo Bermudez *leads CERN's Large Magnet Facility.*

Years go by and technology evolves, but fundamental physics is about reality, and that's unchangeable!

1972

The Theoretical Physics Department, or Theory Division as it used to be known, dates back to the foundation of CERN, when it was first established in Copenhagen under the direction of Niels Bohr, before moving to Geneva in 1957. Theory flourished at CERN in the 1960s, hosting many scientists from CERN's member states and beyond, working side-by-side with experimentalists with a particular focus on strong interactions.

In 1972, when Murray Gell-Mann visited CERN and had this discussion with Mary Gaillard, the world of particle



physics was at a turning point. The quark model had been proposed by Gell-Mann in 1964 (similar ideas had been proposed by George Zweig and André Peterman) and the first experimental evidence of their reality had been discovered in deep-inelastic electron scattering at SLAC in 1968. However, the dynamics of quarks was a puzzle. The weak interactions being discussed by Gaillard and Gell-Mann in this picture were also puzzling, though Gerard 't Hooft and Martinus Veltman had just shown that the unified theory of weak and electromagnetic interactions proposed earlier by Shelly Glashow, Abdus Salam and Steven Weinberg was a calculable theory.

The first evidence for this theory came in 1973 with the discovery of neutral currents by the Gargamelle neutrino experiment at CERN, and 1974 brought the discovery of the charm quark, a key ingredient in what came to be known as the Standard Model. This quark had been postulated to explain properties of K mesons, whose decays are being discussed by Gaillard and Gell-Mann in this picture, and Gaillard, together with Benjamin Lee, went on to play a key role in predicting its properties. The discoveries of neutral currents and charm ushered in the Standard Model, and CERN theorists were active in exploring its implications – notably in sketching out the phenomenology of the Brout–Englert–Higgs mechanism. We worked with experimentalists particularly closely during the 1990s, making precise calculations and interpreting the results emerging from LEP that established the Standard Model.

CERN Theory in the 21st century has largely been focused on the LHC experimental programme and pursuing new ideas for physics beyond the Standard Model, often in relation to cosmology and astrophysics. These are likely to be the principal themes of theoretical research at CERN during its eighth decade.

John Ellis *served as head of CERN's Theoretical Physics Department from 1988 to 1994.*

1974

From 1959 to 1992, Linac1 accelerated protons to 50 MeV, for injection into the Proton Synchrotron, and from 1972 into the Proton Synchrotron Booster. In 1974, their journey started in this ion source. High voltage was used to achieve the first acceleration to a few percent of the speed

CERN-PHOTO-7403120

of light. It wasn't only the source itself that had to be at high voltage, but also the power supplies that feed magnets, the controllers for gas injection, the diagnostics and the controls. This platform was the laboratory for the ion source. When operational, the cubicle and everything in it was at 520 kV, meaning all external surfaces had to be smooth to avoid sparks. As pictured, hydraulic jacks could lift the lid to allow access for maintenance and testing, at which point a drawbridge would be lowered from the adjacent wall to allow the engineers and technicians to take a seat in front of the instruments.

The discoveries of neutral currents and charm ushered in the Standard Model, and CERN theorists have been active in exploring its implications

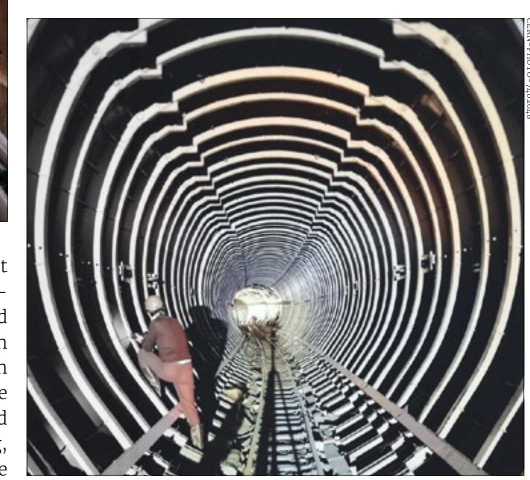
Thanks to the invention of radio-frequency quadrupoles by Kapchinsky and Teplyakov, radio-frequency acceleration can now start from lower proton energies. Today, ion sources use much lower voltages, in the range of tens of kilovolts, allowing the source installations to shrink dramatically in size compared to the 1970s.

Richard Scrivens *is CERN's deputy head of accelerator and beam physics.*

1974

CERN's labyrinth of tunnels has been almost continuously expanding since the lab was founded 70 years ago. When CERN was first conceived, who would have thought that the 7 km-long Super Proton Synchrotron tunnel shown in this photograph would have been constructed, let alone the 27 km LEP/LHC tunnel? Similar questions were raised about the feasibility of the LEP tunnel to those that are being posed today about the proposed Future Circular Collider (FCC) tunnel. But if you take a step back and look at the history of CERN's expanding tunnel network, it seems like the next logical step for the organisation.

This vintage SPS photograph from the 1970s shows the tunnel's secondary lining being constructed. The concrete was transported from the surface down the 50 m-deep shafts and then pumped behind the metal formwork to create the tunnel walls. This technology is still used today, most recently for the HL-LHC tunnels. However, for a mega-project like the FCC, a much quicker and more sophisticated methodology is envisaged. The



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Today, we find fewer chalk boards at CERN and more casual clothing, but one thing remains the same: CERN's dedication to education and communication

tunnels would be excavated using tunnel boring machines, which will install a pre-cast concrete segmental lining using robotics immediately after the excavation of the rock, allowing 20 m of tunnel to be excavated and lined with concrete per day.

John Osborne *is a senior civil engineer at CERN.*

1977

Detector development for fundamental physics always advances in symbiosis with detector development for societal applications. Here, Alan Jeavons (left) and David Townsend prepare the first positron-emission tomography (PET) scan of a mouse to be performed at CERN. A pair of high-density avalanche chambers (HIDACs) can be seen above and below Jeavons' left hand. As in PET scans in hospitals today, a radioactive isotope introduced into the biological tissue of the mouse decays by emitting a positron that travels a few millimetres before annihilating with an electron. The resulting pair of coincident and back-to-back 511 keV photons was then converted into electron avalanches which were reconstructed in multiwire proportional chambers – a technology invented by CERN physicist Georges Charpak less than a decade earlier to improve upon bubble chambers and cloud chambers in high-energy physics experiments. The HIDAC detector later contributed to the development of three-dimensional PET image reconstruction. Such testing now takes place at dedicated pre-clinical facilities.

Today, PET detectors are based on inorganic scintillating crystals coupled to photodetectors – a technology that is also used in the CMS and ALICE experiments at the LHC. CERN's Crystal Clear collaboration has been continuously developing this technology since 1991, yielding benefits for both fundamental physics and medicine.

CERN

One of the current challenges in PET is to improve time resolution in time-of-flight PET (TOF-PET) below 100 ps, and towards 10 ps. This will eventually enable positron annihilations to be pinpointed at the millimetre level, improving image quality, speeding up scans and reducing the dose injected into patients. Improvements in time resolution are also important for detectors in future high-energy experiments, and the future barrel timing layer of the CMS detector upgrade for the High-Luminosity LHC was inspired by TOF-PET R&D.

Etiennette Auffray Hillemanns *is spokesperson for the Crystal Clear collaboration and technical coordinator for the CMS electromagnetic calorimeter.*

1979

In this photo, we see Rafel Carreras, a remarkable science educator and communicator, sharing his passion for science with an eager audience of young learners. Known for his creativity and enthusiasm, Carreras makes the complex world of particle physics accessible and fun. His

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particle-physics textbook *When Energy Becomes Matter* includes memorable visualisations that we still use in our education activities today. One such visualisation is the "fruity strawberry collision", wherein two strawberries collide and transform into a multitude of new fruits, illustrating how particle collisions produce a shower of new particles that didn't exist before.

Today, we find fewer chalk boards at CERN and more casual clothing, but one thing remains the same: CERN's dedication to education and communication. Over the years, CERN has trained more than 10,000 science teachers, significantly impacting science education globally. CERN Science Gateway, our new education and outreach centre, allows us to welcome about 400,000 visitors annually. It offers a wide range of activities, such as interactive exhibitions, science shows, guided tours and hands-on lab experiences, making science exciting and accessible for everyone. Thanks to hundreds of passionate and motivated guides, visitors leave inspired and curious to find out more about the fascinating scientific endeavours and extraordinary technologies at CERN.

Julia Woithe *coordinates educational activities at CERN's new Science Gateway.*

- *These photographs are part of a collection curated by* **Renilde Vanden Broeck**, *which will be exhibited at CERN in September.*

OPINION VIEWPOINT

Look to the Higgs self-coupling

Matthew McCullough argues that beyond-the-Standard Model physics may be most strongly expressed in the Higgs self-coupling.


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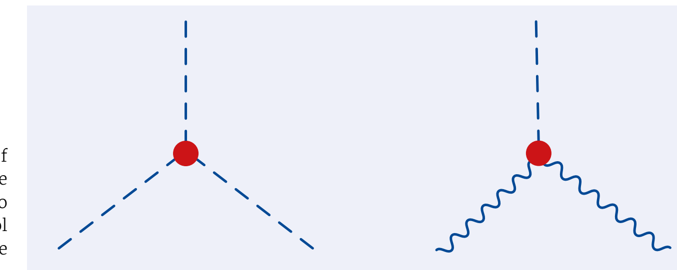
Matthew McCullough *is a theoretical physicist at CERN.*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Informed agnosticism *The Higgs boson's self-coupling (left) is harder to measure than its coupling to the Z boson (right), but naive dimensional analysis suggests that new physics could modify its value more strongly.*

What are the microscopic origins of the Higgs boson? As long as we lack the short-wavelength probes needed to study its structure directly, our best tool to confront this question is to measure its interactions.

Let's consider two with starkly contrasting experimental prospects. The coupling of the Higgs boson to two Z bosons (HZZ) has been measured with a precision of around 5%, increasing to around 1.3% by the end of High-Luminosity LHC (HL-LHC) operations. The Higgs boson's self-coupling (HHH) has so far only been measured with a precision of the order of several hundred percent, improving to around the 50% level by the end of HL-LHC operations – though it's now rumoured that this latter estimate may be too pessimistic.

Good motives

As HZZ can be measured much more precisely than HHH, is it the more promising window beyond the Standard Model (SM)? An agnostic might say that both measurements are equally valuable, while a "top down" theorist might seek to judge which theories are well motivated, and ask how they modify the two couplings. In supersymmetry and minimal composite Higgs models, for example, modifications to HZZ and HHH are typically of a similar magnitude. But "well motivated" is a slippery notion and I don't entirely trust it.

Fortunately there is a happy compromise between these perspectives, using the tool of choice of the *informed* agnostic: effective field theory. It's really the same physical principle as trying to look within an object when your microscope operates on wavelengths greater than its physical extent. Just as the microscopic structure of an atom is imprinted, at low energies, in its multipolar (dipole, quadrupole and so forth) interactions with photons, so too would the microscopic structure of the Higgs boson leave its trace in modifications to its SM interactions.

There are more universality classes in heaven and Earth than are dreamt of in our well-motivated scenarios

All possible coupling modifications from microscopic new physics can be captured by effective field theory and organised into classes of "UV-completion". UV-completions are the concrete microscopic scenarios that could exist. (Here, ultraviolet light is a metaphor for the short-wavelength probes needed to study the Higgs boson's microscopic origins in detail.) Scenarios with similar patterns are said to live in the same universality class. Families of universality classes can be identified from the *bottom up*. A powerful tool for this is naïve dimensional analysis (NDA).

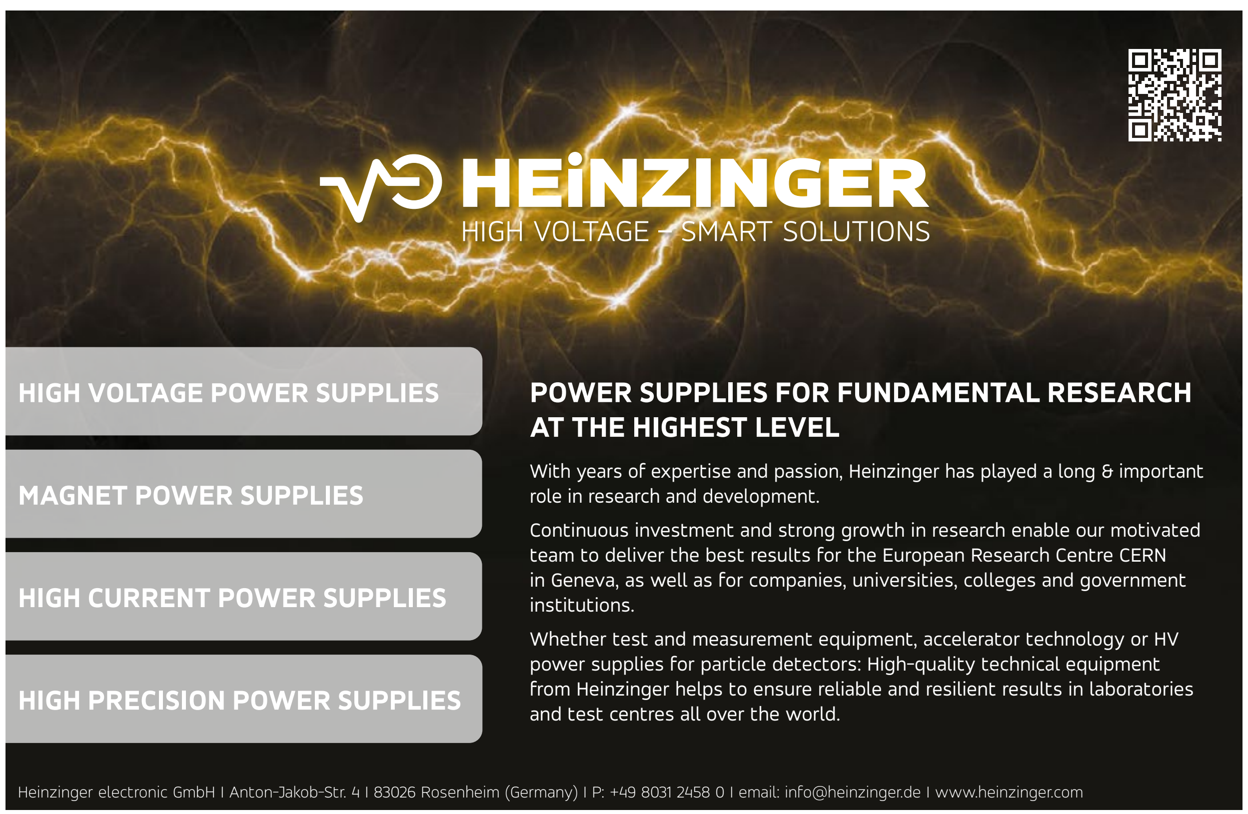
One particularly sharp arrow in the NDA quiver is ℏ counting, which establishes how many couplings and/or ℏs must be present in the EFT modification of an interaction. Couplings tell you the number of fundamental interactions involved. ℏs establish the need for quantum effects. For instance, NDA tells us that the coefficient of the Fermi interaction must have two couplings, which the electroweak theory duly supplies – a W boson transforms a neutron into a proton, and then decays into an electron and a neutrino.

For our purposes, NDA tells us that modifications to HZZ must necessarily involve one more ℏ or two fewer couplings than any underlying EFT interaction that modifies HHH. In the case of one more ℏ, modifications to HZZ could potentially be an entire quantum loop factor smaller than modifications to HHH. In the case of two fewer couplings, modifications to HHH could be as large as a factor g^2 greater than for HZZ, where g is a generic coupling. Either way, it is theoretically possible that the BSM modifications could be up to a couple of orders of magnitude greater for HHH than for HZZ. (Naively, a loop factor counts as around $1/16\,\pi^2$ or about 0.01, and in the most strongly interacting scenarios, g^2 can rise to about $16\,\pi^2$.)

Why does this contrast so strongly with supersymmetry and the minimal composite Higgs? They are simply in universality classes where modifications to HZZ and HHH are comparable in magnitude. But there are more universality classes in heaven and Earth than are dreamt of in our well-motivated scenarios.

Faced with the theoretical possibility of a large hierarchy in coupling modifications, it behoves the effective theorist to provide an existence proof of a concrete UV-completion where this happens, or we may have revealed a universality class of measure zero. But such an example exists: the custodial quadruplet model. I often say it's a model that only a mother could love, but it could exist in nature, and gives rise to coupling modifications a full loop factor of about 200 greater for HHH than HZZ.

When confronted with theories beyond the SM, all Higgs couplings are not born equal: UV-completions matter. Though HZZ measurements are arguably the most powerful general probe, future measurements of HHH will explore new territory that is inaccessible to other coupling measurements. This territory is largely uncharted, exotic and beyond the best guesses of theorists. Not bad circumstances for the start of any adventure.



OPINION INTERVIEW

Steering the ship of member states

CERN Council President Eliezer Rabinovici tells the *Courier* that CERN's member states are demonstrating unity, resilience and farsightedness as they chart CERN's role in the future of fundamental exploration.

CERN turns 70 at the end of September. How would you sum up the contribution the laboratory has made to human culture over the past seven decades?
CERN's experimental and theoretical research laid many of the building blocks of one of the most successful and impactful scientific theories in human history: the Standard Model of particle physics. Its contributions go beyond the best-known discoveries, such as of neutral currents and the seemingly fundamental W, Z and Higgs bosons, which have such far-reaching significance for our universe. I also wish to draw attention to the many dozens of new composite particles at the LHC and the incredibly high-precision agreement between theoretical calculation performed in quantum chromodynamics and the experimental results obtained at the LHC. These amazing discovering were made possible thanks to the many technological innovations made at CERN.

But knowledge creation and accumulation are only half the story. CERN's human ecosystem is an oasis in which the words "collaboration among peoples for the good of humanity" can be uttered without grandstanding or hypocrisy.

Untangling strings *A professor at the Hebrew University of Jerusalem, Eliezer Rabinovici's research focuses on the phase structure of gauge theories, string theory and quantum gravity. He has served as an Israeli delegate to the CERN Council since 2004, as vice president from 2016 to 2018, and as president since 2022, with his three-year term set to conclude in December.*

What role does the CERN Council play?
CERN's member states are each represented by two delegates to the CERN Council. Decisions are made democratically, with equal voting power for each national delegation. According to the convention approved in 1954, and last revised in 1971, Council determines scientific, technical and administrative policy, approves CERN's programmes of activities, reviews its expenditures and approves the laboratory's budget. The Director-General and her management team work closely with Council to develop the Organization's policies, scientific activities and budget. Director-General Fabiola Gianotti and her management team are now collaborating with Council to forge CERN's future scientific vision.

What's your vision for CERN's future?
As CERN Council president, I have a responsibility to be neutral and reflect the collective will of the member states. In early 2022, when I took up the presidency, Council delegates unanimously endorsed my evaluation of their vision: that CERN should continue to offer the world's best experimental high-energy physics programme using the best technology possible. CERN now needs to successfully complete the High-Luminosity LHC (HL-LHC) project and agree on a future flagship project.

I strongly believe the format of the future flagship project needs to crystallise as soon as possible. As put to me recently in a letter from the ECFA early-career researchers panel: "While the HL-LHC constitutes a much-anticipated and necessary advance in the LHC programme, a clear path beyond it for our future in the field must be cemented with as little delay as possible." It can be daunting for young people to speak out on strategy and the future of the field, given the career insecurities they face. I am very encouraged by their willingness to put out a statement calling for immediate action.

At its March 2024 session, Council agreed to ignite the process of selecting the next flagship project by going ahead with the fourth European Strategy for Particle Physics update. The strategy group are charged, among other things, with recommending what this flagship project should be to Council. As I laid down the gavel concluding the meeting I looked around and sensed genuine excitement in the Chambers – that of a passenger ship leaving port. Each passenger has their own vision for the future. Each is looking forward to seeing what the final destination will look like. Several big pieces had started falling into place, allowing us to turn on the engine.

What are these big pieces?
Acting upon the recommendation of the 2020 update of the European Strategy for Particle Physics, CERN in 2021 launched a technical and financial feasibility study for a Future Circular Collider (FCC) operating first as a Higgs, electroweak and top factory, with an eye to succeeding it with a high-energy proton–proton collider. The report will include the physics motivation, technological and geological feasibility, territorial implementation, financial aspects, and the environmental and sustainability challenges that are deeply important to CERN's member states and the diverse communes of our host countries.

It is also important to add that CERN has also invested, and continues to invest, in R&D for alternatives to FCC such as CLIC and the muon collider.

CLIC is a mature design, developed over decades, which has already precipitated numerous impactful societal applications in industry and medicine; and to the best of my knowledge, at present no laboratory has invested as much as CERN in muon-collider R&D.

A mid-term report of FCC's feasibility study was submitted to subordinate bodies to the CERN management mid-2023, and their resulting reports were presented to CERN's finance and scientific-policy committees. Council received the outcomes with great appreciation for the work involved during an extraordinary session on 2 February, and looks forward to the completion of the feasibility study in March 2025. Timing the European strategy update to follow hot on its heels and use it as an input was the natural next step.

At the June Council session, we started dealing with the nitty gritty of the process. A secretariat for the European Strategy Group was established under the chairmanship of Karl Jakobs, and committees are being appointed. By January 2026 the Council could have at its disposal a large part of the knowledge needed to chart the future of the CERN vision.

How would you encourage early-career researchers (ECRs) to engage with the strategy process?

ECRs have a central role to play. One of the biggest challenges when attempting to build a major novel research infrastructure such as the proposed FCC – which I sometimes think of as a *frontier* circular collider – is to maintain high-quality expertise, enthusiasm and optimism for long periods in the face of what seem like insurmountable hurdles. Historically, the physicists who brought a new machine to fruition knew that they would get a chance to work on the data it produced or at least have a claim for credit for their efforts. This is not the case now. Success rests on the enthusiasm of those who are at the beginning of their careers today just as much as senior researchers. I hope ECRs will rise to the challenge and find ways to participate in the coming European Strategy Group-sponsored deliberations and become future leaders of the field. One way to engage is to participate in ECR-only strategy sessions like those held at the yearly FCC weeks. I'd also encourage other countries to join the UK in organising nationwide ECR-only forums for debating the future of the field, such as I initiated in Birmingham in 2022.

M Cavazza/CERN-PHOTO-202406-133-7

Charting the future *Director-General Fabiola Gianotti and her management team collaborate with Council to forge CERN's future scientific vision.*

I thank member states for their steadfast support and I applaud them for their economic and scientific foresight over the past seven decades

What's the outlook for collaboration and competition between CERN and other regions on the future collider programme?

Over decades, CERN has managed to place itself as the leading example of true international scientific collaboration. For example, by far the largest national contingent of CERN users hails from the US. Estonia has completed the process of joining CERN as a new member state and Brazil has just become the first American associate member state. There is a global agreement among scientists in China, Europe, Japan and the US that the next collider should be an electron–positron Higgs factory, able to study the properties of the Higgs boson with high precision. I hope that – patiently, and step by step – ever more global integration will form.

Do member states receive a strong return on their investment in CERN?

Research suggests that fundamental exploration actively stimulates the economy, and more than pays for itself. Member states and associate member states have steadfastly supported CERN to the tune of CHF 53 billion (unadjusted for inflation) since 1954. They do this because their citizens take pride that their nation stands with fellow member states at the forefront of scientific excellence in the fundamental exploration of our universe. They also do this because they know that scientific excellence stimulates their economies through industrial innovation and the waves of highly skilled engineers, entrepreneurs and scientists who return home trained, inspired and better connected after interacting with CERN.

A bipartisan US report from 2005 called "Rising above the gathering storm" offered particular clarity, in my opinion. It asserted that investments in science and technology benefit the world's economy, and it noted both the abruptness with which a lead in science and technology can be lost and the difficulty of recovering such a lead. One should not be shy to say that when CERN was established in 1954, it was part of a rather crowded third place in the field of experimental particle physics, with the Soviet Union and the United States at the fore. In 2024, CERN is the leader of the field – and with leadership comes a heavy responsibility to chart a path beneficial to a large community across the whole planet. As CERN Council president, I thank member states for their steadfast support and I applaud them for their economic and scientific foresight over the past seven decades. I hope it will persist long into the 21st century.

Is there a role for private funding for fundamental research?

In Europe, substantial private-sector support for knowledge creation and creativity dates back at least to the Medici. Though it is arguably less emphasised in our times, it plays an important role today in the US, the UK and Israel. Academic freedom is a *sine qua non* for worthwhile research. Within this limit, I don't believe there is any serious controversy in Council on this matter. My sense is that Council fully supports the clear division between recognising generosity and keeping full academic and governance freedom.

What challenges has Council faced during your tenure as president?

In February 2022, the Russian Federation, an observer state, invaded Ukraine, which has been an associate member state since 2016. This was a situation with no precedent for Council. The shape of our decisions evolved for well over a year. Council members decided to cover from their own budgets the share of Ukraine's contribution to CERN. Council also tried to address as much as possible the human issues resulting from the situation. It decided to suspend the observer status in the Council of the Russian Federation and the Joint Institute for Nuclear Research. Council also decided to not extend its International Collaboration Agreements with the Republic of Belarus and the Russian Federation. CERN departments also undertook initiatives to support

the Ukrainian scientific community at CERN and in Ukraine.

A second major challenge was to mitigate the financial pressures being experienced around the world, such as inflation and rising costs for energy and materials. A package deal was agreed upon in Council that included significant contributions from the member states, a contribution from the CERN staff, and substantial savings from across CERN's activities. So far, these measures seem to have addressed the issue.

While these key challenges were tackled, management worked relentlessly on preparing an exhaustive FCC feasibility study, to ensure that CERN stays on course in developing its scientific and technological vision for the field of experimental high-energy physics.

The supportive reaction of Council to these challenges demonstrated its ability to stay on course during rough seas and strong side winds. This cohesion is very encouraging for me. Time and again, Council faced difficult decisions in recent years. Though convergence seemed difficult at first, thanks to a united will and the help of all Council members, a way forward emerged and decisions were taken. It's important to bear in mind that no matter which flagship project CERN embarks on, it will be a project of another order of magnitude. Some of the methods that made the LHC such a success can continue to accompany us, some will need to evolve significantly, and some new ones will need to be created.

CERN's human ecosystem is an oasis in which the words "collaboration among peoples for the good of humanity" can be uttered without grandstanding or hypocrisy

Has the ideal of Science for Peace been damaged?

Over the years CERN has developed the skills needed to construct bridges. CERN does not have much experience in dismantling bridges. This issue was very much on the mind of Council as it took its decisions.

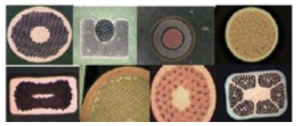
Do you wish to make some unofficial personal remarks?

Thanks. Yes. I would like to mention several things I feel grateful for.

Nobody owes humanity a concise description of the laws of physics and the basic constituents of matter. I am grateful for being in an era where it seems possible, thanks to a large extent to the experiments performed at CERN. Scientists from innumerable countries, who can't even form a consensus on the best 1970s rock band, have succeeded time and again to assemble the most sophisticated pieces of equipment, with each part built in a different country. And it works. I stand in awe in front of that.

The ecosystem of CERN, the experimental groups working at CERN and the CERN Council are how I dreamt as a child that the United Nations would work. The challenges facing humanity in the coming centuries are formidable. They require international collaboration among the best minds from all over the planet. CERN shows that this is possible. But it requires hard work to maintain this environment. Over the years serious challenges have presented themselves, and one should not take this situation for granted. We need to be vigilant to keep this precious space – the precious gift of CERN.

Interview by **Mark Rayner** *editor.*



OPINION
REVIEWS

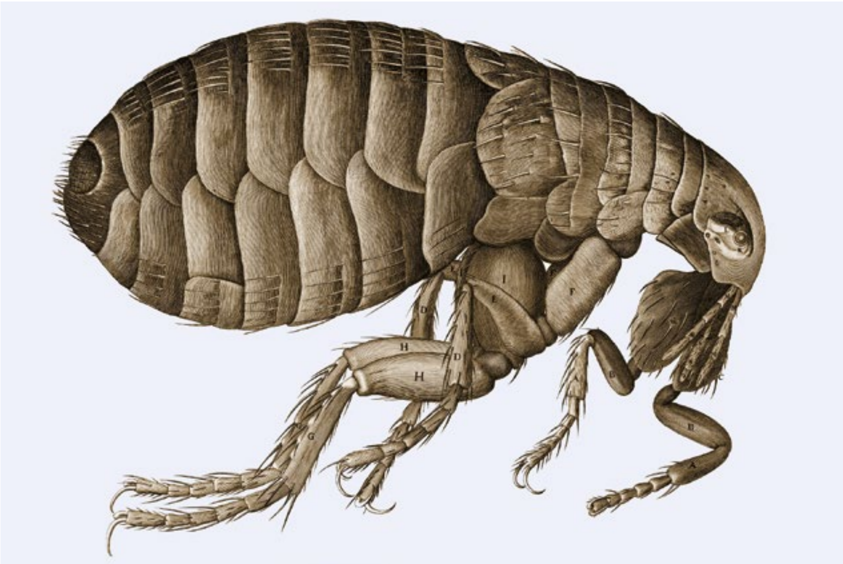
Wonderstruck wanderings

Wonderstruck: How Wonder and Awe Shape the Way We Think

By Helen De Cruz

Princeton University Press

The wonder and awe that we sense when we look at the starry skies is a major motivation to do science. Both Plato (*Theaetetus* 155d) and Aristotle (*Metaphysics* 982b12) wrote that philosophy starts in wonder. Plato went even further to declare that the eye's primary purpose is none other than to see and study the stars (*Timaeus* 47c). But wonder and awe also play a wider role beyond science, and are fundamental to other endeavours of human civilisation, such as religion. In *Wonderstruck: How Wonder and Awe Shape the Way We Think*, Helen De Cruz (Saint Louis University) traces the relationship between wonder and awe and philosophy, religion, magic and science, and the development of these concepts throughout history.



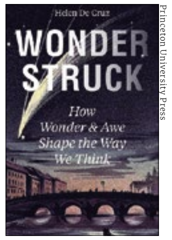
National Library of Wales

Head-scratcher *An illustration of a flea from Robert Hooke's* Micrographia, *which was the first text to include what were awe-inspiring microscopic images.*

Essential emotion

De Cruz's book is rich in content, drawing from psychology, anthropology and literature. Aptly for particle physicists, she points out that it is not only the very largest scales that fill us with awe, but also the very smallest, as for example in Robert Hooke's *Micrographia*, the first book to include illustrations of insects and plants as seen through a microscope. Everyday things may be sources of wonder, according to philosopher and rabbi Abraham J Heschel, who has written on religion as a response to the awe that we feel when we look at the cosmos. Even hard-nosed economists recognise the fundamental role of wonder, she observes: Adam Smith, the famous economist who wrote *The Wealth of Nations*, believed that wonder is an essential emotion that underlies the pursuit of science, as it prompts people to explore the unknown and seek knowledge about the world. Although particle physics is not mentioned explicitly in the book – the closest instance is a quote from Feynman's *Lectures on Physics* – the implications are clear. And while the sources quoted are mostly Western, other traditions are not ignored, with references to Chinese and Japanese culture present, among others.

This book reminds us that the major motivation of a new telescope or collider is to push into the frontiers of the unknown



Princeton University Press

The book also motivates questions that it does not address, some of which are especially interesting for fundamental physics. For example, modern human beings who live and work in cities spend most of their lives in an environment that alienates them from nature, and nature-induced awe must compete with technology-driven amazement. One can maybe glimpse that in outreach, where curiosity about technology sometimes, though not always, eclipses interest about the fundamental questions of science. While the book discusses this topic in the context of climate change – a reality that reminds us that we cannot ignore nature – there is more one can do with respect to the effects of such an attitude in motivating fundamental science.

At a time when large scientific projects, such as CERN's proposed Future Circular Collider, are being considered, generating a lot of discussions about cost and benefit, this book reminds us that the major motivation of a new telescope or collider is to push into the frontiers of the unknown – a process that starts and finishes with wonder and awe. As such, the book is very useful reading for scientists doing fundamental research, especially those who engage with the public.

Nikolaos Rompotis *University of Liverpool.*

BWT Water Dispensers at CERN: A Sustainable Hydration Solution

Since 2011, BWT (Best Water Technology) has been a proud partner of CERN, supplying state-of-the-art water dispensers to various sites and buildings within the vast CERN complex, which spans both Switzerland and France. Our partnership with CERN is rooted in our shared commitment to sustainability, innovation, and exceptional service. Today, we are pleased to report that there are over 150 BWT water dispensers installed and actively serving the CERN community.

Enhancing Hydration at CERN

Our water dispensers provide a range of hydration options to meet the diverse needs of CERN's staff, visitors, and contractors. With the water dispenser in use, we offer cold water, ambient water, sparkling water, and even hot water. These dispensers are strategically placed throughout CERN's numerous facilities, ensuring that hydration is always within easy reach.

CERN's community is a dynamic and international one, with over 17,500 people from around the world working together to push the boundaries of scientific knowledge. This includes approximately 2,500 permanent staff members, as well as countless visitors and collaborators. Ensuring access to high-quality, sustainable hydration solutions is crucial in such an environment, where long hours and intense focus are the norms.

Sustainability at the Core

BWT's partnership with CERN goes beyond providing high-quality water; it's about embedding sustainability into everyday practices. Our water dispensers are designed to encourage the use of reusable bottles and cups. By offering easily accessible water stations, we help reduce the reliance on single-use plastic bottles, significantly cutting down on plastic waste.

The dispensers' user-friendly design, with spouts specifically engineered to accommodate reusable bottles, further promotes this eco-friendly practice. This is particularly important at CERN, where sustainability is a core value. By choosing BWT, CERN demonstrates its commitment to environmental stewardship and the promotion of sustainable practices within the scientific community.

Technical Excellence and Reliable Service

CERN has trusted BWT not only for the quality of our products but also for our outstanding technical service. Gaining access to CERN's premises requires authorization, reflecting the high-security environment of the world's leading particle physics laboratory. Despite these stringent access controls, BWT's technical team has consistently provided timely and efficient service, ensuring that all water dispensers operate at peak performance.

Our service includes regular maintenance and swift responses to any technical issues, ensuring minimal disruption to CERN's daily operations. This reliable support has been a key factor in the long-standing relationship between BWT and CERN.

Meeting the Needs of a Diverse Community

The versatility of BWT water dispensers caters to the diverse hydration preferences of CERN's international community. Whether someone prefers chilled water to stay refreshed during hot summer days, sparkling water for a fizzy treat, or hot water for a quick cup of tea, our dispensers deliver. This flexibility is highly appreciated in a setting as dynamic and varied as CERN.

Moreover, the availability of multiple water options in a single dispenser minimizes the need for separate machines, saving space and reducing energy consumption. This aligns perfectly with CERN's efforts to optimize resource use and minimize its environmental footprint.

BWT's water dispensers are more than just hydration stations; they are a testament to our commitment to sustainability, innovation, and excellent service. Our partnership with CERN highlights the importance of providing sustainable, high-quality water solutions in environments where excellence and precision are paramount.

As CERN continues to explore the frontiers of science, BWT is proud to support its mission by ensuring that the people driving these groundbreaking discoveries stay hydrated. Together, we are making strides towards a more sustainable future, one refillable bottle at a time.

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Become a Particle Physicist in Eight Simple Moves

By Simone Ragoni

Acrobat Edizioni Di Marchetti Nicola

Simone Ragoni is passionate about outreach. His Instagram page, quark-tastic, has more than 10 thousand followers, and is one of the very few that successfully makes particle physics and academia relatable. He wrote *Become a Particle Physicist in Eight Simple Moves* while completing his PhD on the ALICE experiment. The first move is to sip his favourite beverage: coffee.

As a social-media manager and communicator, I've been following Ragoni for years. His main tool is humour. And I'm proof it works. I will always remember the basic structure of a proton, because life is indeed full of "ups" and "downs".

Acrobat Edizioni Di Marchetti Nicola

Did I say gentle humour? Nah. Ragoni goes all the way. But he confesses that his humour can only be understood by a handful of people. Particle physics is esoteric – and readers will want to join the club. His book invites you into the world of a young particle physicist. Being a nerd is the new cool.

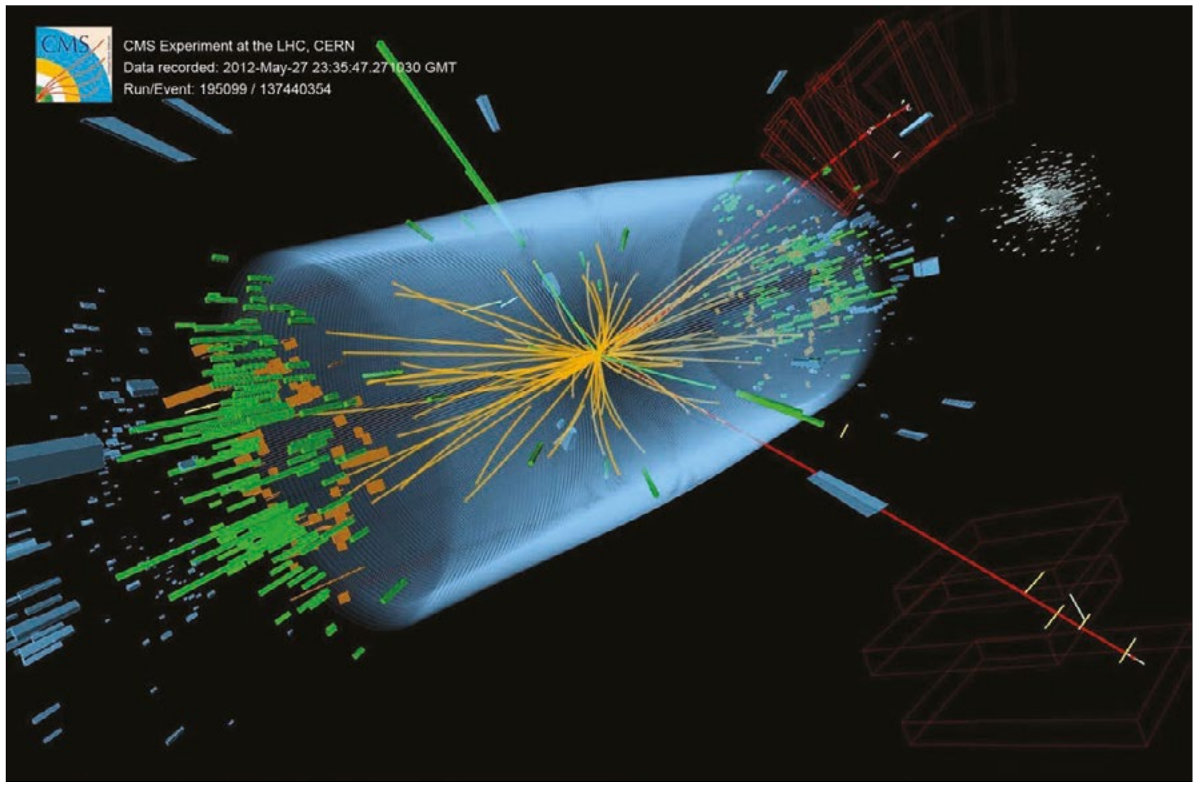
A highlight is when Ragoni describes how to keep those distributions fit. If you know, you know. There is a pun here and the author explains it very well. He next turns to the tedious work that goes into publishing a paper. "Monte Carlo simulations are our real playground," he writes, "where we unleash all our fantasy, the perfect world where everything is nice." But particle physicists are cautious. Five sigma is needed to claim a discovery – a one in 3.5 million chance of being wrong. The author concludes with encouragement to make your own measurements using CERN's open data.

A delightful gift for anyone whom you want to inspire to become a particle physicist

Ragoni's book is a delightful gift for anyone whom you want to inspire to become a particle physicist of tomorrow or simply to convey the excitement of what you do, with a quirky bonus of being presented bilingually in English and Italian, should you be keen on improving your physics vocab in one of those languages. It is a gateway to the captivating world of particle physics, skilfully blending humour with profound insights, and inspiring readers to explore further and consider joining the ranks of future particle physicists.

Chetna Krishna *CERN.*

Element Six Synthetic Diamond Protects CERN Particle Detectors in Higgs boson Experiment Results



Back in 2012, CERN (European Organization for Nuclear Research) particle detection systems used Element Six synthetic diamond in their first line of defence against beam-induced radiation damage in their Higgs boson experiment results.

Element Six, a world leader in synthetic diamond supermaterials, supplied its highest purity synthetic diamond as an integral part of the CERN LHC (Large Hadron Collider) CMS (Compact Muon Solenoid) and ATLAS Beam Condition Monitoring Systems, used in the milestone experiments which revealed the discovery of the Higgs boson.

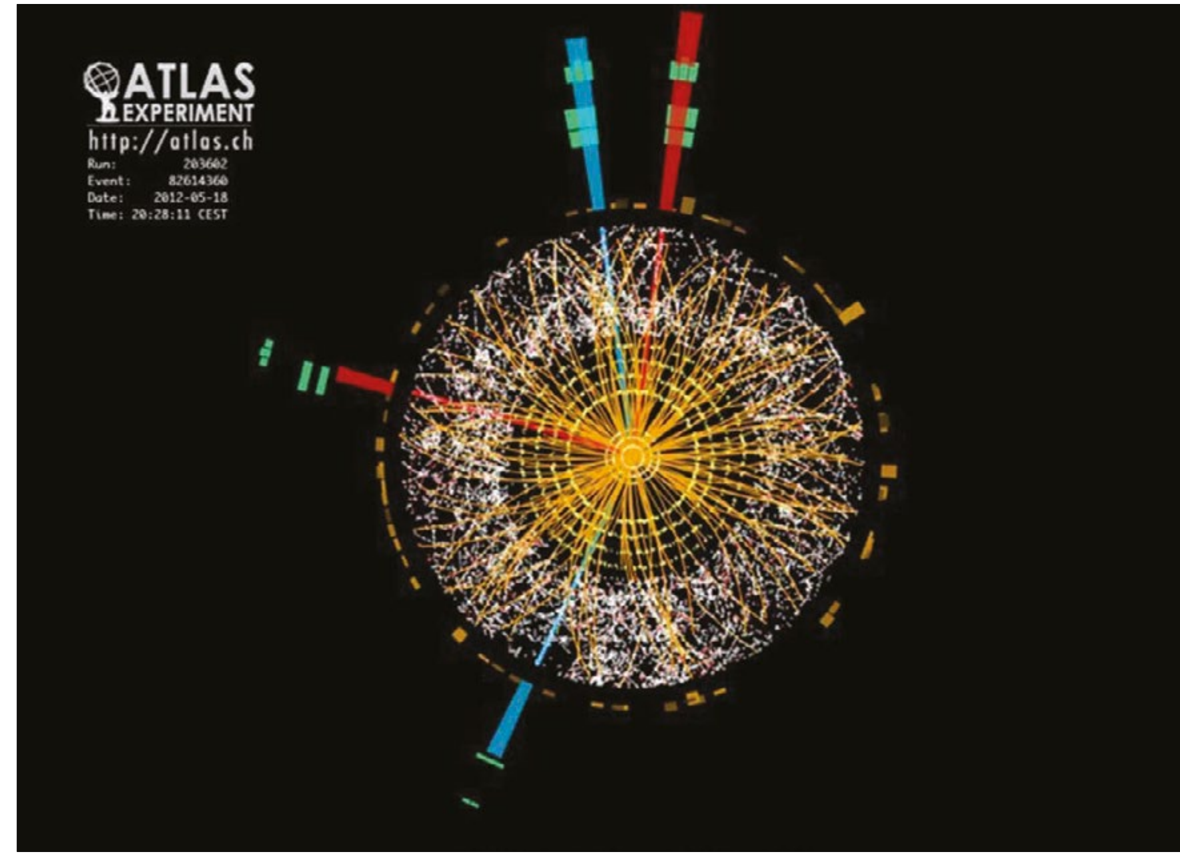
"The diamond synthesised by Element Six measures LHC beam conditions in key areas of the main experiments that have been used in the search for the Higgs boson," said Heinz Pernegger, CERN scientist at the ATLAS experiment.

"The CMS experiment relies on the stability of the synthetic diamond sensors produced by Element Six to monitor the LHC beam arriving to the CMS experiment and the particles created in the collision. The robustness of this synthetic diamond-based system is crucial in protecting the most sensitive components of the 66 million channel pixel-tracking detector," said Anna Dabrowski, CERN scientist at the CMS experiment.

"The use of synthetic diamond sensors was essential for a smooth operation of the LHC and the collection of high quality data by the LHC experiments, making the observation of the new particle possible," concluded Professor Wolfgang Lohmann from the Brandenburg University of Technology.

Element Six electronic grade synthetic diamond was selected as the optimum detector material by CERN scientists over the decade-long development of CERN's CMS and ATLAS Beam Condition Monitoring Systems. Synthetic diamond was shown to be the most robust sensor material available which could withstand the harsh, high radiation environment and react almost instantaneously to be able to protect the advanced measurement systems.

Element Six manufactures the synthetic diamond used in the detectors using a



process called chemical vapour deposition (CVD). This process takes a mixture of gases and forms plasma with the extreme high temperature of a sun spot to allow carbon to precipitate onto a substrate layer as synthetic diamond.

The purpose of the CERN CMS and ATLAS experiments was to count, track and characterise the different particles produced from the particle collisions inside the LHC. The synthetic diamond detectors in the monitoring system protected the experiments from adverse beam conditions and contributed to the luminosity measurement, which was crucial for obtaining the five sigma result.

Leveraging Element Six's over 70 years of innovation leadership and patented technology, the grades of synthetic diamond used in these monitoring systems are grown to ultra high levels of purity, incorporating less than one part per billion of boron, and less than 50 parts per billion of nitrogen. When diamond is synthesised with these levels of purity, it becomes an ideal radiation detector material. It can exhibit properties such as very low leakage current with negligible temperature dependence, a fast signal response and a vastly improved radiation hardness and reduction of leakage-current compared to silicon, the material traditionally used for detectors.

Dr Daniel Twitchen, Chief Technologist at Element Six, said:

"We are incredibly proud of the small, but important, contribution our synthetic diamond has made in helping the CMS and ATLAS experiments that enabled the team at CERN realise their milestone discoveries."

"This is yet another demonstration of why synthetic diamond is an ideal advanced engineering material capable of delivering extreme performance in the toughest environments. At Element Six, we are committed to engineering and manufacturing the highest purity synthetic diamond to help our partners meet their scientific and technology application challenges."

Professor Dr. Erich Griesmayer, CEO at CIVIDEC, with more than 20 years' experience of working at CERN, added:

"Beam condition monitoring is critical to the safe operation of the LHC at CERN. The diamond synthesised by Element Six was able to provide that protection in key areas of the main experiments that have been used in the search for the Higgs boson. Now that the synthetic diamond has been proven in this application, there is scope for its further use in medicine such as radiation therapy and diagnostic imaging."

To find out more about Element Six's collaboration with CIVIDEC, read the related case study here

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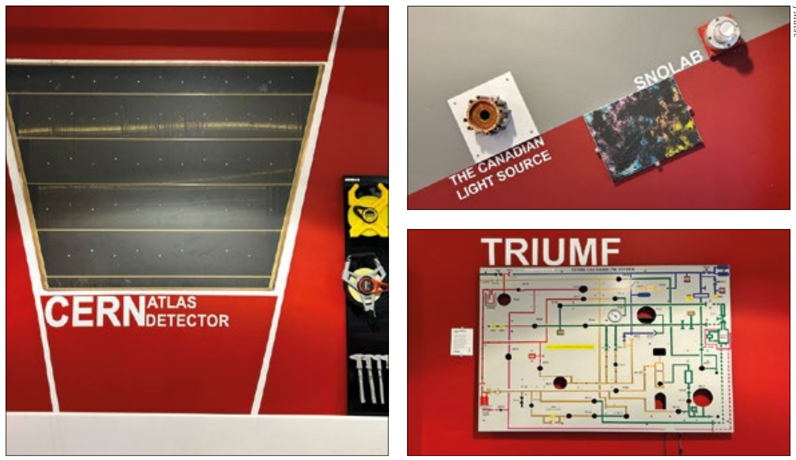
I built a physics museum in my classroom

Inspired by CERN's international teacher programme and visits to other major labs, Joe Muise has found a powerful way to inspire physics students.



Inspirational *Museum-style displays produced from old TRIUMF, SNOLAB and CERN equipment.*

Teaching modern physics to high-school students presents many challenges: overpacked curricula focusing on classical physics; the depth of knowledge needed by students (and teachers) to understand these topics; and students being over-focused on grades and university admissions. By exposing my students to the work being done at major research laboratories around the world, I have managed to find a way to overcome many of those obstacles.

Some time ago, British Columbia removed provincial examinations, giving teachers a bit more freedom to make additions to their curricula. I chose to insert small one- or two-day units throughout the year, which give my students multiple exposure to modern physics topics. These short introductions over a two-year period mean that physics students don't need to know all the fine details, which decreases their stress and concerns.

Knowledge sharing

Physics teachers are lucky to have access to high-quality professional development via workshops run by CERN, LIGO, the Perimeter Institute (which produces excellent resources for use in physics classes) and others. These often-week-long events give teachers an overview of how a given research facility works, in the hope that they will bring that knowledge back to their students. Along the way, the teachers attend lectures from leading researchers and see first-hand careers in the field that they can bring back to share with their class.

I have been fortunate enough to attend workshops at these facilities. I have also taken part in a research experience at SNOLAB, brought students on tours of TRIUMF and mentored my students as they conducted research at the Canadian Light Source. All these experiences have given me the knowledge and confidence to introduce the facilities and the work done at them to my students in a way that hopefully piques their curiosity.

> **The pieces provide a starting point for conversations around what these decommissioned parts were used for and the kind of science they supported**

While at CERN for the 2019 international teacher programme, I had the opportunity to visit both the CMS and ALICE detectors and to attended lectures from renowned particle physicists. We spent time in S'Cool LAB and visited many of the behind-the-scenes parts of CERN. While all of these experiences left an imprint on my teaching, it was during quiet visits to what was then called the Microcosm garden – which hosts decommissioned pieces of accelerators and detectors as a form of art – that helped transform the physical space in my classroom.

In 2022 my school in British Columbia renovated a large, old classroom to become our new physics lab. Knowing that I had more space to work with than before, I was inspired to start building my own version of the Microcosm garden on my classroom walls. I soon connected with the outreach team at TRIUMF who were excited to help get my project started with a photomultiplier tube, a control panel from a xenon-gas handling system, a paddle scintillator and a light guide. Since then, I have added a Lucas cell from SNOLAB, a piece of the electron gun from the Canadian Light Source and, most recently, a small-strip half-gap prototype from the New Small Wheel upgrade of the ATLAS detector. The pieces provide a starting point for conversations with students around what these decommissioned parts were used for, and the kind of science they supported.

Equipped with some knowledge of what modern research in the field looks like, I have successfully built a system where I am able to inspire students to want to study physics. Since attending my first major workshop in 2018, I have seen an increase in the number of students entering physics majors. Some of them have already gone on to internships at CERN and TRIUMF, after getting their first exposure to these organisations in my classes. My hope is that by having pieces of the facilities I talk about displayed on my classroom walls, this will further inspire more of my students to want to learn about them, possibly setting them on paths to careers in physics.

Joe Muise *St. Thomas More Collegiate, British Columbia, Canada.*

CERNCOURIER
Volume 64 Number 5 September/October 2024
IOP Publishing

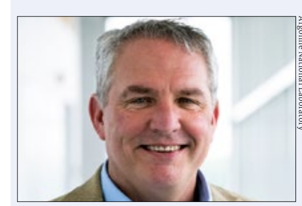
Appointments and awards

New director at IN2P3

Christelle Roy succeeds Reynald Pain as director of the CNRS National Institute of Nuclear and Particle Physics (IN2P3), effective since February. A heavy-ion experimentalist by training, Roy worked on the STAR experiment at Brookhaven before joining the ALICE experiment at CERN, where she was spokesperson for the EMCAL project. From 2011 to 2017, she directed the Hubert Curien Pluridisciplinary Institute in Strasbourg, after which she served as vice president for strategy and development at the University of Strasbourg. Roy joined the CNRS management in November 2020 and was appointed director of the Europe and international department in 2021.

LBNF/DUNE leadership

Fermi National Accelerator Laboratory has announced Jim Kerby, formerly at Argonne National Laboratory, as project director for the Long-Baseline Neutrino Facility for the Deep Underground Neutrino Experiment (LBNF/DUNE-US), currently under construction. Kerby has over 30 years of engineering and technical management experience at US national labs. He previously worked at Fermilab, starting in 1986, where he contributed to multiple projects, including the CDF end-plug upgrade and ultimately leading the $200M US-LHC Accelerator Project. He returns to Fermilab having led the $815M upgrade of Argonne's



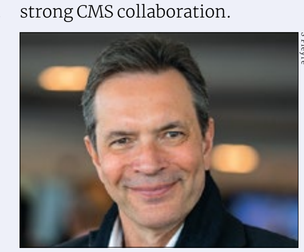
Advanced Photon Source and will be responsible for managing all aspects of the LBNF/DUNE project in the US. On 15 August, a ceremony at the Sanford Underground Research Facility in Lead, South Dakota marked the completion of excavation work for LBNF/DUNE.

Geant4 spokesperson

Alberto Ribon (CERN) has been elected the new spokesperson of the Geant4 collaboration, taking over from Marc Verderi. Geant4 is an open-source toolkit widely used to simulate the passage of particles through matter. First released in December 1998 following four years of R&D, the toolkit has applications ranging from high-energy, nuclear and accelerator physics to medical and space science. During his two-year mandate, Ribon intends to focus on the effective transfer of knowledge between generations of developers, ensure a good balance between maintenance, development and technology innovation, and strengthen the Geant4 validation and testing suite, geant-val.

New CMS management

On 1 September, Gautier Hamel de Monchenault (CEA-IRFU) took over from Patricia McBride as spokesperson for the 6000-strong CMS collaboration.



Formerly a member of the DELPHI collaboration at LEP and of the BaBar collaboration at SLAC, Hamel de Monchenault was head of the IRFU particle-physics department from 2016 to 2020. His two-year mandate, supported by deputy spokespersons Hafeez Hoorani (CERN) and Anadi Canepa (Fermilab), will see the end of the third data-taking period of the LHC and the start of the installation of detector upgrades in preparation for its high-luminosity upgrade.

Kaon pioneer recognised

In 1948, while undertaking a PhD at the University of Bristol, Rosemary Fowler discovered kaons, contributing to the award of the 1950 Nobel Prize in Physics to her supervisor Cecil Powell. Having decided to leave the university to raise her three young children during a time of food rationing, her contribution to the understanding of fundamental interactions has often been attributed to Powell

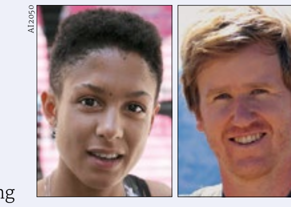
and her husband Peter Fowler. Acknowledging her vital role, the University of Bristol granted Rosemary an honorary doctor of science degree at a ceremony on 14 July. In 2004 she donated to the Royal Astronomical Society to set up the annual Fowler Award for Early Achievement in Astronomy.

ICTP Dirac Medal

The International Centre for Theoretical Physics in Trieste has awarded its 2024 Dirac Medal to four physicists who have made pioneering contributions to the understanding of quantum entropy in gravity and quantum field theory. In work related to the Bekenstein–Hawking formula, Shinsei Ryu (Princeton) and Tadashi Takayanagi (Kyoto) made a ground-breaking proposal that the von Neumann entropy of a gravitational system is given by the area of a minimal-area surface in the spacetime geometry. Studying quantum-entanglement entropy, Horacio Casini and Marina Huerta (CONICET and Bariloche Atomic Centre) derived important general results about the structure of quantum field theories.

IUPAP early-career awards

The International Union of Pure and Applied Physics early-career scientist awards 2024 in particles and fields were presented to Jennifer Ngadiuba (Fermilab, pictured left) and Ian Moult



(Yale, right) during a ceremony at ICHEP 2024 in Prague. Ngadiuba, a member of the CMS collaboration, developed novel machine-learning techniques with a focus on ultra-fast real-time data analysis on hardware triggers and for model-agnostic searches for new-physics signals at the LHC, while Moult is recognised for the invention of novel jet-substructure observables and for developing new effective field theory techniques to enable high-precision calculations.

CHIPP prize 2024

Gabriela Rodrigues Araujo (Zurich) is the winner of this year's Swiss Institute of Particle Physics prize for the best thesis in particle physics: "Advancing Neutrinoless Double Beta Decay Search with LEGEND and MONUMENT, and Exploring Passive Neutrino Detectors with PALEOCCENE". Equally at home in detector development and data analysis, and a keen science

communicator, Gabriela is now a postdoc at the University of Zurich where she leads R&D in imaging techniques for PALEOCCENE – which offers the potential for room-temperature, passive and robust detectors in the gram-to-kilogram range for the detection of low-energy nuclear recoil events.

CERNCOURIER
Volume 64 Number 5 September/October 2024
IOP Publishing

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PEOPLE OBITUARIES

RUDOLF BOCK 1927–2024

A pioneer of relativistic heavy-ion physics

Renowned experimental physicist and co-initiator of relativistic heavy-ion physics, Rudolf Bock, passed away on 9 April 2024 aged 96.

Rudolf Bock was born in Mannheim, Germany in May 1927 and obtained his diploma in physics from the University of Heidelberg in 1954. He conducted his doctoral thesis on deuteron-induced nuclear reactions at the cyclotron of the Max Planck Institute for Medical Research in Heidelberg and received his doctorate from Heidelberg University in 1958. He then investigated nuclear reactions at the newly founded MPI for Nuclear Physics (MPIK) at the tandem accelerators there, initially with light ions and from 1963 with heavier ions.

In 1967 he was appointed full professor at the University of Marburg and was involved in the development of a joint accelerator project for heavy-ion research, ultimately leading to the UNILAC accelerator project. On 17 December 1969, the research centre GSI (Gesellschaft für Schwerionenforschung) was founded in Darmstadt-Wixhausen. As one of its founding fathers and subsequently as a long-standing member of the GSI board of directors, Rudolf Bock played a decisive role in the development of nuclear physics with heavy ions. At the same time, he maintained his contacts with Heidelberg as an honorary professor and as an external scientific member of the MPIK. In 2000 he was awarded an honorary doctorate from Goethe University Frankfurt.

Research with relativistic heavy-ion beams soon led to great successes. From 1974 Rudolf Bock established a working group at GSI under the leadership of Hans Gutbrod and Reinhard Stock, who set up and successfully carried out two major experiments at the Berkeley Bevalac accelerator. These resulted in the discovery of compressed, hot nuclear matter with hydrodynamic flow behaviour and thus formed the basis for his later experiments on quark–gluon plasma at CERN.


© Otto/GSI Helmholtzzentrum

Rudolf Bock was one of the founding fathers of GSI.

From the mid-1980s, the heavy-ion synchrotron SIS18 was set up at GSI under the leadership of director Paul Kienle. Thanks to Rudolf Bock's guidance and in cooperation with surrounding universities, three new experiments (FOPI, KAOS and TAPS) were created, which focused on the formation of compressed nuclear matter as well as on hadron production and in particular the formation of light atomic nuclei. Around the same time, he was working on plans for experiments at much higher energies, which could ultimately only be realised at the CERN SPS accelerator, with decisive contributions from GSI and LBL Berkeley. This led to the development of today's global programme in ultra-relativistic nuclear–nuclear collisions, which has been pursued since the 1990s at the AGS and SPS, from 2000 with four experiments at RHIC and, since 2010, has been led by ALICE at the LHC at the highest energies.

The cooperation between GSI and LBL Berkeley was not only the beginning of relativistic heavy-ion physics. Supported by Hermann Grunder, then head of the LBL accelerator department, Rudolf Bock started the inertial confinement fusion programme in Germany. He also laid an important foundation for ion-beam therapy by supporting the secondment of Gerhard Kraft from GSI to the cancer-therapy programme at LBL. After his retirement in December 1995, Rudolf Bock maintained his scientific activities at GSI, his primary interest being the development of experiments on plasma physics and inertial-confinement fusion with high-intensity ion and laser beams.

Throughout the course of his scientific career, Rudolf Bock established numerous new research collaborations with institutes in Germany and abroad. As he himself had taken part in the Second World War and had spent several years as a prisoner of war in Russia, the idea of international understanding and peacekeeping was an important concern for him. As early as 1969 he invited many Russian scientists to the nuclear-physics conference at MPIK, and from the 1970s he promoted many collaborations between GSI and Russian institutes. He also pushed for Russia to become the largest member state in the GSI/FAIR project. The Russian invasion of Ukraine in February 2022 was therefore a great disappointment for him and for all of us.

Rudolf Bock was regularly present at GSI until his last days and continued to take an interest in current research and developments on campus. His advice and foresight will be sorely missed.

Peter Braun-Munzinger, **Paolo Giubellino**, **Klaus-Dieter Groß** *and* **Hans Gutbrod** *GSI Helmholtzzentrum;* **Reinhard Stock** *and* **Horst Stöcker** *Goethe-Universität Frankfurt.*

ILARIO BOSCOLO 1940–2024

An esteemed experimentalist and teacher

Ilario Boscolo, who was one of the proponents of the AEgIS experiment at CERN, passed away on 16 April 2024 at the age of 84.

Ilario Boscolo was born in Codevigo, Italy in 1940 and graduated from the nearby University of Padua. In 1968 he joined the University of Lecce, where he initiated research in accelerator physics, high-intensity electron beams and free electron lasers (FELs), and far-infrared and CO_2 lasers. Among his important scientific contributions at that time were the development of a prototype electrostatic accelerator, investigations on far-infrared lasers optically pumped in a cavity, and a much-cited theoretical proposal for a two-stage FEL for coherent harmonic amplification (an optical klystron). Ilario spent long periods of study in international research institutes, including the ENEA fusion energy centre in Frascati and the University of California Santa Barbara, where he collaborated with world-leading FEL researchers Luis Elias and William Colson.

In 1987 Ilario was called to the University of Milan, where he became full professor, to participate in the INFN project ELFA (electron laser facility for acceleration) and was responsible for the photocathode emission. His interest then turned to other topics, including efficient electron sources based on field emission from carbon nanotubes or ferroelectric ceramics and, within CERN, pulsed laser phase coding systems for new acceleration facilities. Within the INFN SPARC–SPARX initiative, started in 2003 and based in Frascati, he focused on ▷

laser applications for the development of pulsed, high-brightness UV and X-ray FEL sources. In particular, he showed that the high beam quality of the electron sources depends on suitable shaping of comb laser pulses, the study of which was realised in a dedicated laser laboratory at Milan founded by Ilario.

In 2007 Ilario was one of the proponents of the AEgIS experiment at the CERN Antiproton Decelerator, which aimed to investigate the properties of antimatter, in particular its gravitational interactions. This required the production of a low-energy beam of antihydrogen atoms, obtained by a charge-exchange process with positronium atoms laser-excited at Rydberg levels. Led by Ilario, the Milan laser laboratory was responsible for the laser system that was required to make this pairing possible. AEgIS demonstrated the first pulsed-production of antihydrogen atoms in 2018, enabling a series of antimatter studies that are ongoing.

In all his activities, Ilario showed great passion and enthusiasm for both science and its applications. This positive attitude was also widely displayed through his didactical activity in various courses at the University of Milan. He was responsible for a new physics laboratory for the biology programme and for the laser laboratory for the physics programme. In addition, his greatest success was the complete reconstruction of the general physics laboratory for first-year students. By encouraging students to practice and elaborate on their own, with only little guidance from the teacher, this laboratory left an indelible mark on their training as physicists.


Family photograph

Ilario Boscolo demonstrated great passion and enthusiasm in all that he did.

Another strong passion of Ilario was civil commitment, reflected in his constant engagement with university governance and studies of politics and economics, to which he dedicated himself with his usual inexhaustible enthusiasm, particularly after his retirement.

Ilario is remembered by his collaborators and students as a person of great culture, of brilliant insights, of a willingness to discuss physics and politics with anyone, and as an exquisite friend. He was a true scientist, leaving a deep mark on physics and a bright memory for everyone who had the honour of knowing him.

Fabrizio Castelli *Department of Physics of the University of Milan, on behalf of the AEgIS collaboration.*

WERNER RÜHL 1937–2023

An open mind for new developments

Theoretical physicist Werner Rühl died on 31 December 2023 in Füssen, Germany at the age of 86.

He was born in 1937, at a time when theoretical physics in Germany was being destroyed by the Nazis. After the Second World War, the ongoing study of cosmic rays and the availability of higher energies from accelerators made particle physics the most interesting field for budding researchers like him. Part of the way ahead was obvious: learn from the US and profit from the new spirit of European unity embodied by the creation of CERN.

Rühl followed this path in the straightest possible way. He obtained his PhD in 1962 in Cologne and became a research associate at CERN in 1964. Two years later he took up a postdoc at Rockefeller University, New York, before returning to CERN as a staff member in 1967, and obtained a chair in 1970 at the newly founded University of Kaiserslautern.

A more difficult decision concerned mathematics, for which many experimentalists had little regard. Initially, Einstein had shared this attitude, but then he worked hard on Riemannian geometry to understand gravity. Heisenberg's successes were based on deep mathematics, too, but he tried his best to limit its scope. SU(2) and the analogy between spin and isospin were fundamental, and the representation theory of SU(2) had been fully explored in the context of atomic physics. Dirac's understanding of spinors and his introduction of the delta distribution opened the way for a thorough investigation of non-compact groups like SL(2,C). This allowed us to break the wall between maths and physics, which happened initially in the Soviet Union. Rühl was very aware of this fact and was deeply impressed by the work of Israel Moiseevich Gelfand. In winter 1967/1968 he gave a series of lectures on this topic for the academic training programme at CERN, which in 1970 became the core of his book *The Lorentz group and harmonic analysis*. A mathematical fruit was his elementary proof of the Plancherel theorem for classical groups, published in 1969.


U Pohlan

Werner Rühl maintained a strong interest in experimental physics.

Rühl's appointment to a chair at Kaiserslautern was a happy choice for both sides. Internationally recognised professors like Rühl had adequate resources for students, visitors and conferences, and four theory colleagues were hired between 1970 and 1973. In 1983–1985 Rühl was chairman of the physics department and member of the university senate. He published good papers with his PhD students and supported the global development of science, in particular through his work with postdocs from Oran University. For many years he also worked as a mentor for gifted students from all faculties for the prestigious *Studienstiftung des deutschen Volkes* scholarship foundation.

Despite his dominating affinity for mathematics, Rühl maintained an interest in experimental physics and occasionally published related work. His understanding of Russia facilitated successful collaborations with outstanding colleagues who had moved to the West, with some of his most important contributions stemming from his collaborations with colleagues from Yerevan. After his retirement in 2004 he continued to publish as before. Eleven years later he moved to Füssen near the Alps. For five years he could enjoy his passion for skiing, before an accident impaired his health.

Werner Rühl always had an open mind for new developments. He had studied the large-N behaviour of theories with symmetries like O(N) and did respected work on lattice theories. From the 1980s, his citation rate increased more and more – a tendency that lasted way beyond his retirement. The original take on AdS/CFT duality in the context of O(N) sigma models and high-spin theories stands out the most. At the end of his life it must have been a great satisfaction for Werner Rühl to watch the ripening of these late fruits.

Werner Nahm *Dublin Institute for Advanced Studies.*

CERNCOURIER
VOLUME 64 NUMBER 5 SEPTEMBER/OCTOBER 2024
IOP Publishing

Armin Hermann 1933–2024

From theory to history

Within CERN circles, Armin Hermann is mainly known as one of the co-editors of the authoritative *History of CERN* volumes covering the period from the beginnings of the Organization up to 1965. But he did so much more in the field of the history of science.

Armin Hermann was born on 17 June 1933 in Vernon, British Columbia, Canada and grew up in Upper Bavaria in Germany. He studied physics at Ludwig Maximilian University in Munich and obtained his doctorate in theoretical physics in 1963 with a dissertation on the "Mott effect for elementary particles and nuclei of electromagnetic structure". He worked for a few years at DESY and performed synchrotron-oscillation calculations with an IBM 650 computer. Subsequently, Hermann decided to change his focus from physics proper to its history, which had preoccupied him since his student days.

Hermann was the first to occupy a chair in the history of science and technology at the University of Stuttgart – a chair not situated either at a science or mathematics faculty but rather among general historians. During his 30 year-long tenure, he authored important monographs

Armin Hermann was invited to write the history of CERN in its early days.

on quantum theory, quantum mechanics and elementary particle theory. He wrote books on the history of atomic physics titled *Weltreich der Physik: Von Galilei bis Heisenberg*, *The New Physics: The Route into the Atomic Age*, and *How Science Lost its Innocence*, alongside numerous biographies (including Planck, Heisenberg, Einstein and Wirtz) and historical studies on companies, notably on the German optics firm Carl Zeiss. All became very popular among the physics community.

Meanwhile at CERN, the attitude among physicists towards studies in the history of science was rather negative – the mantra was "We don't care of history, we *make* history". However, in 1980, the advisory committee for the CERN History Project examined a feasibility study conducted by Hermann and decided to establish a European study team to write the history of CERN from its early beginnings until at least 1963, with an overview of later years. The project was to be completed within five years and financed outside the CERN budget. Hermann was asked by CERN Council to assume responsibility for the project, and from 1982 to 1985 he was freed from teaching obligations in Stuttgart to conduct research at CERN. He became co-editor of first two volumes on the history of CERN: *Launching the European Organization for Nuclear Research* and *Building and Running the Laboratory, 1954–1965*. A third volume covering the story of the history of CERN from the mid-1960s to the late 1970s later appeared under the editorship of John Krige in 1996.

Armin passed away in February 2024 in his home in Oberstarz near Miesbach, nestled among the alpine hills, which he had always felt attached to and which was also the main reason why he declined several tempting calls to other renowned universities. His wife Steffi, his companion of many decades, was by his side to the very end. Many historians of physics, science and technology in Germany and abroad mourn the loss of this influential pioneer in the history of science.

Klaus Hentschel *University of Stuttgart and* **Dieter Hoffmann** *MPI for the History of Science, Berlin.*

Atsuhiko Ochi 1969–2024

Brilliance in detectors

Atsuhiko Ochi, a brilliant, passionate detector and experimental physicist, passed away on 29 April 2024 at the untimely age of 54. A source of innovative ideas at the forefront of radiation detectors, he made outstanding contributions to the development of micropattern gaseous detectors (MPGDs) that are recognised worldwide. He was also a distinguished lecturer whose inexhaustible passion, dedication and remarkable character captivated the many students he mentored.

Atsuhiko began his research at the Tokyo Institute of Technology, initially focusing on large-area avalanche photodiodes as fast photon and soft X-ray detectors. In 1998 he defended his PhD thesis "Study of Micro Strip Gas Chamber as a Time-Resolved X-ray Area Detector", earning the second High Energy Physics Young Researcher's Award from the Japan Association of High Energy Physicists. In 2000, alongside Toru Tanimori, he introduced the micro pixel chamber (micro-PIC), a new gaseous detector for X-ray, gamma-ray and charged-particle imaging. It was fully developed using printed circuit board technology and free of floating structures like wires, mesh or foils, featuring a pin-shaped anode surrounded by a ring-shaped cathode.

Kobe University

Atsuhiko Ochi made significant contributions to MPGD and other gaseous detectors.

In 2001 Atsuhiko moved to Kobe University, where he joined the ATLAS experiment and devoted his efforts to commissioning the ATLAS thin gap chambers (TGCs). He was also in charge of integrating the front-end electronics on the KEK TGC detectors and of detector quality assurance and control. Later, at CERN, he led the acceptance quality control of the ATLAS TGCs.

Atsuhiko could always merge his love for experiments with a passion for new ideas. "We need new 'eyes' to catch a glimpse of science's frontier", he once said. Along with his group in Kobe, while making significant contributions in ATLAS to the design and construction of the new large resistive micromegas for the Muon New Small Wheel, he conducted R&D on the use of sputtered layers of diamond-like carbon (DLC) as resistive elements to quench discharges and played a crucial role in connecting with Japanese industry. He was among the first to test the technology with micromegas, apply it to the micro-PIC detector, and pioneer its use as electrodes for the novel resistive plate chambers he proposed for the MEG II experiment. He supported the use of DLC in the final TPC micromegas of the near detectors of the T2K experiment while serving as a liaison person with BE-Sput in Kyoto. DLC is now the predominant approach in most new resistive MPGD detectors.

In his research, Atsuhiko always placed great emphasis on mentoring students and giving them access to a worldwide community of experts, facilities and experiments. He meticulously shared all relevant research conducted by Japanese colleagues, ensuring proper visibility and recognition for his community. This has been crucial in the international RD51 collaboration on MPGD technologies, within which he played a significant role in its formation and management. During the transition from the MPGD-based RD51 collaboration to the upcoming DRD1, which encompasses a broader scope of technologies and applications, Atsuhiko made a crucial contribution by maintaining strong ties with the Asian community.

Atsuhiko's vibrant enthusiasm and infectious smile leave an irreplaceable void. His departure is a profound loss, leaving behind a loving wife and two children.

His colleagues and friends.

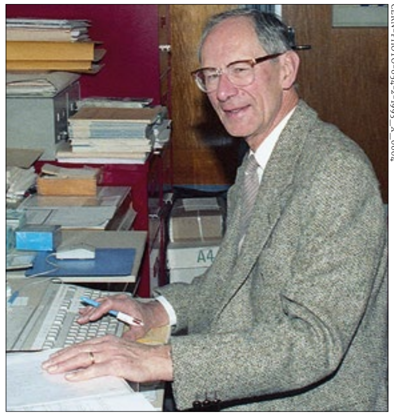
ALEC GEOFFREY HESTER 1928–2024

The end of a chapter

Alec Hester, a former editor of *CERN Courier* and later physics subject specialist at the CERN library for nearly 30 years, passed away in Geneva on 9 March at the age of 96.

Born in Hatfield, to the north of London, in 1928, Alec graduated in physics from Imperial College London in 1949. He continued there for his PhD, building a Van de Graaff accelerator to study (p, alpha) reactions in light nuclei. Yes, in those days postgraduate students built their own accelerators! One of his older fellow students was Don Perkins, who passed away in 2022.

In 1952 Alec interrupted his studies to take a job in the publicity department of General Electric at its site in Kent, England. Nine years later he came to CERN to take over the editorship of *CERN Courier* from Roger Anthoine. The *Courier* was then just two years old, and it was during Alec's period as editor that it began to move beyond its initial role as the house journal for CERN staff to one that communicated the work of CERN and other laboratories to a wider scientific and technical readership. Marking the end of



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Former Courier editor Alec Hester in his office in 1993.

Alec's editorship in the December 1965 issue, Anthoine wrote: "The editing and production of our periodical, with limited means, requires not only very definite intellectual qualities, for collecting and processing information from all over the Laboratory, but also considerable physical and moral toughness to cope with the many dictates of production, which are the lot of every editor… It is mainly thanks to [Alec's] drive that *CERN Courier*, which now has a circulation of 6000 copies (French and English versions combined), has risen from the rank of 'internal information journal' to that of 'world spokesman for European sub-nuclear physics'."

In 1966 Alec moved to the CERN scientific information service as the physics subject specialist, remaining there until his retirement in February 1993. His accurate and painstaking work developing the library's bibliographic databases provided the nucleus for those searchable on the CERN Document Server today.

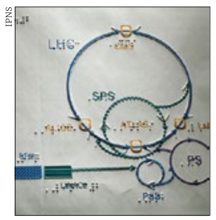
Alec leaves behind Annemarie, his wife for over 70 years, his daughters Barbara and Dagmar, and his four grandchildren.

David Dallman *CERN.*

BACKGROUND

Notes and observations from the high-energy physics community

Particle physics in braille



Detailed explanations of subjects such as the Brout–Englert–Higgs field are rare in accessible formats. Equations and figures can be challenging to render, and few translators possess scientific expertise. Ten researchers from the Institute of Particle and Nuclear Studies of KEK collaborated with the braille team at the Research and Support Center for Higher Education for People with Disabilities to produce a groundbreaking book in Japanese braille (www2.kek.jp/ipns/en/braillebook_project/). Ten chapters written by physicists across Japan cover subjects ranging from what the universe is made of to whether it is stable. The book is available for loan to individuals, universities and research institutions, with plans to donate sets to libraries and services for the visually impaired. "This project reflects the resilience and potential of braille," says Hitoshi Tanaka of the National University Corporation Tsukuba University of Technology, which offers higher education specifically designed for students with visual and hearing impairments. "I hope that readers will find it as enriching as I have".

Higgs boson to hit Broadway

Particle Fever, the critically acclaimed 2013 documentary following physicists from the start-up of the LHC through to the discovery of the Higgs boson, is to be turned into a musical. Billed as a love letter to science, and written by Tony Award-winner David Henry Hwang, the production is still "in the lab" and had its first industry-only reading in New York City this summer. "What I think is so beautiful about the story is these folks that were working on a problem that had a pretty high chance of failure," producer Megan Kingery told *The New York Times*. "That's beautiful. That's amazing. We should all aspire to that."

Media corner

"That paper is madness. It's like they gave an open mic to anyone at Fermilab who had a grievance."

Dark-matter experimentalist **Juan Collar** (University of Chicago) commenting on a lengthy indictment of Fermilab management posted on arXiv by anonymous authors (*Science* 14 August).

"This marks the first ever physics result on neutrinos from a particle collider."

FASERν collaborator **Akitaka Ariga** (Chiba University) on the direct observation of neutrino interactions at the LHC (*Interesting Engineering* 12 August).

"Based on the evidence that we have now, I am not willing to discard the constant-dark-energy model just yet."

Cosmologist **Licia Verde** (University of Barcelona) reflects on recent results from DESI, which hint at a possible slowing of the universe's expansion rate (*Quanta Magazine* 19 August).

"The result indicates that we started observing a signal."

Super-K spokesperson **Masayuki Nakahata** (University of Tokyo) on the possibility that the 30-year-old Cherenkov detector is seeing evidence of neutrinos from supernovae across cosmic history (*Nature* 9 July).

From the archive: November/December 1984

1984 and all that

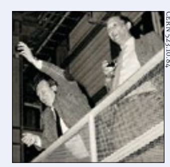
30 years of CERN ...

September marked the 30th anniversary of the coming into force of the Convention establishing the European Organization for Nuclear Research (CERN). A formal ceremony, attended by the King of Spain, was the highlight of the celebrations. Distinguished speakers at CERN's 30th anniversary ceremony (above) were, from left to right, Isidor Rabi at the podium, who launched the 'CERN resolution' at the 1950 UNESCO Conference, Pierre Aubert, Sir Alec Merrison, King Juan Carlos of Spain, Herwig Schopper, Hubert Curien and Peter Brooke.

10 years of SIN ...

On the 10th anniversary of SIN (Schweizerisches Institut für Nuklearforschung, Swiss Institute for Nuclear Research), Director J-P Blaser (pictured) was presented with ten bottles of wine, nine from vineyards of the corresponding Canton of the nine Swiss institutes using SIN, and one from the German user community across the Rhine.

... and a Nobel prize



There was general jubilation at CERN when Carlo Rubbia (left) and Simon van der Meer were nominated for the 1984 Nobel Prize 'for their decisive contributions to the large project which led to the discovery of the field particles W and Z, communicators of the weak interaction'. These discoveries, made at CERN in 1983, confirmed a picture of nature which unifies electromagnetism with the weak nuclear force. The quest began 50 years ago with Enrico Fermi's first formulation of the theory of the weak force, followed by the elegant 'electroweak' picture which earned the Nobel award for Sheldon Glashow, Abdus Salam and Steven Weinberg in 1979.

● Text adapted from *CERN Courier* Nov/Dec 1984 pp 371, 379, 419.

Compiler's note

In 1949 George Orwell famously envisioned a dystopian view of life as it would be by 1984. However, for particle-physics research, 1984 marked a period of sustained progress and, as evidenced in the celebration of CERN's 70th anniversary, the following 40 years have been no less successful. Having started with 12 CERN member states in 1954, the formal entry of Estonia in September 2024 doubled the number. At present, there are more than 12,000 CERN users from both member and non-member states, 1000 graduates and fellows, and over 1500 students and associates, supported by around 2500 staff members. The confidence and interest shown in the facilities provided by the laboratory give firm grounds for expecting its growth and achievements to continue well into the future.

10^4 Number of LHC "fills" so far, reached on 13 August, of which less than one fifth are for physics: the others are associated with dry test cycles, machine commissioning, machine experiments and repeated injection phases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