WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the July/August 2024 issue of *CERN Courier*.

Insulators rather than conductors. Pillars rather than cavities. Microns rather than centimetres. Over the past 30 years, a handful of research groups have been quietly reimagining the electron linac in miniature. Their work is developing rapidly, with focusing, bunching and net acceleration over hundreds of optical cycles all now demonstrated "on chip". This is acceleration, but not as we know it (p35).

This research is no scholarly abstraction. Tens of thousands of conventional electron linacs are used in medicine and industry. In this edition's interview, International Cancer Expert Corps' Manjit Dosanjh and CERN's Steinar Stapnes tell the *Courier* about the need to increase access to medical linacs in low- and middle-income countries. Their newly funded project is based on open science and international cooperation – and it will require the full toolkit of the experimental high-energy physicist (p46).

Elsewhere on these pages: Andrzej Buras identifies the six rare decays that are best placed to probe beyond the energy frontier this decade (p30); CALET studies cosmic-ray anomalies on the International Space Station (p24); DUNE takes shape in Ray Davis Jr's gold mine (p41); ATLAS and CMS hunt the Higgs boson's self-interaction (p7); Wolfgang Lerche reviews *On the Origin of Time* (p49); Silvia Pascoli on the next 10 years in astroparticle physics (p45); electroweak delights from Moriond (p18); and how big is a neutrino? (p8).

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EDITOR: MARK RAYNER, CERN
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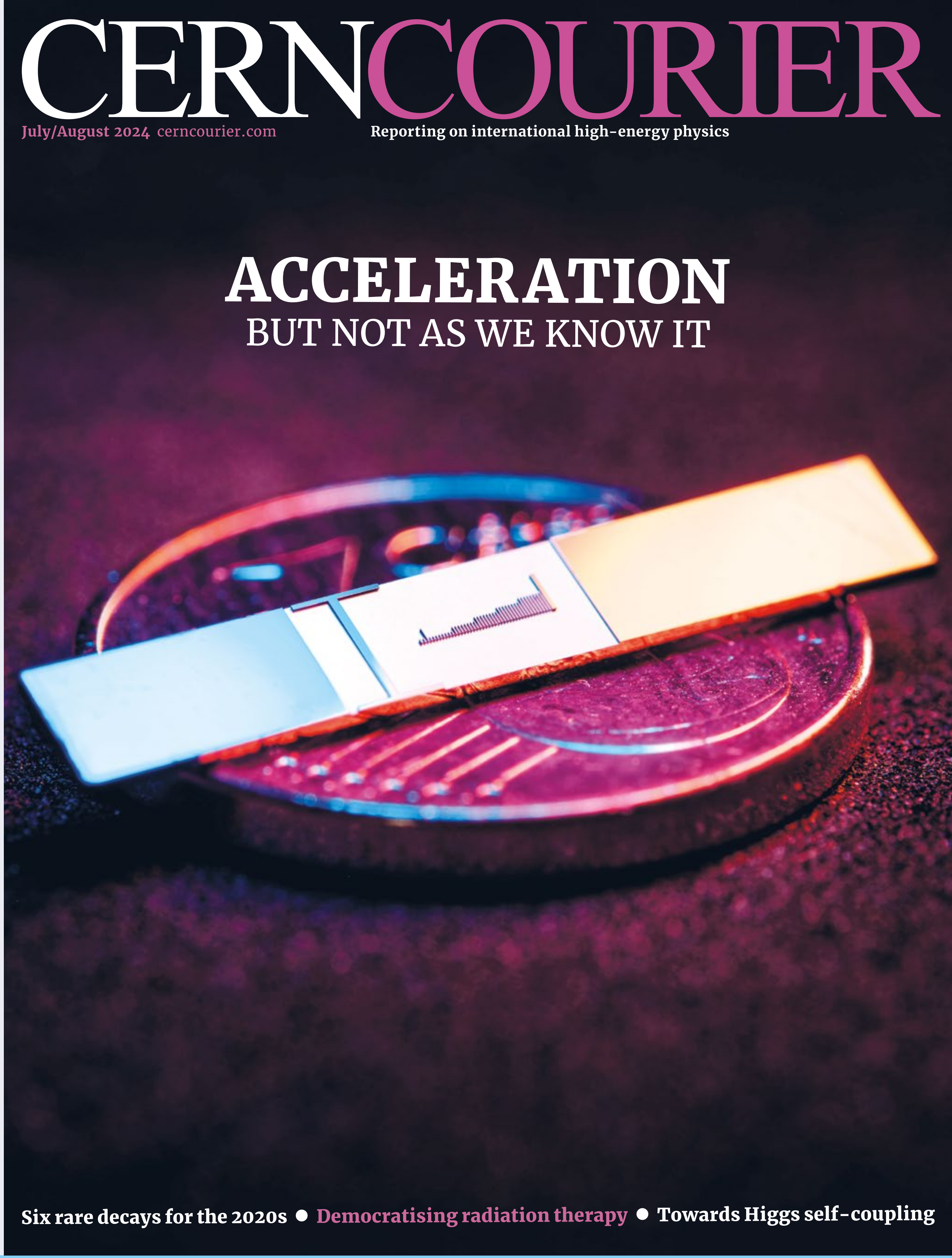

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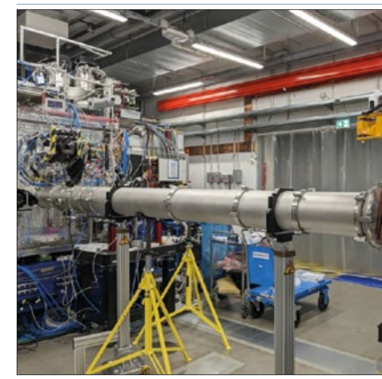

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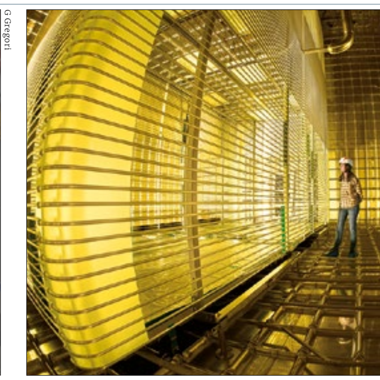

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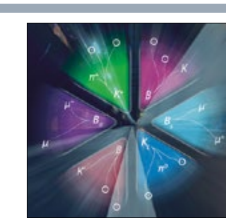

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FROM THE EDITOR

Two new directions for the electron linac

Mark Rayner
Editor

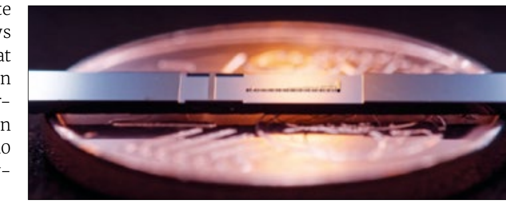
The map of cancer mortality looks alarmingly opposite to the map of GDP per capita. It's no coincidence, says International Cancer Expert Corps' Manjit Dosanjh, that the majority of the world's 18,000 radiotherapy units are in high-income countries. According to figures from the International Atomic Energy Agency, doctors diagnosed 19 million new cases in 2020 alone, and 10 million people died. By 2040 these annual rates are expected to increase by half, with low- and middle-income countries suffering most.

Though hadron-therapy facilities are popping up in affluent regions, the electron linac is the workhorse that cures cancer and relieves pain. But despite the maturity of the technology, these machines are out of reach for many low- and middle-income countries, with costs rising. To disrupt the market and reverse this trend, Dosanjh and colleagues, including CERN's Steinar Stapnes, last month launched an initiative to design a durable and affordable medical linac for the next decade. The project is based on open science and international cooperation, they say – and it will require the full toolkit of the experimental high-energy physicist (p46).

A durable and affordable medical linac will require the full toolkit of the experimental high-energy physicist

Others are thinking bigger by getting smaller. Over the past 30 years, a handful of research groups have been quietly reimagining the electron linac in miniature. Their efforts promise a step change in a field that has advanced incrementally for decades. Insulators rather than conductors. Pillars rather than cavities. Microns rather than centimetres. This is acceleration, dear reader, but not as we know it.

In the 1920s, Rolf Widerøe accelerated particles in oscillating electric fields powered by radio waves. In the 1940s, Vladimir Veksler and Edwin McMillan bunched particles by accelerating them on the edge of the electric field rather than the peak. In the 1950s, Ernest Courant, Hartland Snyder and Nicholas Christofilos focused the bunches like beams of light on a 17th-century optician's bench. Since then, radio waves have been squeezed towards the microwave band, and countless innovations have optimised every aspect of beam control, but the fundamental principles of working accelerators have remained fixed. The implementation of these principles could soon be radically miniaturised. The key, explain Robert Byer, Joel England, Peter Hommelhoff and Roy Shiloh, is powering accelerators using optical lasers. Dielectric laser accelerators are now developing rapidly, with focusing, bunching and net acceleration over hundreds of optical cycles all demonstrated "on chip" (p35).



On the money *40 electron linacs on a chip the size of a Euro-cent coin.*

Six rare decays for the 2020s

Elsewhere on these pages, Andrzej Buras lays out a manifesto for pursuing physics beyond the Standard Model in the second half of the 2020s. Though creating particles in a collider will undoubtedly remain the most powerful way to explore the energy frontier, a little jiggery-pokery with Heisenberg's uncertainty principle can steal a glance at scales as small as a zeptometre and masses as high as 100 TeV, with new physics potentially making its presence felt in decays that ought to be strongly suppressed. Of course, such claims can be made for any number of rare decays, but Buras has selected the most promising six. They exist in the sweet spot where experimental accessibility this decade and accurate predictions overlap. Two are kaon decays. Four are B-meson decays. Three will be measured at CERN and three in Japan. All six promise a glimpse beyond the energy frontier (p30).

Also in this edition: CALET studies cosmic-ray anomalies on the International Space Station (p24); the latest from DUNE (p41); ATLAS and CMS on the Higgs boson's self-interaction (p7); Wolfgang Lerche reviews *On the Origin of Time* (p49); Silvia Pascoli on the next 10 years in astroparticle physics (p45); electroweak delights from Moriond (p18); and how big is a neutrino? (p8).

Reporting on international high-energy physics

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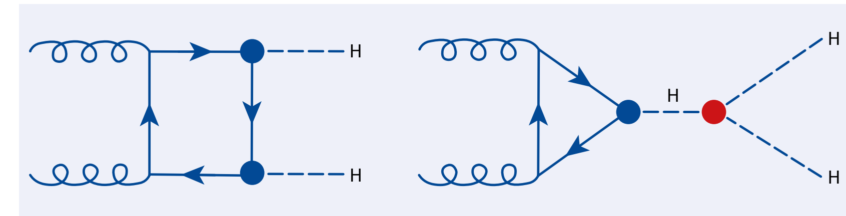
NEWS ANALYSIS

HIGGS AND ELECTROWEAK

Homing in on the Higgs self-interaction

The simplest possible interaction in nature is when three identical particle lines, with the same quantum numbers, meet at a single vertex. The Higgs boson is the only known elementary particle that can exhibit such behaviour. More importantly, the strength of the coupling between three or even four Higgs bosons will reveal the first picture of the shape of the Brout–Englert–Higgs potential, responsible for the evolution of the universe in its first moments as well as possibly its fate.

Since the discovery of the Higgs boson at the LHC in 2012, the ATLAS and CMS collaborations have measured its properties and interactions with increasing precision. This includes its couplings to the gauge bosons and to third-generation fermions, its production cross sections, mass and width. So far, the boson appears as the Standard Model (SM) says it should. But the picture is still fuzzy, and many more measurements are needed. After all, the Higgs boson may interact with new particles suggested by theories beyond the SM to shed light on mysteries including the nature of the electroweak phase transition.



Dominant diagrams *Non-resonant (left) and resonant (right) processes driving di-Higgs production at the LHC. Di-Higgs production offers access to the Higgs trilinear coupling strength (red vertex).*

Line of attack

"The Higgs self-coupling is the next big thing since the Higgs discovery, and di-Higgs production is our main line of attack," says Jana Schaarschmidt of ATLAS. "The experiments are making tremendous progress towards measuring Higgs-boson pair production at the LHC – far more than was imagined would be possible 12 years ago – thanks to improvements in analysis techniques and machine learning in particular."

The dominant process for di-Higgs production at the LHC, gluon–gluon fusion, proceeds via a box or triangle diagram, the latter offering access to the trilinear Higgs coupling constant λ (see figure). Destructive interference between the two processes makes di-Higgs production extremely rare, with a cross section at the LHC about 1000 times smaller than that for single-Higgs production. Many different decay channels are available to ATLAS and CMS. Those with a high probability to occur are chosen if they can also provide a clean way to be distinguished from backgrounds. The most sensitive channels are those with one Higgs boson decaying to a b-quark pair and the other decaying either to a pair of photons, τ leptons or b quarks.

The Higgs self-coupling is the next big thing since the Higgs discovery

During this year's Rencontres de Moriond (p18), ATLAS presented new results in the HH → bbbb and HH → multileptons channels and CMS in the HH → γγττ channel. In May, ATLAS released a combination of searches for HH production in five channels using the complete LHC Run 2 dataset. The combination provides the best expected sensitivities to HH production (excluding values more than 2.4 times the SM prediction) and to the Higgs boson self-coupling. A combination of HH searches published by CMS in 2022 obtains a similar sensitivity to the di-Higgs cross-section limits. "In late 2023 we put out a preliminary result combining single-Higgs and di-Higgs analyses to constrain the Higgs self-coupling, and further work on combining all the latest analyses is ongoing," explains Nadjieh Jafari of CMS.

Considerable improvements are expected with the LHC Run 3 and much larger High-Luminosity LHC (HL-LHC) datasets. Based on extrapolations of early subsets of its Run 2 analyses, ATLAS expects to detect SM di-Higgs production with a significance of 3.2σ (4.6σ) with (without) systematic uncertainties by the end of the HL-LHC era. With similar progress at CMS, a di-Higgs observation is expected to be possible at the HL-LHC even with current analysis techniques, along with improved knowledge of λ. ATLAS, for example, expects to be able to constrain λ to be between 0.5 and 1.6 times the SM expectation at the level of 1σ.

Testing the foundations

Physicists are also starting to place limits on possible new-physics contributions to HH production, which can originate either from loop corrections involving new particles or from non-standard couplings between the Higgs boson and other SM particles. Several theories beyond the SM, including two-Higgs-doublet and composite-Higgs models, also predict the existence of heavy scalar particles that can decay resonantly into a pair of Higgs bosons. "Large anomalous values of λ are already excluded, and the window of possible values continues to shrink towards the SM as the sensitivity grows," says Schaarschmidt. "Furthermore, in recent di-Higgs analyses ATLAS and CMS have been able to establish a strong constraint on the coupling between two Higgs bosons and two vector bosons."

For Christophe Grojean of the DESY theory group, the principal interest in di-Higgs production is to test the foundations of quantum field theory: "The basic principles of the SM are telling us that the way the Higgs boson interacts with itself is mostly dictated by its expectation value (linked to the Fermi constant, i.e. the muon and neutron lifetimes) and its mass. Verifying this prediction experimentally is therefore of prime importance."

Further reading

ATLAS Collab. 2024 arXiv:2405.20040.
CMS Collab. 2023 CMS-PAS-HIG-23-006.

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NEUTRINOS

Tabletop experiment constrains neutrino size

How big is a neutrino? Though the answer depends on the physical process that created it, knowledge of the size of neutrino wave packets is at present so wildly unconstrained that every measurement counts. New results from the Beryllium Electron capture in Superconducting Tunnel junctions (BeEST) experiment in TRIUMF, Canada, set new lower limits on the size of the neutrino's wave packet in terrestrial experiments – though theorists are at odds over how to interpret the data.

Neutrinos are created as a mixture of mass eigenstates. Each eigenstate is a wave packet with a unique group velocity. If the wave packets are too narrow, they eventually stop overlapping as the wave evolves, and quantum interference is lost. If the wave packets are too broad, a single mass eigenstate is resolved by Heisenberg's uncertainty principle, and quantum interference is also lost. No quantum interference means no neutrino oscillations.

"Coherence conditions constrain the lengths of neutrino wave packets both from below and above," explains theorist Evgeny Akhmedov of MPI-K Heidelberg. "For neutrinos, these constraints are compatible, and the allowed window is very large because neutrinos are very light. This also hints at an answer to the frequently asked question of why charged leptons don't oscillate."

The spatial extent of the neutrino wavepacket has so far only been constrained to within 13 orders of magnitude by reactor-neutrino oscillations, say the BeEST team. If wave-packet sizes were at the experimental lower limit set by the world's oscillation data, it could have impacted future oscillation experiments, such as the Jiangmen Underground Neutrino Observatory (JUNO) that is currently under construction in China.


Garry McLeod/LLNL

A TRIUMF *The BeEST experiment has set new lower limits on the size of the neutrino's wave packet.*

"This could have destroyed JUNO's ability to probe the neutrino mass ordering," says Akhmedov, "however, we expect the actual sizes to be at least six orders of magnitude larger than the lowest limit from the world's oscillation data. We have no hope of probing them in terrestrial oscillation experiments, in my opinion, though the situation may be different for astrophysical and cosmological neutrinos."

BeEST uses a novel method to constrain the size of the neutrino wavepacket. The group creates electron neutrinos via electron capture on unstable ^{7}Be nuclei produced at the TRIUMF–ISAC facility in Vancouver. In the final state there are only two products: the electron neutrino and a newly transmuted ^{7}Li daughter atom that receives a tiny energy "kick" by emitting the neutrino. By embedding the ^{7}Be isotopes in superconducting quantum sensors at 0.1K, the collaboration can measure this low-energy recoil to high precision. Via the uncertainty principle, the team infers a limit on the spatial localisation of the entire final-state system of 6.2pm – more than 1000 times larger than the nucleus itself.

Consensus has not been reached on how to infer the new lower limit on the size of the neutrino wave packet, with the preprint quoting two lower limits in the vicinity of 10^{-11} m and 10^{-8} m based on different theoretical assumptions. Although they differ dramatically, even the weaker limit improves upon all previous reactor oscillation data by more than an order of magnitude, and is enough to rule out decoherence effects as an explanation for sterile-neutrino anomalies, says the collaboration.

"I think the more stringent limit is correct," says Akhmedov, who points out that this is only about 1.5 orders of magnitude lower than some theoretical predictions. "I am not an experimentalist and therefore cannot judge whether an improvement of 1.5 orders of magnitude can be achieved in the foreseeable future, but I very much hope that this is possible."

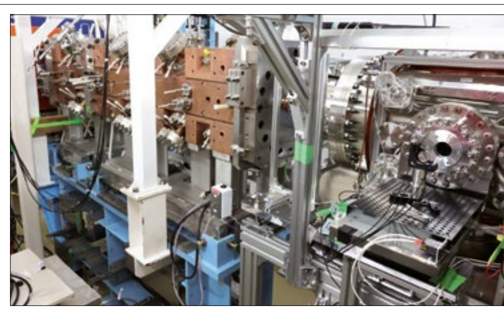
Further reading

J Smolsky *et al.* 2024 arXiv:2404.03102.

ACCELERATOR PHYSICS

Muons cooled and accelerated in Japan

In a world first, a research group working at the J-PARC laboratory in Tokai, Japan, has cooled and accelerated a beam of antimatter muons (μ^+). Though muon cooling was first demonstrated by the Muon Ionisation Cooling Experiment in the UK in 2020 (*CERN Courier* March/April 2020 p7), this is the first time that the short-lived cousins of the electron have been accelerated after cooling – an essential step for applications in particle physics.


J-PARC

World first *The experimental set up for muon cooling and acceleration at J-PARC. A beam of antimatter muons enters the apparatus from the right.*

The cooling method is ingenious – and completely different to ionisation cooling, where muons are focused in absorbers to reduce their transverse momentum. Instead, μ^+ are slowed to 0.002% of the speed of light in a thin silica-aerogel target, capturing atomic electrons to form muonium, an atom-like compound of an antimatter muon and an electron. Experimenters then ionise the muonium using a laser to create a near monochromatic beam that is reaccelerated in radiofrequency (RF) cavities. The work builds on the acceleration of negative muonium ions – an antimatter muon bonded to two electrons – which the team demonstrated in 2017 (*CERN Courier* July/August 2018 p8).

Though the analysis is still to be finalised, with results due to be published soon, the cooling and acceleration effect is unmistakable. In accelerator physics, cooling is traditionally quantified by a reduction in beam emittance – an ▷

otherwise conserved quantity that reflects the volume occupied by the beam in the abstract space of orthogonal displacements and momenta. Estimates indicate a beam cooling effect of more than an order of magnitude, with the beam then accelerated from 25 meV to 100 keV. The main challenge is transmission. At present one antimatter muon emerges from the RF for every 10 million, which impact the aerogel. Muon decay is also a challenge given that the muonium is nearly stationary in the laboratory frame, with time dilation barely extending the muon's 2.2 μs lifetime. Roughly a third of the μ^+ decay before exiting the J-PARC apparatus.

The first application of this technology will be the muon g-2/EDM experiment at J-PARC, where data taking is due to start in 2028. The experiment will add valuable data points to measurements thought to have exceptional sensitivity to new physics (*CERN Courier* May/June 2021 p25). In the case of the anomalous magnetic moment (g-2) of the muon, theoretical showdowns later this year may either dissipate or reinforce intriguing hints of beyond-the-Standard-Model physics from the Muon g-2 experiment at Fermilab, potentially adding strong motivation to an independent test.

We are very impressed with the progress of our colleagues at J-PARC and congratulate them on their success

"Although our current focus is the muon g-2/EDM experiment, we are open to any possible applications of this technology in the future," says spokesperson Tsutomu Mibe of KEK. "We are communicating with experts to understand if our technology is of any use in a muon collider, but note that our method cannot be adapted for negative muons."

While proposals for a $\mu^+\mu^+$ or μ^+e^- collider exist, a $\mu^+\mu^-$ collider remains the most strongly motivated machine. "Much of the physics interest in e^+e^- and $\mu^+\mu^-$ colliders comes from the annihilations of the initial particles into a photon and/or a Z boson, or a Higgs boson in the case of $\mu^+\mu^-$," says John Ellis of CERN/KCL. "These possibilities are absent for a μ^+e^- or $\mu^+\mu^+$ collider, making them less interesting in my opinion." From an accelerator-physics perspective, it remains to be demonstrated that the technique can deliver the beam intensity needed for an energy-frontier collider – not least while keeping the emittance low.

"We are very impressed with the progress of our colleagues at J-PARC and congratulate them on their success," says International Muon Collider study leader Daniel Schulte of CERN. "This will profit the development of muon-beam technology and use. We are in contact to understand how we can collaborate."

Further reading

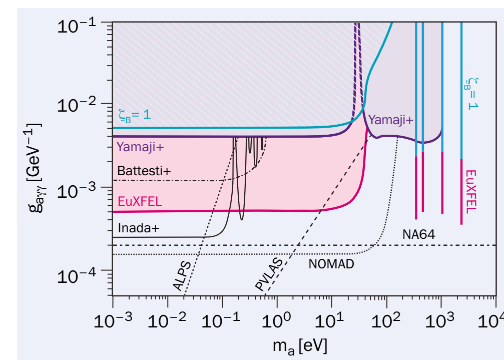
M Abe *et al.* 2019 *PTEP* **5** 053C02.
Y Hamada *et al.* 2022 *PTEP* **5** 053B02.

SEARCHES FOR NEW PHYSICS

XFELs join hunt for axion-like particles

A first-of-its-kind experiment performed at the European X-Ray Free-Electron Laser (European XFEL) in Hamburg, Germany, has placed new constraints on axion-like particles in a mass range that is relatively unconstrained by laboratory searches. While similar searches have been performed at advanced storage-ring-based synchrotron X-ray sources, the new study exploits the higher brightness of the European XFEL's beams to improve the sensitivity of axion searches in the 10^{-3}–10^4 eV mass range.

The axion is predicted to arise from the breaking of Peccei–Quinn symmetry, proposed in the mid-1970s to explain the observed absence of CP violation in strong interactions. Indeed, axion-like particles (ALPs) appear in any quantum field theory with a spontaneously broken global symmetry and arise naturally in many models based on string theory. They are also a promising candidate for dark matter. As such, ALPs are the target of a growing number and variety of experiments worldwide. While not yet able to reach the sensitivity of astrophysical experiments, lab-based searches are less model-dependent as they enable direct control of the axion production process.



arXiv:2404.17333

New territory *Bounds on the axion–photon coupling from the latest study (pink) compared with those from previous results from synchrotron X-ray facilities (purple) and other lab searches.*

Most laboratory searches for axions exploit the Primakoff effect: photons in the presence of a strong external electric field convert into axions, which then convert back into photons after passing through an opaque wall. This "light shining through a wall" technique has been employed in experiments with optical lasers and external magnetic fields, such as ALPS (and now ALPS II) at DESY and OSQAR at CERN. Stringent bounds on heavy axions have also been placed by the CERN Axion Solar Telescope, which looked for the conversion of photons to axions in the strong magnetic field of an LHC dipole magnet pointed at the Sun, and constraints have been set by accelerator experiments such as Belle II at KEK and NA64 at CERN.

The use of X-rays can improve the detection sensitivity by exploiting the strong electric fields (up to 10^{11} Vm^{-1}, which corresponds to magnetic field strengths of order 1kT) present in crystalline materials. Gianluca Gregori of the University of Oxford and co-workers used the European XFEL's HED/HiBEF instrument, in which axion production and photon regeneration are expected to take place via the electric field within a pair of germanium crystals. Orienting the crystals such that their lattice planes are parallel to one another leads to a coherent effect analogous to Bragg scattering, while the much shorter duration and higher brightness of photon pulses from the European XFEL compared to previous synchrotron X-ray experiments allows for a more accurate discrimination of the signal against background.

Using three days of beam time, the team was able to improve on previous lab-based searches at several discrete axion masses. For masses greater than about 200 eV, the team claims to have surpassed the sensitivity of bounds from all previous searches for lab-generated axions except those at NA64. Further improvements in sensitivity – for example by enabling a higher X-ray flux and bunch-number, and by cooling the first crystal to extend the data-acquisition time – are possible, says the team, perhaps bringing the estimated bounds close to the expectation for QCD axions to be dark matter.

"This study shows the power of XFELs, alongside their principal role in more applied domains, to probe fundamental physics mysteries," says Gregori. "This experiment required a difficult interpretation of a non-standard measurement, and it is hoped that further work will improve on these first limits."

Further reading

J W D Halliday *et al.* 2024 arXiv:2404.17333.

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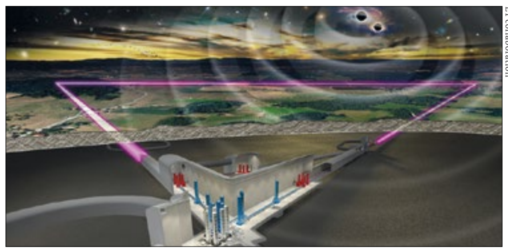
FACILITIES

CERN teams up with ET on civil engineering



ET collaboration

Deep view *The Einstein Telescope will make it possible to explore gravitational waves throughout cosmic history.*

The Einstein Telescope (ET), a proposed third-generation gravitational-wave observatory in Europe with a much higher sensitivity than existing facilities, requires a new underground infrastructure in the form of a triangle with 10 km-long arms. At each corner a large cavern will host complex mirror assemblies that detect relative displacements as small as 10^{-22} m caused by momentary stretches and contractions of space–time. Access to the underground structure, which needs to be at a depth of between 200 and 300 m to mitigate environmental and seismic noise, will be provided by either vertical shafts or inclined tunnels. Currently there are two candidate sites for the ET: the Meuse–Rhine Euroregion and the Sardinia region in Italy, each with their own geology and environment.

CERN is already sharing its expertise in vacuum, materials, manufacturing and surface treatments with the gravitational-wave community. Beginning in 2022, a collaboration between CERN, Nikhef and INFN is exploring practical solutions for the ET vacuum tubes which, with a diameter of 1 to 1.2 m, would represent the largest ultrahigh vacuum systems ever built (*CERN Courier* September/October 2023 p45).

In September 2023, the ET study entered a further agreement with CERN to support the preparation of a site-independent technical design report. With civil-engineering costs representing a significant proportion of the overall implementation budget, detailed studies are needed to ensure a cost-efficient design and construction methodology. Supported financially by INFN, Nikhef and IFAE, CERN will provide technical assistance on how to optimise the tunnel placement, for example via software tools to generate geological profiles. Construction methodology and management of excavated materials, carbon footprint, environmental impact, and project cost and schedule, are other key aspects. CERN will also provide recommendations during the technical review of the associate documents that feed into the site selection.

"We are advising the ET study on how we managed similar design studies for colliders such as CLIC, ILC, the FCC and the HL-LHC upgrade," explains John Osborne of CERN's site and civil-engineering department. "CERN is acting as an impartial third party in the site-selection process."

A decision on the most suitable ET site is expected in 2027, with construction beginning a few years later. "The collaboration with CERN represents an element of extreme value in the preparation phase of the ET project," says ET civil-engineering team leader Maria Marsella. "CERN's involvement will help to design the best infrastructure at any selected sites and to train the future generation of engineers who will have to face the construction of such a large underground research facility."

POLICY

US and CERN sign joint statement of intent

US Department of State

Forging the future *Deirdre Mulligan of the White House Office of Science and Technology (left) and CERN Director-General Fabiola Gianotti.*

In April, CERN and the US government released a joint statement of intent concerning future planning for large research infrastructures, advanced scientific computing and open science. The statement was signed in Washington, DC by CERN Director-General Fabiola Gianotti and principal deputy US chief technology officer Deirdre Mulligan of the White House Office of Science and Technology.

Acknowledging their longstanding partnership in nuclear and particle physics, CERN and the US intend to enhance collaboration in planning activities for large-scale, resource-intensive facilities. Concerning the proposed Future Circular Collider, FCC-ee, the text states: "Should the CERN Member States determine that the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the US intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals." A technical and financial feasibility study for the proposed FCC is due to be completed in March 2025.

CERN and the US also intend to discuss potential collaboration on pilot projects to incorporate new analysis techniques and tools such as AI into particle-physics research at scale, and affirm their collective mission "to take swift strategic action that leads to accelerating widespread adoption of equitable open research, science and scholarship throughout the world".

ASTROWATCH

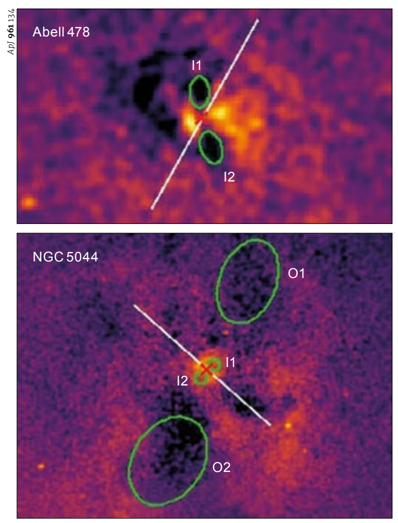
Super-massive black holes quickly repoint their jets

With masses up to 10^{15} times greater than that of the Sun, galaxy clusters are the largest concentrations of matter in the universe. Within these objects, the space between the galaxies is filled with a gravitationally bound hot plasma. Given time, this plasma accretes on the galaxies, cools down and eventually forms stars. However, observations indicate that the rate of star formation is slower than expected, suggesting that processes are at play that prevent the gas from accreting. Violent bursts and jets coming from super-massive black holes in the centre of galaxy clusters are thought to quench star formation. A new study indicates that these jets rapidly change their directions.

Violent bursts and jets are thought to quench star formation

Super-massive black holes form the centre of all galaxies, including our own, and can undergo periods of activity during which powerful jets are emitted along their spin axes. In the case of galaxy clusters, these bursts can be spotted in real time by looking at their radio emission, while their histories can be traced using X-ray observations. As the jets are emitted, they crash into the intra-cluster plasma, sweeping up material and leaving behind bubbles, or cavities, in the plasma. As the plasma emits in the X-ray region, these bubbles reveal themselves as voids when viewed with X-ray detectors. After their creation, they continue to move through the plasma and remain visible long after the original jet has disappeared (see image below).

Francesco Ubertosi of the University of Bologna and co-workers studied a sample of about 60 clusters observed using the Very Long Baseline Array, which produces highly detailed radio information, and the Chandra X-ray telescope. The team studied the angle between the cavities and the current radio jet and found that most cavities are simply aligned, indicating that the current jet points in the same direction as those responsible for the cavities produced in the past. However, around one third of the studied objects show significant angles, some as large as 90°.



ApJ **961** 134

Into the void *Two galaxy clusters observed by the Chandra X-ray Observatory, showing the cavities (green ellipses), the current direction of the radio jets (white line), and the location of their parent super-massive black hole (red cross).*

This study therefore shows that the source of the jet, the super-massive black hole, appears to be able to reorient itself over time. More importantly, by dating the cavities the team showed that this can happen within time scales of just one million years. To get an idea of the rapidity of this change, consider that the solar system takes 225 million years to revolve around the super-massive black hole at the centre of the Milky Way. Analogously, Earth takes 365 days for one revolution around the Sun. Therefore, if the Milky Way's super-massive black hole altered its spin axis on the timescale of one million years, it would be as if the Sun were to change its spin axis in a matter of a few days.

These observations raise the question of how the re-orientation of jets from super-massive black holes takes place. The authors find that the results are unlikely to be due to projection effects, or perturbations that significantly shift the position of the cavities. Instead, the most plausible explanation is that the spin axes of the super-massive black hole tilt significantly, likely affected by complex accretion flows. The results therefore reveal important information about the accretion dynamics of super-massive black holes. They also offer important insights into how stars form in these clusters, as the reorientation would further suppress star formation.

Further reading

F Ubertosi *et al.* 2024 *ApJ* **961** 134.

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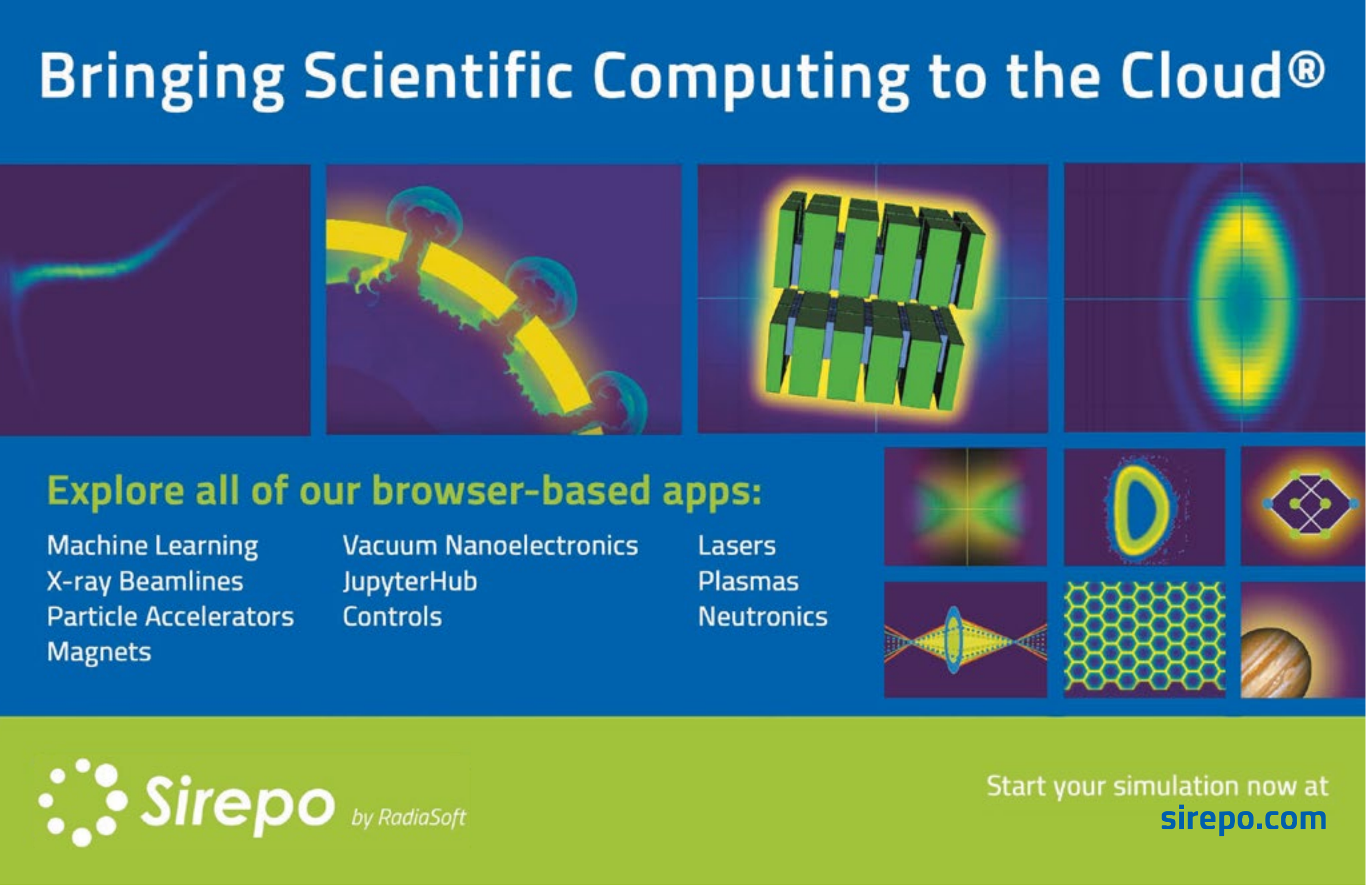


NEWS DIGEST

Quantum centenary

During a brief period 100 years ago, de Broglie, Heisenberg, Pauli, Born, Jordan, Schrödinger, Dirac and others rocked physicists' notions about nature. To raise awareness of the impact of quantum mechanics on technological progress, sustainable development and education, the United Nations on 7 June proclaimed 2025 as the International Year of Quantum Science and Technology.

Entangled tops at CMS

Probing the tenets of quantum mechanics at the highest energies ever, the CMS collaboration has twice observed entanglement in $t\bar{t}$ production at the LHC. An observation of entanglement in the top quark–antiquark system was recently reported by ATLAS (*CERN Courier* November/December 2023 p15). The first CMS result differs in that it measures entanglement at the parton rather than particle level, says the collaboration, and considers non-relativistic bound-state effects in the production threshold (arXiv:2406.03976). A second measurement unique to CMS deals with top quarks that are produced at high momentum, for the first time observing entanglement in events with high $t\bar{t}$ mass (CMS-TOP-23-007). The observed level of entanglement cannot be explained by the classical exchange of information between the two particles alone.

Dark-meson first

By extending the Standard Model (SM) with a strongly coupled gauge theory in which fermion representations transform under the electroweak group, dark matter can arise in the form of composite mesons or baryons that are the direct analogue of the known QCD states. Intriguingly, such a dark sector is only weakly constrained by precision electroweak or Higgs-coupling measurements, while in some models Higgs-boson interactions break the global symmetry and allow dark mesons to decay into pure SM states. The ATLAS collaboration has now reported the results of the first direct search for dark mesons arising from such a model. No excess above the SM background expectation was observed, placing the first direct collider constraints on "stealth dark matter" and significantly extending the phase space previously excluded through re-interpretations of other collider searches (arXiv:2405.20061).

South Pole on ice

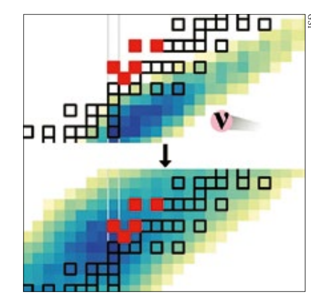
The Cosmic Microwave Background Stage 4 experiment – which would see multiple telescopes in Chile and at the South Pole measure the anisotropies in the cosmic microwave background in much finer detail (*CERN Courier* March/April 2022 p36) – will not progress "in its current form", stated the US National Science Foundation on 7 May. While acknowledging the strong scientific support for the experiment, which was marked as "absolutely central" and "ready for construction" in the recent US P5 report, the agency "must prioritise the recapitalisation of critical infrastructure at the South Pole so that the groundbreaking research it enables can continue to thrive". The team is working to reformulate CMB-S4 to move forward within these new logistical constraints, likely entirely in Chile, says co-spokesperson Jeff McMahon.

Rarest hyperon decay

The LHCb collaboration has reported the observation of $\Sigma^+ \to p\mu^+\mu^-$, the rarest known hyperon decay (LHCb-CONF-2024-002). In addition to observing a large peak at the Σ^+ mass containing 279 ± 19 events, the collaboration compared the background-subtracted $\mu^+\mu^-$ mass spectrum with different simulations. Interest in the $\Sigma^+ \to p\mu^+\mu^-$ dimuon mass spectrum arose after the HyperCP collaboration found an unexpected hint of a narrow resonance structure, albeit with low statistics. This feature is absent in the latest LHCb data.

Neutrino nucleosynthesis

Introducing neutrinos to the mechanisms of stellar nucleosynthesis can account for the puzzling existence of neutron-deficient heavy nuclei, according to a model proposed by researchers at GSI Darmstadt. Fusion processes in massive stars produce nuclei up to iron and nickel, beyond which most of the stable heavy nuclei are produced via neutron-capture processes. For the rest, the rarer neutron-deficient "p-nuclei", a variety of nucleosynthesis processes have been suggested. But it has remained a challenge



GSI

Nuclide map with p-nuclei in red.

to explain the large abundances of $^{92,94}Mo$, $^{96,98}Ru$ and ^{92}Nb in the Solar System. The new "νr-process", proposed to operate in neutron-rich outflows in astrophysical explosions, suggests that neutrinos catalyse a series of capture reactions to enable the simultaneous production of all those nuclei (*Phys. Rev. Lett.* **132** 192701).

QUIET beneath Fermilab

A new quantum sensor and computing research centre QUIET (Quantum Underground Instrumentation Experimental Testbed), which will allow

D Svoboda/Fermilab

Noises off.

researchers to understand the difference between the impact of gamma rays, X-rays, muons and electrons on superconducting qubits, opened on 30 May. QUIET is located 100 m beneath Fermilab. Its slightly noisier neighbour, LOUD, which resides above ground, has been operating for over a year.

Pions in, nothing out

The NA64 collaboration at the CERN SPS has presented the first results from a novel search for invisible decays of η and η' mesons produced via charge-exchange reactions of 50 GeV pions on the nuclei of an active target. Such decays would reveal themselves via a striking signature, possibly hinting towards dark matter: the complete disappearance of the incoming beam energy in the detector. Analysing 2.9×10^9 pions on target accumulated during one day of data taking, no evidence for such events was found, setting an upper limit on the $\eta' \to$ *invisible* branching ratio (2.1×10^{-4}) that improves the previous bound by a factor of about three (arXiv:2406.01990).

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ALICE

Intrigue in charm hadronisation

Quantum chromodynamics (QCD) is one of the pillars of the Standard Model of particle physics, but much remains to be understood about its emergent behaviours, and theoretical calculations often disagree. A new result from the ALICE collaboration has now added fresh intrigue to interpretations of hadronisation – the process by which quarks and gluons become confined inside colour-neutral groupings such as baryons and mesons.

The production of heavy charm and beauty quarks in proton–proton collisions at the LHC is a rather fast process (~7×10^{-24} s) and subject to perturbative QCD calculations. On the other hand, the transformation of heavy quarks into hadrons requires substantially more time (~3×10^{-23} s). This separation of time scales has motivated the idea that the hadronisation process of heavy quarks is independent of the colliding system and collision energy. However, the production of baryons carrying a heavy quark in proton–proton collisions at the LHC has been found to be enhanced compared to more elementary e^+e^- collisions. This surprising finding seems to invalidate the concept of universal hadronisation of heavy quarks, which is an important basis for calculations of particle production in QCD.

A new dimension

Heavy-flavour baryons carrying charm and strange quarks add a new dimension to these measurements. Such measurements are challenging because they suffer from low production rates. Due to the short lifetime of charm baryons (typically a fraction of a picosecond), they are usually observed through the detection of their decay products. The probability of how often they decay into a particular set of daughter particles, known as the branching ratio (BR), is poorly known for many of the strange-charm baryons. Knowledge of the precise branching ratio is crucial for interpreting the production results of these baryons.

Recently, the ALICE collaboration has measured the production of Ω_c^0 (css) baryons via the semileptonic decay channel $\Omega_c^0\to\Omega^-e^+\nu_e$ (and its charge-conjugate modes) as a function of transverse momentum (p_T) in proton–proton collisions at 13 TeV at midrapidity (|y| < 0.8). The Ω_c^0 candidates are built by pairing an electron or positron candidate track with an Ω baryon candidate using a Kalman Filter vertexing algorithm. The Ω candidates are reconstructed via the cascading decay chain $\Omega^-\to\Lambda K^-$, followed by the decay $\Lambda\to p\pi^-$. The missing momentum of the neutrino was corrected by using an unfolding technique. Figure 1 shows the invariant-mass distribution of the Ω_c^0 candidates.

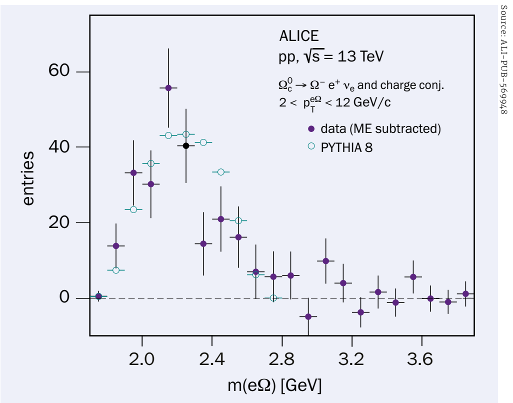


Fig. 1. *The invariant-mass distribution of the Ω_c^0 candidates.*

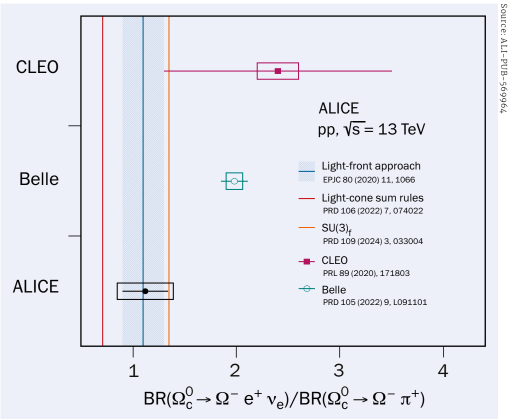


Fig. 2. *A comparison of $BR(\Omega_c^0\to\Omega^- e^+\nu_e)/BR(\Omega_c^0\to\Omega^-\pi^+)$ from experimental measurements and theoretical calculations.*

ALICE is on the way to collecting a data sample that will enable more precise measurements of other decay modes

Figure 2 compiles measurements of the decay by CLEO, Belle and now ALICE. Due to the lack of an absolute BR, results are quoted relative to the BR of $\Omega_c^0\to\Omega^-\pi^+$. Combined with the earlier measurement of $\Omega_c^0\to\Omega^-\pi^+$, the relative probability of the two decay modes is obtained: $BR(\Omega_c^0\to\Omega^-e^+\nu_e)/BR(\Omega_c^0\to\Omega^-\pi^+) = 1.12 \pm 0.22$ (stat.) $\pm$ 0.27 (syst.). The Belle and CLEO collaborations have measured this ratio to be 1.98 ± 0.13 (stat.) ± 0.08 (syst.) and 2.4 ± 1.1 (stat.) ± 0.2 (syst.). Model predictions using the light-front approach and light-cone sum rules predict values of 1.1 ± 0.2 and 0.71, respectively. Another approach calculates decay modes and probabilities of charmed-baryon decays based on $SU(3)_f$ flavour symmetry in the quark model, resulting in a computed branching fraction ratio of 1.35.

The ALICE result is consistent with theory calculations and is 2.3σ lower than the more precise value reported by the Belle collaboration. The present measurement provides constraints on the decay probabilities of the Ω_c^0 baryons. It demonstrates that such measurements are now possible at the LHC with a precision similar to that at e^+e^- colliders.

With the ongoing Run 3 at the LHC and thanks to the recent upgrades, ALICE is on the way to collecting a data sample that is about a thousand times larger for these types of analyses, which will enable more precise measurements of other decay modes. Thanks to these data, we expect to resolve the question of universal hadronisation in the near future.

Further reading

ALICE Collab. 2024 arxiv:2404.17272.

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ATLAS

Zooming in on leptonic W decays

In the Standard Model of particle physics, the three charged lepton flavours couple to the electroweak gauge bosons W and Z with the same strength – an idea known as lepton flavour universality (LFU). This implies that differences in the rates of processes involving W or Z bosons together with electrons, muons and tau leptons should arise only from differences in the leptons' masses. Experimental results agree with LFU at the 0.1–0.2% level in the decays of tau leptons, kaons and pions, but hints of deviations have been seen in B-meson decays, for example in the combination of measurements of $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}\mu\nu$ decays at the BaBar, Belle and LHCb experiments.

The W and Z bosons are so heavy that the probabilities for them to decay to electrons, muons and tau leptons are expected to be equal to very high precision, if LFU holds. This implies that the ratios of these probabilities such as $R(\mu/e)$, which compares $W \to \mu\nu$ with $W \to e\nu$, and $R(\tau/\mu)$, which compares $W \to \tau\nu$ and $W \to \mu\nu$, should be unity. Experiments at the LEP electron–positron collider measured a surprisingly large value of $R(\tau/\mu) = 1.070 \pm 0.026$, but a more precise measurement from the ATLAS collaboration at the LHC found $R(\tau/\mu) = 0.992 \pm 0.013$, in agreement with LFU. This measurement made use of the large sample of top-quark pair events produced at ATLAS during Run 2 of the LHC from 2015 to 2018. These top-quark events can be cleanly selected, with each event containing two W bosons and two b-quarks produced from the decays of the top quarks.

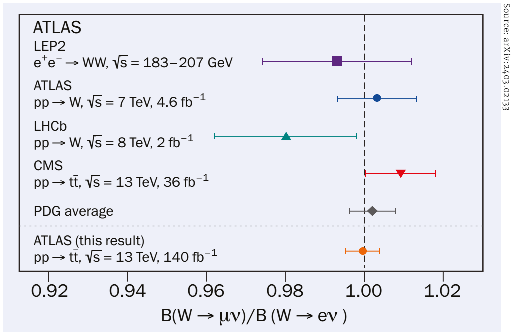

Fig. 1. *Measurements of $R(\mu/e)$, the ratio of probabilities for the W boson to decay to muons and electrons.*

In a new measurement, ATLAS has turned its attention to the comparison of W decays to muons and electrons, via the ratio $R(\mu/e)$. The collaboration again used top-quark pair events as a clean and copious source of W bosons. Counting the number of events with one electron from $W \to e\nu$, one muon from $W \to \mu\nu$, and one or two b-tagged jets, provides the cleanest way to measure the rate of top-quark pair production. But this rate can also be measured from the number of top-quark pair events with two electrons or two muons. If $R(\mu/e) = 1$ and $W \to e\nu$ and $W \to \mu\nu$ decays occur with equal probability, the rates of such ee and μμ events should be the same, after correcting for detector efficiencies. Any difference would suggest a violation of LFU.

Some measurement uncertainties have similar effects on the ee and μμ final states, so they largely cancel in the ratio $R(\mu/e)$. However, electrons and muons behave in very different ways in the ATLAS detector, giving different detection efficiencies with differing and uncorrelated uncertainties that do not cancel in the ratio. To reduce the sensitivity of the measured $R(\mu/e)$ to these effects, the double ratio $R(\mu/e)/\sqrt{R(\mu\mu/ee)}$ was measured first, where $R(\mu\mu/ee)$ corresponds to the comparison of $Z \to \mu\mu$ and $Z \to ee$ decay probabilities, determined from the same dataset. The final $R(\mu/e)$ was then obtained by making use of the very precise measurement of $R(\mu\mu/ee)$ from the LEP experiments and the SLD experiment at SLAC, which has an uncertainty of only 0.0028. This latter ratio acts as a calibration of the relative detection efficiencies of electrons and muons in ATLAS, reducing the associated uncertainties in $R(\mu/e)$.

The final result from this new ATLAS analysis is $R(\mu/e) = 0.9995 \pm 0.0045$, perfectly compatible with unity. The measurement is compared to previous results from LHC and LEP experiments (see figure 1). Thanks to the large data sample and careful control of all systematic uncertainties, it improves on the uncertainty of 0.006 from all previous measurements combined. At least in W decays, LFU survives intact.

Further reading

ATLAS Collab. 2024 arXiv:2403.02133.
ATLAS Collab. 2021 *Nature Phys.* **17** 813.
ATLAS Collab. 2023 *JHEP* **2307** 141.

LHCb

LHCb squeezes D-meson mixing

The weak force, unlike other fundamental forces, has a distinctive feature: its interactions slightly differ when involving quarks or antiquarks. This phenomenon, known as CP violation, allows for an asymmetry in the likelihood of a process occurring with matter compared to its antimatter counterpart, which is an essential requirement to explain the large dominance of matter in the universe. However, the size of CP violation predicted by the Standard Model (SM), and in accordance with experimental measurements so far, is not large enough to explain this cosmological imbalance. This is why physicists are actively searching for new sources of CP violation and striving to improve our understanding of the known ones. The phenomenology offered by the quantum-mechanical oscillations of neutral mesons into their antimatter counterparts, the antimesons, provides a particularly rich experimental ground for such studies.

The LHCb collaboration recently measured a set of parameters that determine the matter–antimatter oscillation of the neutral D^0 meson into the $\bar{D}^0$ antimeson with unprecedented precision. This enables the search for the predicted hitherto unobserved CP violation in this oscillation.

D^0 mesons are composed of a charm quark and an up antiquark. Their oscillations are extremely slow, with an oscillation period over a thousand times longer than their lifetimes. As a result, only a very few D^0 mesons transform before they decay. Oscillations are therefore identified as extremely small changes in the flavour mixture – matter or antimatter – as a function of the time at which the D^0 or the $\bar{D}^0$ decays.

These findings call for future analyses of this and other decays of the D^0 meson using data from the third and fourth run of the LHC

In LHCb's analysis, the initial matter–antimatter flavour of the neutral meson is experimentally inferred from the charge of the accompanying pion in the CP-conserving decay chains $D^*(2010)^+ \to D^0\pi^+$ and $D^*(2010)^- \to \bar{D}^0\pi^-$. The mixing effect (or oscillation) then appears as a decay-time dependence of the ratio, R, of the number of "suppressed" and "favoured" decay processes of the neutral meson. The suppressed decays can occur with or without a net oscillation of the D^0 meson, while the favoured decays are largely dominated by the direct process. In the absence of mixing, this ratio is predicted to be constant as a function of the D^0 ▷

decay time while, in the case of mixing, it approximately follows a parabolic behaviour, increasing with time. Figure 1 shows the ratio R, including data for both matter (R^+ for $D^0 \to K^+\pi^-$) and antimatter (R^- for $\bar{D}^0 \to K^-\pi^+$) processes, and corresponding model predictions. The variation depends not only on the oscillation parameters but also on the various observables of CP violation, which differentiate between matter and antimatter.

This analysis is the most precise measurement of these parameters to date, improving the uncertainty on both mixing and CP-violating observables by a factor of 1.6 compared to the previous best result, also by LHCb. This improvement is largely due to an unprecedentedly large sample of about 1.6 million suppressed decays and 421 million favoured decays collected during Run 2, making LHCb unique in probing up-type quark transitions. The results confirm the matter–antimatter oscillation of the D^0 meson and show no evidence of CP violation in the oscillation.

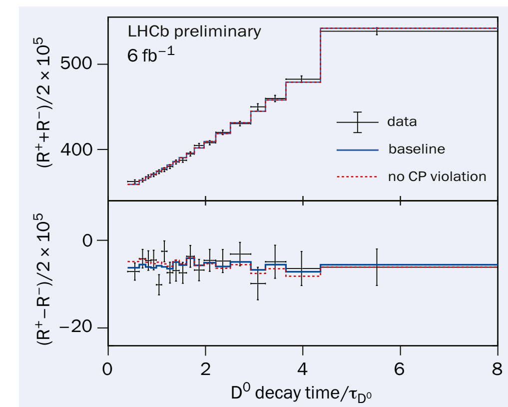

Fig. 1. *The half sum (top) and half difference (bottom) of suppressed-to-favoured yield ratios for $K^+\pi^-$ (R^+) and $K^-\pi^+$ (R^-) final states of neutral D-meson decays. The non-flat dependence of the half-sum on decay time reveals the presence of D^0–$\bar{D}^0$ oscillations.*

These findings call for future analyses of this and other decays of the D^0 meson using data from the third and fourth run of the LHC, exploiting the potential of the currently operating detector upgrade (Upgrade I). The detector upgrade proposed for the fifth and sixth runs of the LHC (Upgrade II) would provide a six-times-bigger sample, yielding the precision needed to definitively test the predictions of the SM.

Further reading

LHCb Collab. 2024 LHCb-PAPER-2024-008.

CMS

CMS studies single-top production

Being the most massive known elementary particle, top quarks are a focus for precision measurements and searches for new phenomena. At the LHC, they are copiously produced in pairs via quantum chromodynamic (QCD) interactions, and, to a much lesser extent, in single modes through the electroweak force. Precisely measuring the single-top cross section provides a stringent test for the electroweak sector of the Standard Model (SM) of particle physics.

In September 2022, only four months after the start of the Run 3, the CMS collaboration released the first measurement using data at the new collision energy of 13.6 TeV: the production cross section of a top quark together with its antiparticle ($t\bar{t}$). The collaboration can now also report a measurement of the production of a single top quark in association with a W boson (tW) based on the full dataset recorded in 2022. As well as testing the electroweak sector, constraining tW allows it to be better disentangled from the dominant $t\bar{t}$ process – a channel where precision improves our knowledge of higher orders of accuracy in perturbative QCD.

tW is a challenging measurement as it is 10 times less likely than $t\bar{t}$ production but has almost the same detection signature. This analysis selects events where both the top quark and the W boson ultimately decay to leptons. The signal therefore consists of two leptons (electrons or muons), a jet initiated from a bottom quark, and possibly extra jets coming from additional radiation. No single observable can discriminate the signal from the background, so a random forest (RF) is employed in events that contain either one or two jets, one of which comes from a bottom quark. The RF is a collection of decision trees collaborating to distinguish the tW signal from the $t\bar{t}$ background. The output of the RF, for events with one jet identified as coming from a bottom quark, is shown in figure 1. The higher the RF discriminant, the higher the relative proportion of signal events.

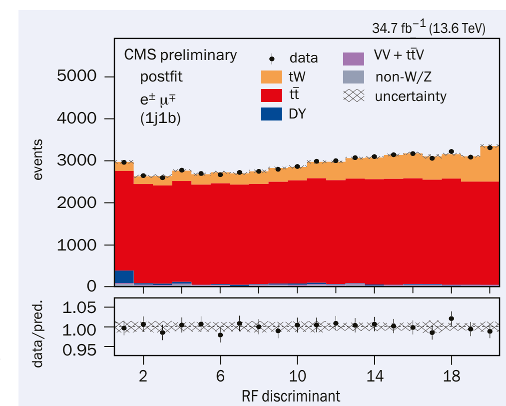

Fig. 1. *The tW signal (orange) increases in proportion to the $t\bar{t}$ background (red) as a function of the random forest output. These events have one jet identified as coming from a b quark.*

To achieve a higher precision, an extra handle is used to control the $t\bar{t}$ background: information from events with two b-quark jets. Such events are more likely to come from the decay of a $t\bar{t}$ pair. The measurement yields a precise value for the tW cross section. Figure 2 shows tW cross-section measurements by CMS at different centre-of-mass energies, including the new measurement in proton–proton collisions of 13.6 TeV. All measurements are consistent with state-of-the-art theory calculations. The first tW measurement at the new LHC energy frontier uses only part of the data but is already as precise as the entire Run 2 sample at 13 TeV. Exploiting the full Run 3 data sample will push the precision frontier forward and provide an even more stringent SM probe in the top quark sector.

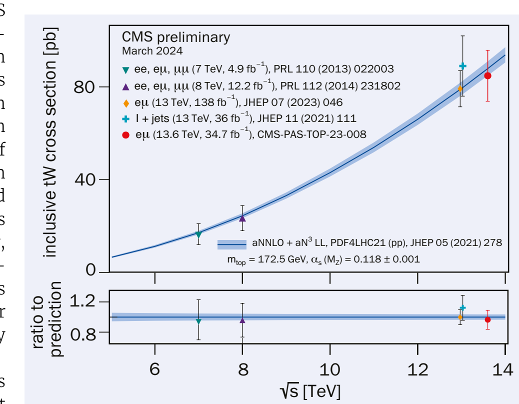

Fig. 2. *CMS measurements of the tW cross section at four centre-of-mass energies. The red circle represents the new Run 3 measurement at 13.6 TeV.*

Further reading

CMS Collab. 2024 CMS-PAS-TOP-23-008.

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FIELD NOTES

Reports from events, conferences and meetings

58th Rencontres de Moriond

Moriond's electroweak delights

Packed sessions, more than 100 talks and lively discussions at Rencontres de Moriond electroweak, held from 24 to 31 March in La Thuile, Italy, captured the latest thinking in the field. The Standard Model (SM) emerged intact, while new paths of enquiry were illuminated.

Twelve years after the discovery of the Higgs boson, H, a wide variety of analyses by ATLAS and CMS are bringing the new scalar into sharper focus. This includes its mass, for which CMS has reported the most precise single measurement using the $H \to ZZ \to 4\ell$ channel: 125.04 ± 0.11 (stat) ± 0.05 (syst) GeV. A Run 2 legacy mass measurement combining ATLAS and CMS results is under way, while projections for the HL-LHC indicate that an uncertainty at the 10–20 MeV level is attainable. For the H width, which is potentially highly sensitive to new physics but notoriously difficult to measure at a hadron collider, the experiments constrain its value to be less than three times the SM width at 95% confidence level using an indirect method with reasonable assumptions. A precision of about 20% is expected from the full HL-LHC dataset.

58th Rencontres de Moriond

Rapt attention *Participants at Moriond 2024 in Italy, where a 58th successful edition was celebrated.*

New generation

The measured H cross sections in all channels continue to support the simplest incarnation of the SM H sector, with a new result from CMS testing the bbH production mode in the $\tau\tau$ and WW channels. Now that the H couplings to the most massive particles are well established, the focus is moving to the second-generation fermions. Directly probing the shape of the Brout–Englert–Higgs potential, and sensitive to new-physics contributions, the H self-coupling is another key target. HH production has yet to be observed at the LHC due to its very low cross section (the combined ATLAS and CMS limit is currently 2.5–3 times the SM value), but an extensive measurement programme utilising multiple channels is under way and Moriond saw new results presented based on $HH \to bbbb$ and $HH \to \gamma\gamma\tau\tau$ decays (p7).

Searches for exotic H decays, or for additional low-mass scalar bosons as predicted by two-Higgs-doublet extensions to the SM, were a Moriond highlight. A wide scope of new H-boson (a, A) searches have been released by ATLAS and CMS, including a new search for $H \to aa \to$ muons by CMS in the mass range 0.2–60 GeV and, on the higher mass side, new limits on $H/A \to t\bar{t}$ by ATLAS and $A \to ZH \to \ell\ell\, t\bar{t}$ by CMS. Although none show significant deviations from the SM, most of the searches are statistically limited and there remains a large amount of phase space available for extended H sectors. Generating much conversation in the corridors was a new-physics interpretation of ATLAS and CMS data in terms of a Higgs-triplet model, based on results in the $HH \to \gamma\gamma$ channel and top-quark differential distributions.

The LHC experiments are making stunning progress in precision electroweak measurements, as exemplified by a new measurement by CMS of the effective leptonic electroweak mixing angle $\sin^2\theta^{\ell}_{\rm eff} = 0.23157 \pm 0.00031$, the first LHC measurement of the W-boson width by ATLAS, and precise measurements of the W and Z cross sections at 13.6 TeV. ATLAS announced at Moriond the most precise single-experiment test of lepton–flavour universality in comparisons between W-boson decays to muons and electrons (p13). A wide-ranging presentation of electroweak results based on two-photon collisions at the LHC described recent attempts by CMS to extract the anomalous magnetic moment of the tau lepton. And LHCb showcased its capabilities in providing an independent measurement of the W-boson mass and the Z-boson cross section. Participants heard about the increasing relevance of lattice QCD in precision electroweak measurements, for example in determining the running of alpha and the weak mixing angle. A tension between the predictions from lattice QCD and from more traditional dispersive approaches exists, with a similar origin to that for the anomalous magnetic moment of the muon.

Following the recent observation of entanglement in top-quark pairs by ATLAS and CMS, a presentation addressing the intriguing ability of colliders to carry out fundamental tests of quantum mechanics generated much discussion. Offering full access to spin information, collider experiments can study quantum correlations, wavefunction collapse and decoherence at unprecedented energies, possibly enabling a Bell measurement at the HL-LHC and the first observation of toponium.

Seeking signals from beyond

Searches for long-lived particles by ATLAS, CMS and LHCb – including the first at LHC Run 3 by CMS – were high on the Moriond agenda. Heavy gauge and scalar bosons, left-right gauge boson masses and heavy neutral leptons are among other new-physics scenarios being constrained. Casting the net as wide as possible, the LHC experiments are developing AI anomaly-detection algorithms, while the power of effective field theory (EFT) in parameterising the effect of heavy new particles on LHC ▷

measurements continues to grow via a diverse range of analyses. Even at O(6) in the SMEFT, no fewer than 59 Wilson coefficients, each related to different underlying physics processes, need to be to measured.

Tensions between theory and experiment remain in some processes involving $b \to s$ or $b \to c$ quark transitions. Moriond saw much discussion on such processes, including new results from Belle II on the branching ratio of the highly suppressed decay $B \to K\nu\nu$. Participants heard about the need for theory progress, as has been the case recently with impressive calculations of $b \to s\gamma$. Predictions for $b \to s\mu\mu$ – which show a tension with experiment and that are independent of the R(K) parameters clocking the relative rates of $B \to K\mu^+\mu^-$ and $B \to Ke^+e^-$ – are excellent ways to probe new physics. Concerning $b \to c$ transitions, updates on $R(D^*)$ from Belle II and on $R(D^*)$ and R(D) from LHCb based on the muonic decay of the tau lepton take the world-average tension to 3.17σ. The stability of the SM prediction of $R(D^*)$ was also questioned.

58th Rencontres de Moriond

Rencontre at Moriond *Attendees had the chance to engage in animated discussions about matters such as how astrophysical, cosmological and collider measurements are eating into the parameter space for new physics.*

New flavours

The flavour sector is awash with new results. LHCb presented fresh analyses exploring mixing and CP violation in the charm sector – a unique gateway to the flavour structure of up-type quarks – while CMS presented a new measurement of CP violation in $B_s \to J/\psi K^+K^-$ decays. In ultra-rare kaon decays, KOTO presented a new upper limit on the branching ratio of $K^0_L \to \pi\nu\nu$ ($< 2 \times 10^{-9}$ at 90% confidence level) and projects a sensitivity $< 10^{-13}$ with the proposed KOTO II upgrade. NA62 presented a preliminary measurement of the branching ratio of the very rare decay $\pi^0 \to e^+e^-$ ($5.86 \pm 0.37 \times 10^{-8}$), in agreement with the SM, and results for $K^+ \to \pi\gamma\gamma$, the latter offering the first evidence that second-order terms must be included in chiral perturbation theory. Belle and Belle II showed new radiative and electroweak penguin results concerning processes such as $B^0 \to \gamma\gamma$, and BESIII presented a precise measurement of the CKM matrix element V_{cs}. A sweeping theory perspective on the mysterious flavour structure of the SM introduced participants to "flavour modular symmetries" – a promising new game in town for a potential theory of flavour based on modular forms, which are well known in mathematics and were used in the proof of Fermat's last theorem.

The final sessions of Moriond electroweak turned to neutrinos, dark matter and astroparticle physics. KATRIN is soon to release an update on the neutrino mass limit based on six times more data, with an expected uncertainty of $m_\nu < 0.5$ eV, and is undertaking R&D towards a proposed upgrade (KATRIN++) that would use new technology to push the mass limit down further. The collaboration is also stepping up its search for new physics via high-precision spectroscopy and is working towards an upgrade called TRISTAN that will soon zone in on the sterile neutrino hypothesis.

In Japan, the T2K facility has undergone an extensive renewal period including its first operation with the near-detector ND280 upgrade in August 2023, which increased the acceptance. Designed to explore neutrino mass ordering and leptonic CP violation, T2K data so far show a slight preference for the "normal" mass ordering while admitting a CP-conserving phase at the level of 2σ. However, a joint analysis between T2K and NOvA, a neutrino oscillation experiment in the US with a longer baseline and complementary sensitivity, prefers a more degenerate parameter space where either CP conservation or the inverted ordering are acceptable solutions. The combined data place a strong constraint on Δm_{32}.

Neutrinoless double-beta decay (NDBD), which would reveal the neutrino to be a Majorana particle and be an unambiguous sign of new physics, continues to be hunted by a host of experiments. LEGEND-200's first physics data was shown, setting up an ultimate goal of placing a lower limit on the NDBD half-life of 10^{28} years for ^{76}Ge. Also located at Gran Sasso, CUORE, which has been collecting data since 2019, will operate for one more year before an upgrade is planned. In parallel, designs for a next-generation tonne-scale upgrade, CUPID, are being finalised. Neutrino aficionados were also treated to scotogenic three-loop models, in which neutrinos gain a Dirac mass term from radiative corrections, and to the latest results from FASER at the LHC, including the first emulsion-detector measurements of the ν_e and ν_μ cross sections at TeV energies, and a search for axion-like particles.

Neutrinoless double-beta decay, which would be an unambiguous sign of new physics, continues to be hunted by a host of experiments

IceCube, which studies resonant disappearance of antineutrinos due to matter effects, showed intriguing results that delve into new-physics territory. Adding sterile neutrinos improves global fits by 7σ, participants heard, but brings inconsistencies too. Generating much interest, the global p-value for the null hypothesis of the sterile neutrino in the muon disappearance channel is 3.1%, in tension with MINOS. The Deep Core IceCube upgrade will increase the number of strings in the observatory, while the more significant Gen-2 upgrade will expand its overall area. A theory overview of the status of sterile neutrinos, taking into account recent results from MiniBooNE, MicroBooNE, PROSPECT, STEREO, GALEX, SAGE, BEST and others, concluded that experimental evidence for such a fourth neutrino state is fading but not excluded. The so-called reactor anomaly is probably explained by smaller uranium contribution than previously accounted for, while the upgraded Neutrino-4 experiment will shed light on tensions with PROSPECT and STEREO.

Cosmological constraints

The status of dark photons was also reviewed. Constraints are being placed from many sources, including colliders, astrophysical and cosmological bounds, haloscopes, and most recently radio telescopes, the James Webb Space Telescope and beam-dump experiments. PandaX-4T, which seeks to constrain WIMP dark matter and NDBD, is about to restart data-taking. LZ, another large liquid-xenon detector, has placed record limits on dark matter based on its first 60 days of data-taking. Results from the first observing run of a novel kind of laser-interferometric detector, LIDA, to observe axion-like particles in the galactic halo are promising.

The latest supersymmetry and dark-matter searches at ATLAS and CMS were also presented, including a new result on R-parity violating supersymmetry and fresh limits on the chargino mass. BESIII reported on exotic searches for massive dark photons, muon-philic particles, glueballs and the QCD axion. Searches for axion-like particles are multiplying in many shapes and forms. In terms of flavour probes of axions, the strongest bounds come from NA62. ▷

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Less conventionally, probing ultralight dark matter by searching for oscillatory behaviour in gravitational waves is gaining traction. Recent NanoGrav data show no signs of such a signal.

All eyes on the muon

No contemporary particle-physics conference would be complete without the anomalous magnetic moment of the muon – a powerful quantity that takes into account all known and unknown particles, for which the measured value is in significant tension with the SM prediction. As the Fermilab Muon g-2 experiment continues to improve the experimental precision (currently 0.2ppm), all eyes are on how the SM calculation is performed – specifically the systematic uncertainty associated with a process called hadronic vacuum polarisation. A huge amount of work is going into understanding this quantity, both in terms of the calculational machinery and underlying data used. When computed using lattice QCD, the tension between experiment and theory is significantly reduced. However, the calculations are so complex that few groups have been able to execute them. That is set to change this year, Moriond participants heard, as new lattice calculations are unblinded ahead of the Lattice 2024 meeting in August, followed by a decision on whether to include such results in the official SM prediction at the seventh plenary workshop of the Muon g-2 Theory Initiative at KEK in September.

No particle-physics conference would be complete without the anomalous magnetic moment of the muon

Experimentally and theoretically, all tools are being thrown at the SM in an attempt to find an explanation for dark matter, the cosmological baryon asymmetry, neutrino masses and other outstanding mysteries. The many high-quality talks at this year's Moriond electroweak session, including an impressive batch of flash talks in dedicated young-researcher sessions, covered all aspects of the adventure and set the standard for future analyses. An incredible interplay between astrophysical, cosmological, collider and other experimental measurements is rapidly eating into the available parameter space for new physics. Ten years ago, the Moriond theory-summary speaker remarked "new physics must be around the corner, but we see no corner". While the same could be said today, physicists have a much clearer view of the road ahead.

Matthew Chalmers *CERN.*

iSAS KICK-OFF

Sustainable accelerator project underway

Particle accelerators have become essential instruments to improve our health, the environment, our safety and our high-tech abilities, as well as unlocking new, fundamental insights into physics, chemistry and biology, and generally enabling scientific breakthroughs that will improve our lives. Accelerating particles to higher energies will always require a large amount of energy. In a society where energy sustainability is critical, keeping energy consumption as low as is reasonably possible is an unavoidable challenge for both research infrastructures (RIs) and industry, which collectively operate more than 40,000 accelerators.

IJCLab

Innovating for sustainable accelerator systems *iSAS is coordinated by (left to right) Giovanni Bisoffi, Jens Knobloch, Achille Stocchi, Jorgen D'Hondt and Maud Baylac.*

Going green

Based on state-of-the-art technology, the portfolio of current and future accelerator-driven RIs in Europe could develop to consume up to 1% of Germany's annual electricity demand. With the ambition to maintain the attractiveness and competitiveness of European RIs, and enable Europe's Green Deal, the Innovate for Sustainable Accelerating Systems (iSAS) project has been approved by Horizon Europe. Its aim is to establish an enhanced collaboration in the field to broaden, expedite and amplify the development and impact of novel energy-saving technologies to accelerate particles.

In general terms, a particle accelerator has a system to create the particles to be accelerated, a system preparing beams with these particles, an accelerating system that effectively accelerates the particle beams, a magnet system to steer the beam, an experimental facility using the particles, and finally a beam dump. In linear accelerating structures, most of the electrical power taken from the grid to operate the accelerator is used by the accelerating system itself.

The core of an accelerating system is a series of cavities that can deliver a high-gradient electric field. For many modern accelerators, these cavities are superconducting and therefore cryogenically cooled to about 2K. They are powered with radio frequency (RF) power generators to deliver the field at a specific frequency and accordingly to provide energy to the particle beams as they traverse. These superconducting RF (SRF) systems are the enabling technology for frontier accelerators, but are energy-intensive devices where only a fraction of the power extracted from the grid is effectively transmitted to the accelerated particles. In addition, the beam energy is radiated by recirculating beams and ultimately dumped and lost. As an example, the European XFEL's superconducting RF system uses 5–6MW for 0.1MW of average beam power, leading to a power conversion of less than 3%.

The collection of energy-saving technologies will be developed with a portfolio of forthcoming applications in mind

The objective of iSAS is to innovate those technologies that have been identified as being a common core of SRF accelerating systems and that have the largest leverage for energy savings with a view to minimising the intrinsic energy consumption in all phases of operation. In the landscape of accelerator-driven ▷

RIs, solutions are being developed to reuse the waste heat produced, develop energy-efficient magnets and RF power generators, and operate facilities on opportunistic schedules when energy is available on the grid. The iSAS project has a complementary focus on the energy efficiency of the SRF accelerating technologies themselves. This will contribute to the vital transition to sustain the tremendous 20th-century applications of accelerator technology in an energy-conscious 21st century.

L Petizon, CNRS/UPSaclay/IJCLab

iSAS has been approved by Horizon Europe to help develop novel energy-saving technologies to accelerate particles

Interconnected technologies

Based on a recently established European R&D roadmap for accelerator technology and based on a collaboration between leading European research institutions and industry, several interconnected technologies will be developed, prototyped and tested, each enabling significant energy savings on their own in accelerating particles. The collection of energy-saving technologies will be developed with a portfolio of forthcoming applications in mind, and to explore energy-saving improvements in accelerator-driven RIs. Considering the developments realised, the new technologies will be coherently integrated into the parametric design of a new accelerating system, a linac SRF cryomodule, optimised to achieve high beam-power in accelerators with an energy consumption that is as low as reasonably possible. This new cryomodule design will enable Europe to develop and build future energy-sustainable accelerators and particle colliders.

On 15 and 16 April, the iSAS kick-off meeting was organised at IJCLab (Orsay, France) with around 100 participants. Each of the working groups enthusiastically presented their impactful R&D plans and, in all cases, concrete work has begun. To save energy from RF power systems, novel fast-reacting tuners are being developed to compensate rapidly for detuning of the cavity's frequency caused by mechanical vibrations, and methods are being invented to integrate them into smart digital control systems. To save energy from the cryogenics, and based on the ongoing Horizon Europe I.FAST project, superconducting cavities with thin films of Nb_3Sn are being further developed to operate with high performance at 4.2K instead of 2K, thereby reducing the grid-power to operate the cryogenic system. The cryogenic system requires three times less cooling power to maintain a 4.2K bath at 4.2K when heat is dissipated in the bath compared to maintaining a 2K bath at 2K. Finally, to save energy from the accelerated particle beam itself, the technology of energy recovery linacs (ERLs) is being improved to operate efficiently with high-current beams by developing novel higher-order mode dampers that significantly avoid heat loads in the cavities.

To address the engineering challenges related to the integration of the new energy-saving technologies, an existing ESS cryovessel will be equipped with new cavities and novel dampers, and the resulting linac SRF cryomodule will be tested in operation in the PERLE accelerator at IJCLab (Orsay, France). PERLE is a growing international collaboration to demonstrate the performance of ERLs with high-power beams that would enable applications in future particle colliders. Its first phase is being implemented at IJCLab with the objective to have initial beams in 2028.

The timescale to innovate, prototype and test new accelerator technologies is inherently long, in some cases longer than the typical duration of R&D projects. It is therefore essential to continue to collaborate and enhance the R&D process so that energy-sustainable technologies can be implemented without delay, to avoid hampering the scientific and industrial progress enabled by accelerators. Accordingly, iSAS plans co-development with industrial partners to jointly achieve a technology readiness level that will be sufficient to enter the large-scale production phase of these new technologies.

Empowering industry

While the readiness of several energy-saving technologies will be prepared towards industrialisation with impact on current RIs, iSAS is also a pathfinder for sustainable future SRF particle accelerators and colliders. Through inter- and multidisciplinary research that delivers and combines various technologies, it is the long-term ambition of iSAS to reduce the energy footprint of SRF accelerators in future RIs by half, and even more when the systems are integrated in ERLs. Accordingly, iSAS will help maintain Europe's leadership for breakthroughs in fundamental sciences and enable high-energy collider technology to go beyond the current frontiers of energy and intensity in an energy-sustainable way. In parallel, the new sustainable technologies will empower and stimulate European industry to conceive a portfolio of new applications and take a leading role in, for example, the semiconductor, particle therapy, security and environmental sectors.

Jorgen D'Hondt *Vrije Universiteit Brussel and* **Achille Stocchi** *IJCLab.*

LHCP 2024

LHC physicists spill the beans in Boston

Dedicated solely to LHC physics, the LHCP conference is a vital gathering for experts in the field. The 12th edition was no exception, attracting 450 physicists to Northeastern University in Boston from 3 to 7 June. Participants discussed recent results, data taking at a significantly increased instantaneous luminosity in Run 3, and progress on detector upgrades planned for the high-luminosity LHC (HL-LHC).

The study of the Higgs boson remains central to the LHC programme. ATLAS reported a new result on Standard Model (SM) Higgs-boson production with decays to tau leptons, achieving the most precise single-channel measurement of the vector-boson-fusion production mode to date. Determining the production modes of the Higgs boson precisely may shed light on the existence of new physics that would be observed as deviations from the SM predictions.

The study of the Higgs boson remains central to the LHC programme

Beyond single Higgs production, the di-Higgs production (HH) search is one of the most exciting and fundamental topics for LHC physics in the coming years as it directly probes the Higgs potential (p7). ATLAS has combined results for HH production in multiple final states, providing the best-expected sensitivity to the HH production cross-section and Higgs-boson self-coupling, allowing κ_λ (the Higgs self-coupling with respect to the SM value) to be within the range $-1.2 < \kappa_\lambda < 7.2$.

The search for beyond-the-SM (BSM) physics to explain the many unre- ▷

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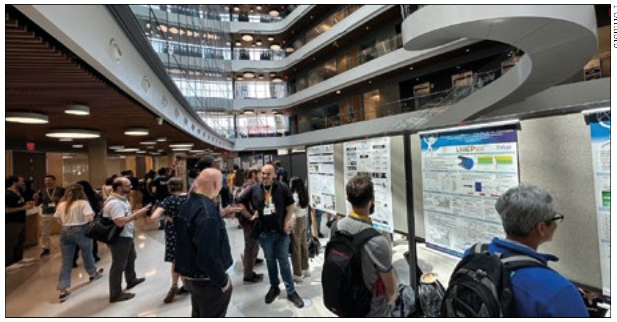

T Orimoto

Boston collisions *The 12th LHCP conference took place at Northeastern University in Boston.*


T Orimoto

Future of the field *Preserving the unique expertise cultivated within the LHC community is imperative.*

solved questions about our universe is being conducted with innovative ideas and methods. CMS has presented new searches involving signatures with two tau leptons, examining the hypotheses of an excited tau lepton and a heavy neutral spin-1 gauge boson (Z′) produced via Drell–Yan and, for the first time, via vector boson fusion. These results set stringent constraints on BSM models with enhanced couplings to third-generation fermions.

Other new-physics theoretical models propose additional BSM Higgs bosons. ATLAS presented a search for such particles being produced in association with top quarks, setting limits on their cross-section that significantly improve upon previous ATLAS results. Additional BSM Higgs bosons could explain puzzles such as dark matter, neutrino oscillations and the observed matter–antimatter asymmetry in the universe.

The dark side

Some BSM models imply that dark-matter particles could arise as composite mesons or baryons of a new strongly-coupled theory that is an extension of the SM. ATLAS investigated this dark sector through searches for high-multiplicity hadronic final states, providing the first direct collider constraints on this model to complement direct dark-matter-detection experimental results (p13).

CMS have used low-pileup inelastic proton–proton collisions to measure event-shape variables related to the overall distribution of charged particles. These measurements showed the particle distribution to be more isotropic than predicted by theoretical models.

The LHC experiments also presented multiple analyses of proton–lead (p–Pb) and pp collisions, exploring the potential production of quark–gluon plasma (QGP) – a hot and dense phase of deconfined quarks and gluons found in the early universe that is frequently studied in heavy-ion Pb–Pb collisions, among others, at the LHC. Whether it can be created in smaller collision systems is still inconclusive.

The future of the field was discussed in a well-attended panel session, which emphasised exploring the full potential of the HL-LHC and engaging younger generations

ALICE reported a high-precision measurement of the elliptic flow of anti-helium-3 in QGP using the first Run-3 Pb–Pb run. The much larger data sample compared to the previous Run 2 measurement allowed ALICE to distinguish production models for these rarely produced particles for the first time. ALICE also reported the first measurement of an impact-parameter-dependent angular anisotropy in the decay of coherently photo-produced ρ^0 mesons in ultra-peripheral Pb–Pb collisions. In these collisions, quantum interference effects cause a decay asymmetry that is inversely proportional to the impact parameter.

CMS reported its first measurement of the complete set of optimised CP-averaged observables from the process $B^0 \to K^{*0}\mu^+\mu^-$. These measurements are significant because they could reveal indirect signs of new physics or subtle effects induced by low-energy strong interactions. By matching the current best experimental precision, CMS contributes to the ongoing investigation of this process.

LHCb presented measurements of the local and non-local contributions across the full invariant-mass spectrum of $B^{0*} \to K^{*0}\mu^+\mu^-$, tests of lepton flavour universality in semileptonic b decays, and mixing and CP violation in $D \to K\pi$ decays.

From a theoretical perspective, progress in precision calculations has exceeded expectations. Many processes are now known to next-to-next-to-leading order or even next-to-next-to-next-to-leading order (N^3LO) accuracy. The first parton distribution functions approximating N^3LO accuracy have been released and reported at LHCP, and modern parton showers have set new standards in perturbative accuracy.

In addition to these advances, several new ideas and observables are being proposed. Jet substructure, for instance, is becoming a precision science and valuable tool due to its excellent theoretical properties. Effective field theory (EFT) methods are continuously refined and automated, serving as crucial bridges to new theories as many ultraviolet theories share the same EFT operators. Synergies between flavour physics, electroweak effects and high-transverse-momentum processes at colliders are particularly evident within this framework. The use of the LHC as a photon collider showcases the extraordinary versatility of LHC experiments and their synergy with theoretical advancements.

Discovery machine

The HL-LHC upgrade was thoroughly discussed, with several speakers highlighting the importance and uniqueness of its physics programme. This includes fundamental insights into the Higgs potential, vector-boson scattering, and precise measurements of the Higgs boson and other SM parameters. Thanks to the endless efforts by the four collaborations to improve their performances, the LHC already rivals historic lepton colliders for electroweak precision in many channels, despite the cleaner signatures of lepton collisions. The HL-LHC will be capable of providing extraordinarily precise measurements while also serving as a discovery machine for many years to come.

The future of the field was discussed in a well-attended panel session, which emphasised exploring the full potential of the HL-LHC and engaging younger generations. Preserving the unique expertise and knowledge cultivated within the CERN community is imperative. Next year's LHCP conference will be held at National Taiwan University in Taipei from 5 to 10 June.

Florencia Canelli *University of Zurich* and **Pamela Ferrari** *Nikhef and Radboud University Nijmegen.*

Electromagnetic Interactions with Nucleons and Nuclei

Photonuclear summit takes place in Paphos

The 15th edition of Electromagnetic Interactions with Nucleons and Nuclei (EINN) attracted 100 delegates to Paphos in Cyprus from 31 October to 4 November 2023. EINN covers theoretical and experimental developments in hadron physics, including the partonic structure of nucleons and hadron spectroscopy, the muon magnetic moment, dark-matter searches, the electroweak structure of light nuclei, new experimental facilities and physics searches, lattice QCD, the integration of machine-learning methodologies in QCD and the potential of quantum computing in QCD.

A highlight of the conference was the evening plenary poster session. Luis Alberto Rodriguez Chacon (The Cyprus Institute), Cornelis Mommers (Mainz University) and Sotiris Pitelis (Mainz) were recognised with the prestigious EPS poster prize, and presented their work on the calculation of the gluon momentum fraction in mesons through lattice QCD simulations, exotic atoms, and the X17 discovery potential from $\gamma D \to e^+e^-pn$ with neutron tagging. This edition of EINN also hosted topical workshops on the QCD analysis of nucleon structure and experimental opportunities at the Electron-Ion Collider. Preceding the conference, a two-day meeting on careers in photonuclear physics was tailored to be a platform for PhD students and postdoctoral researchers to establish professional networks.


EINN2023

QCD forum *The EINN conference is a platform for advancing nuclear and hadron physics.*

With QCD taking a central role in contemporary physics research worldwide, the EINN conference is poised to maintain its crucial role as an international forum for the field.

Barbara Pasquini *University of Pavia.*

IN DEFIANCE OF COSMIC-RAY POWER LAWS


JAXA

Low-Earth orbit *The Calorimetric Electron Telescope (extreme left), attached to the exposure facility of the Japanese Kibo module at the ISS.*

From its pristine vantage point on the International Space Station, the Calorimetric Electron Telescope, CALET, has uncovered anomalies in the spectra of protons and electrons below the cosmic-ray knee.

In a series of daring balloon flights in 1912, Victor Hess discovered radiation that intensified with altitude, implying extra-terrestrial origins. A century later, experiments with cosmic rays have reached low-Earth orbit, but physicists are still puzzled. Cosmic-ray spectra are difficult to explain using conventional models of galactic acceleration and propagation. Hypotheses for their sources range from supernova remnants, active galactic nuclei and pulsars to physics beyond the Standard Model. The study of cosmic rays in the 1940s and 1950s gave rise to particle physics as we know it. Could these cosmic messengers be about to unlock new secrets, potentially clarifying the nature of dark matter?

The cosmic-ray spectrum extends well into the EeV regime, far beyond what can be reached by particle colliders. For many decades, the spectrum was assumed to be broken into intervals, each following a power law, as Enrico Fermi had historically predicted. The junctures between intervals include: a steepening decline at about 3×10^{6} GeV known as the knee; a flattening at about 4×10^{9} GeV known as the ankle; and a further steepening at the supposed end of the spectrum somewhere above 10^{10} GeV (10 EeV).

While the cosmic-ray population at EeV energies may include contributions from extra-galactic cosmic rays, and the end of the spectrum may be determined by collisions with relic cosmic-microwave-background photons – the Greisen–Zatsepin–Kuzmin cutoff – the knee is still controversial as the relative abundance of protons and other nuclei is largely unknown. What's more, recent direct measurements by space-borne instruments have discovered "spectral curvatures" below the knee. These significant deviations from a pure power law range from a few hundred GeV to a few tens of TeV. Intriguing anomalies in the spectra of cosmic-ray electrons and positrons have also been observed below the knee.

THE AUTHORS

Pier Simone Marrocchesi *University of Siena and INFN Pisa, and* **Shoji Torii** *Waseda University.*

Electron origins

The Calorimetric Electron Telescope (CALET; see "Calorimetric telescope" figure) on board the International Space Station (ISS) provides the highest-energy direct measurements of the spectrum of cosmic-ray electrons and positrons. Its goal is to observe discrete sources of high-energy particle acceleration in the local region of our galaxy. Led by the Japan Aerospace Exploration Agency, with the participation of the Italian Space Agency and NASA, CALET was launched from the Tanegashima Space Center in August 2015, becoming the second high-energy experiment operating on the ISS following the deployment of AMS-02 in 2011. During 2017 a third experiment, ISS-CREAM, joined AMS-02 and CALET, but its observation time ended prematurely.

As a result of radiative losses in space, high-energy cosmic-ray electrons are expected to originate just a few thousand light-years away, relatively close to Earth. CALET's homogeneous calorimeter (fully active, with no absorbers) is optimised to reconstruct such particles (see "Energetic electron" figure). With the exception of the highest energies, anisotropies in their arrival direction are typically small due to deflections by turbulent interstellar magnetic fields.

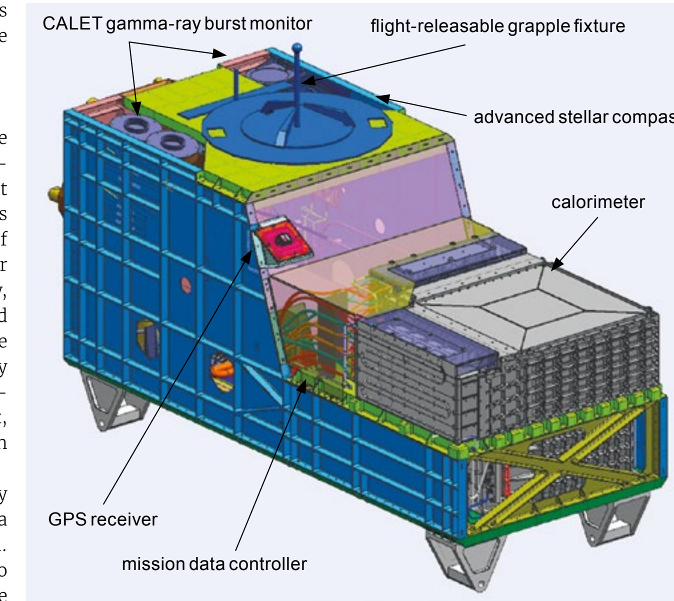
Energy spectra also contain crucial information as to where and how cosmic-ray electrons are accelerated. And they could provide possible signatures of dark matter. For example, the presence of a peak in the spectrum could be a sign of dark-matter decay, or dark-matter annihilation into an electron–positron pair, with a detected electron or positron in the final state.

Direct measurements of the energy spectra of charged cosmic rays have recently achieved unprecedented precision thanks to long-term observations of electrons and positrons of cosmic origin, as well as of individual elements from hydrogen to nickel, and even beyond. Space-borne instruments such as CALET directly identify cosmic nuclei by measuring their electric charge. Ground-based experiments must do so indirectly by observing the showers they generate in the atmosphere, incurring large systematic uncertainties. Either way, hadronic cosmic rays can be assumed to be fully stripped of atomic electrons in their high-temperature regions of origin.

A rich phenomenology

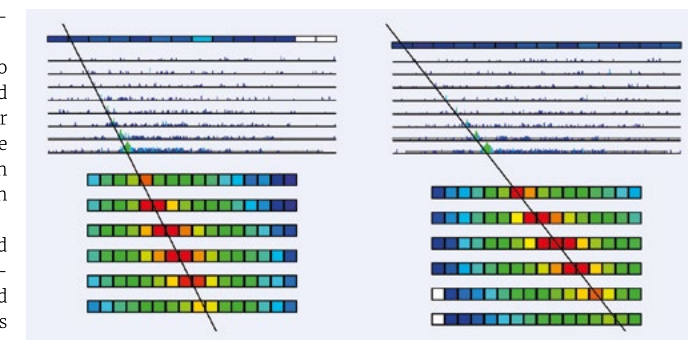
The past decade has seen the discovery of unexpected features in the differential energy spectra of both leptonic and hadronic cosmic rays. The observation by PAMELA and AMS of an excess of positrons above 10 GeV has generated widespread interest and still calls for an unambiguous explanation (*CERN Courier* December 2016 p26). Possibilities include pair production in pulsars, in addition to the well known interactions with the interstellar gas, and the annihilation of dark matter into electron–positron pairs.

Regarding cosmic-ray nuclei, significant deviations of the fluxes from pure power-law spectra have been observed



CALET Collaboration

Calorimetric telescope *The Calorimetric Electron Telescope detector.*


CALET Collaboration

Energetic electron *A candidate electron event in CALET with an estimated energy close to 12 TeV, making it one of the highest-energy cosmic-ray electrons ever recorded. Energy deposition is indicated by colour as the electron moves from top to bottom through CALET's charge detector, imaging calorimeter and total-absorption calorimeter. The two images are orthogonal side projections of the same event.*

by several instruments in flight, including by CREAM on balloon launches from Antarctica, by PAMELA and DAMPE aboard satellites in low-Earth orbit, and by AMS-02 and CALET on the ISS. Direct measurements have also shown that the energy spectra of "primary" cosmic rays is different from those of "secondary" cosmic rays created by collisions of primaries with the interstellar medium. This rich phenomenology, which encodes information on cosmic-ray acceleration processes and the history of their propagation in the galaxy, is the subject of multiple theoretical models.

An unexpected discovery by PAMELA, which had been anticipated by CREAM and was later measured with greater precision by AMS-02, DAMPE and CALET, was the obser-

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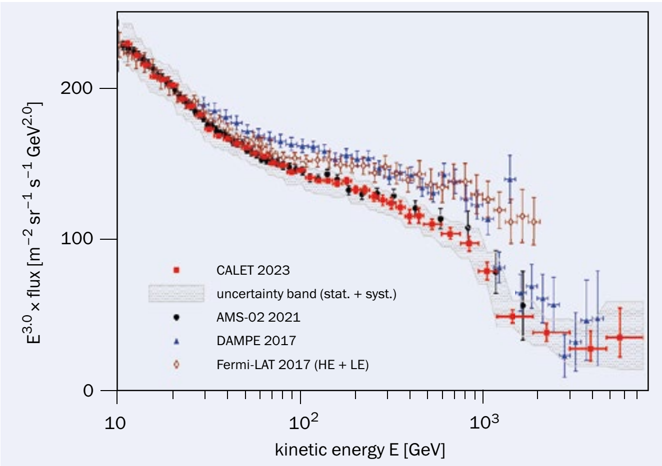


Electron break *Combined electron and positron flux measurements as a function of kinetic energy, E. To illustrate deviations from a pure power law, the combined positron and electron flux is multiplied by $E^{3.0}$.*

Pulsar home *The highest-energy electron cosmic rays may originate in nearby young sources such as the Vela supernova remnant, some 800 light-years distant, which is home to a dense, rotating neutron star: the Vela Pulsar.*

vation of a flattening of the differential energy spectra of protons and helium. Starting from energies of a few hundred GeV, the proton flux shows a smooth and progressive hardening (increase in gradient) of the spectrum that continues up to around 10 TeV, above which a completely different regime is established. A turning point was the subsequent discovery by CALET and DAMPE of an unexpected softening of proton and helium fluxes above about 10 TeV/Z, where the atomic number Z is one for protons and two for helium. The presence of a second break challenges the conventional "standard model" of cosmic-ray spectra and calls for a further extension of the observed energy range, currently limited to a few hundred TeV.

At present, only two experiments in low-Earth orbit have an energy reach beyond 100 TeV: CALET and DAMPE. They rely on a purely calorimetric measurement of the energy, while space-borne magnetic spectrometers are limited to a maximum magnetic "rigidity" – a particle's momentum divided by its charge – of a few teravolts. Since the end of PAMELA's operations in 2016, AMS-02 is now the only instrument in orbit with the ability to discriminate the sign of the charge. This allows separate measurements of the high-energy spectra of positrons and antiprotons – an important input to the observation of final states containing antiparticles for dark-matter searches. AMS-02 is also now preparing for an upgrade: an additional silicon tracker layer will be deployed at the top of the instrument to enable a significant increase in its acceptance and energy reach (*CERN Courier* March/April 2024 p7).

Pioneering observations

CALET was designed to extend the energy reach beyond the rigidity limit of present space-borne spectrometers, enabling measurements of electrons up to 20 TeV and measurements of hadrons up to 1 PeV. As an all-calorimetric instrument with no magnetic field, its main science goal is to perform precision measurements of the detailed shape of the inclusive spectra of electrons and positrons.

Thanks to its advanced imaging calorimeter, CALET can measure the kinetic energy of incident particles well into TeV energies, maintaining excellent proton–electron discrimination throughout. CALET's homogeneous calorimeter has a total thickness of 30 radiation lengths, allowing for a full containment of electron showers. It is preceded by a high-granularity pre-shower detector with imaging capabilities that provide a redundant measurement of charge via multiple energy-loss measurements. The calibration of the two instruments is the key to controlling the energy scale, motivating beam tests at CERN before launch.

A first important deviation from a scale-invariant power-law spectrum was found for electrons near 1 TeV. Here, CALET and DAMPE observed a significant flux reduction, as expected from the large radiative losses of electrons during their travel in space. CALET has now published a high-statistics update up to 7.5 TeV, reporting the presence of candidate electrons above the 1 TeV spectral break (see "Electron break" figure).

This unexplored region may hold some surprises. For example, the detection of even higher energy electrons, such as the 12 TeV candidate recently found by CALET, may indicate the contribution of young and nearby sources such as the Vela supernova remnant, which is known to host a pulsar (see "Pulsar home" image).

A second unexpected finding is the observation of a significant reduction in the proton flux around 10 TeV. This bump and dip were also observed by DAMPE and anticipated by CREAM, albeit with low statistics (see "Proton bump" figure). A precise measurement of the flux has allowed CALET to fit the spectrum with a double-broken power law: after a spectral hardening starting at a few hundred GeV, which is also observed by AMS-02 and PAMELA, and which progressively increases above 500 GeV, a steep softening takes place above 10 TeV.

A similar bump and dip have been observed in the helium flux. These spectral features may result from a single physical process that generates a bump in the cosmic-ray spectrum. Theoretical models include an anomalous diffusive regime near the acceleration sources, the dominance of one or more nearby supernova remnants, the gradual release of cosmic rays from the source, and the presence of additional sources.

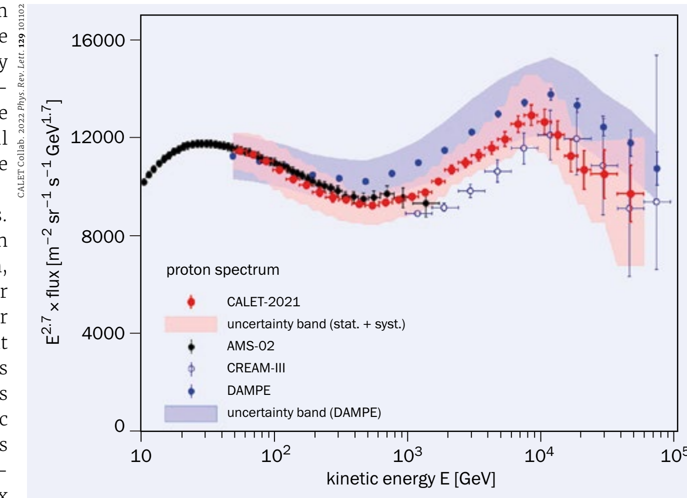
CALET is also a powerful hunter of heavier cosmic rays. Measurements of the spectra of boron, carbon and oxygen ions have been extended in energy reach and precision, providing evidence of a progressive spectral hardening for most of the primary elements above a few hundred GeV per nucleon. The boron-to-carbon flux ratio is an important input for understanding cosmic-ray propagation. This is because diffusion through the interstellar medium causes an additional softening of the flux of secondary cosmic rays such as boron with respect to primary cosmic rays such as carbon (see "Break in B/C?" figure). The collaboration also recently published the first high-resolution flux measurement of nickel (Z = 28), revealing the element to have a very similar spectrum to iron, suggesting similar acceleration and propagation behaviour.

CALET is also studying the spectra of sub-iron elements, which are poorly known above 10 GeV per nucleon, and ultra-heavy galactic cosmic rays such as zinc (Z = 30), which are quite rare. CALET studies abundances up to Z = 40 using a special trigger with a large acceptance, so far revealing an excellent match with previous measurements from ACE-CRIS (a satellite-based detector), SuperTIGER (a balloon-borne detector) and HEAO-3 (a satellite-based detector decommissioned in the 1980s). Ultra-heavy galactic cosmic rays provide insights into cosmic-ray production and acceleration in some of the most energetic processes in our galaxy, such as supernovae and binary-neutron-star mergers.

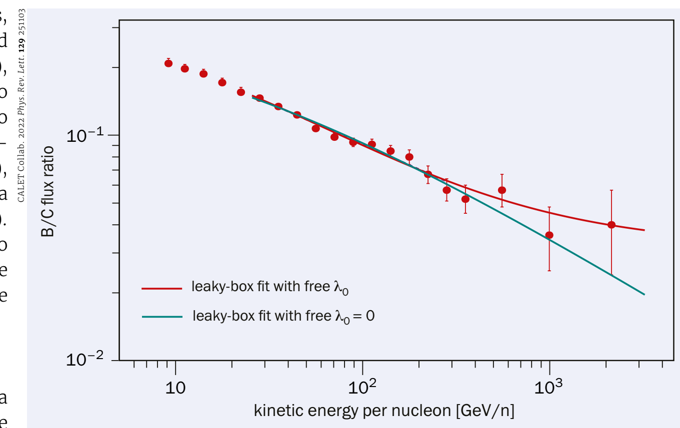
Gravitational-wave counterparts

In addition to charged particles, CALET can detect gamma rays with energies between 1 GeV and 10 TeV, and study the diffuse photon background as well as individual sources. To study electromagnetic transients related to complex phenomena such as gamma-ray bursts and neutron-star mergers, CALET is equipped with a dedicated monitor that to date has detected more than 300 gamma-ray bursts, 10% of which are short bursts in the energy range 7 keV to 20 MeV. The search for electromagnetic counterparts to gravitational waves proceeds around the clock by following alerts from LIGO, VIRGO and KAGRA. No X-ray or gamma-ray counterparts to gravitational waves have been detected so far.

On the low-energy side of cosmic-ray spectra, CALET has contributed a thorough study of the effect of solar activity on galactic cosmic rays, revealing charge dependence on the polarity of the Sun's magnetic field due to the different paths taken by electrons and protons in the heliosphere. The instrument's large-area charge detector has also proven to be ideal for space-weather studies of relativistic electron precipitation from the Van Allen belts in Earth's magnetosphere.



Proton bump *Proton flux measurements as a function of the kinetic energy, E. To illustrate deviations from a pure power law, the proton flux is multiplied by $E^{2.7}$.*



Break in B/C? *CALET measurements of the boron to carbon flux ratio as a function of the kinetic energy per nucleon. The residual path length λ_0 is related to the amount of matter traversed by cosmic rays inside the acceleration region.*

The spectacular recent experimental advances in cosmic-ray research, and the powerful theoretical efforts that they are driving, are moving us closer to a solution to the century-old puzzle of cosmic rays. With more than four billion cosmic rays observed so far, and a planned extension of the mission to the nominal end of ISS operativity in 2030, CALET is expected to continue its campaign of direct measurements in space, contributing sharper and perhaps unexpected pictures of their complex phenomenology. ●

CALET was designed to extend the energy reach beyond the rigidity limit of present space-borne spectrometers

Further reading

CALET Collab. 2023 *Phys. Rev. Lett.* **131** 191001 and 2022 *Phys. Rev. Lett.* **129** 101102.
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Best Model B35ADP Alpha/Deuteron/Proton Cyclotron
Installation of B70 MeV Cyclotron at INFN, Legnaro, Italy.
Best Particle Therapy 400 MeV ion Rapid Cycling Medical Synchrotron (iRCMS)
NEW!
Best Model 200p Cyclotron—Variable Energy Proton Beam for Radiation Therapy
(patent pending)
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TeamBest Global Companies (TBG), in partnership with Best Cure Foundation, plan to manufacture and establish 1000s of medical centers around the globe. These centers will include Best Cure Proactive, Preventive, Primary, Medical, Dental and Eye Care Wellness Centers, as well as treatment centers for cardiac, cancer, diabetes, and infectious diseases.
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SIX RARE DECAYS AT THE ENERGY FRONTIER

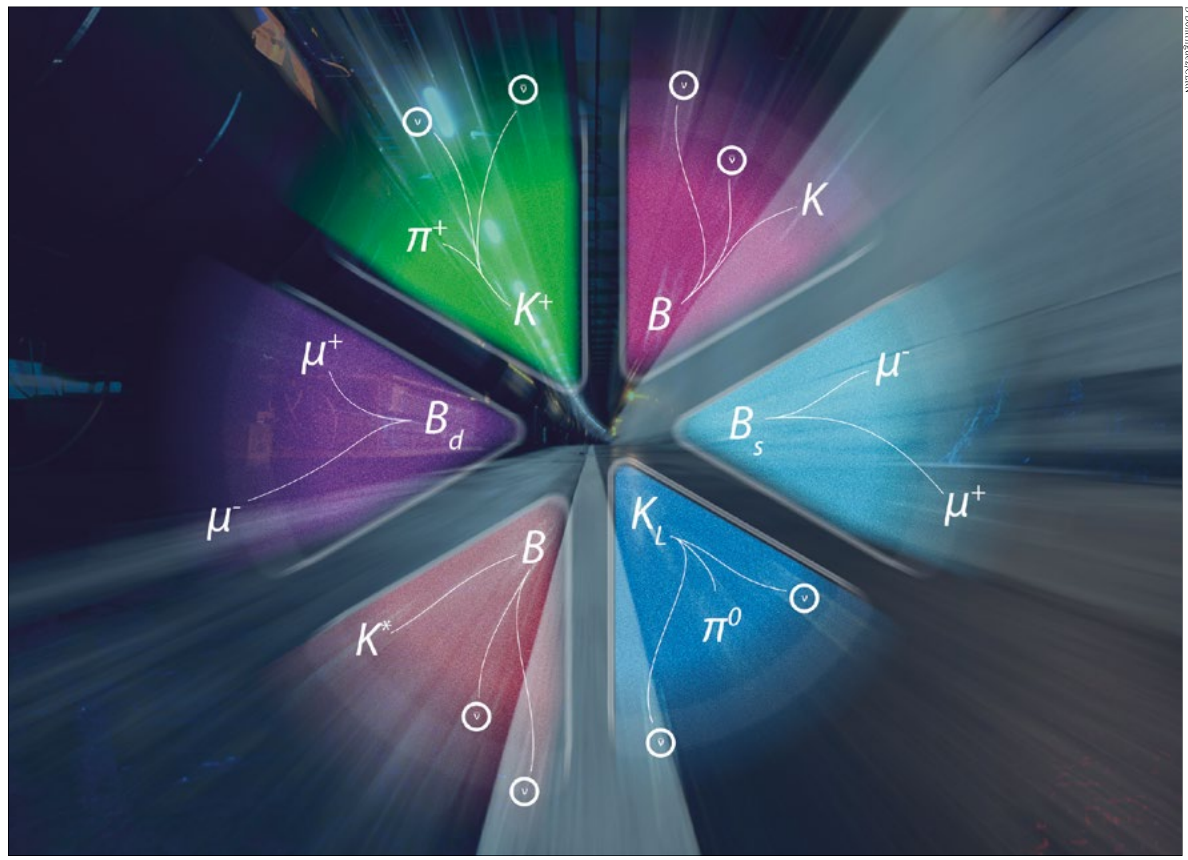
Andrzej Buras explains how two rare kaon decays and four rare B-meson decays will soon probe for new physics beyond the reach of direct searches at colliders.

Thanks to its 13.6 TeV collisions, the LHC directly explores distance scales as short as 5×10^{-20} m. But the energy frontier can also be probed indirectly. By studying rare decays, distance scales as small as a zeptometre (10^{-21} m) can be resolved, probing the existence of new particles with masses as high as 100 TeV. Such particles are out of the reach of any high-energy collider that could be built in this century.

The key concept is the quantum fluctuation. Just because a collision doesn't have enough energy to bring a new particle into existence does not mean that a very heavy new particle cannot inform us about its existence. Thanks to Heisenberg's uncertainty principle, new particles could be virtually exchanged between the other particles involved in the collisions, modifying the probabilities for the processes we observe in our detectors. The effect of massive new particles could be unmistakable, giving physicists a powerful tool for exploring more deeply into the unknown than accelerator technology and economic considerations allow direct searches to go.

The effect of massive new particles could be unmistakable

The search for new particles and forces beyond those of the Standard Model is strongly motivated by the need to explain dark matter, the huge range of particle masses from the tiny neutrino to the massive top quark, and the asymmetry between matter and antimatter that is responsible for our very existence. As direct searches at the LHC have not yet provided any clue as to what these new particles and forces might be, indirect searches are growing in importance. Studying very rare processes could allow us to see imprints of new particles and forces acting at much shorter distance scales than it is possible to explore at current and future colliders.



No trivial pursuit *Six ultra-rare decays stand out for their potential to reveal new physics this decade.*


Needle in a haystack *CERN's NA62 experiment is measuring the branching ratio for a decay channel followed by roughly one in every 10^{10} kaons.*

Anticipating the November Revolution

The charm quark is a good example. The story of its direct discovery unfolded 50 years ago, in November 1974, when teams at SLAC and MIT simultaneously discovered a charm–anticharm meson in particle collisions. But four years earlier, Sheldon Glashow, John Iliopoulos and Luciano Maiani had already predicted the existence of the charm quark thanks to the surprising suppression of the neutral kaon's decay into two muons.

Neutral kaons are made up of a strange quark and a down antiquark, or vice versa. In the Standard Model, their decay to two muons can proceed most simply through the virtual exchange of two W bosons, one virtual up quark and a virtual neutrino. The trouble was that the rate for the neutral kaon decay to two muons predicted in this manner turned out to be many orders of magnitude larger than observed experimentally.

Glashow, Iliopoulos and Maiani (GIM) proposed a simple solution. With visionary insight, they hypothesised a new quark, the charm quark, which would totally cancel the contribution of the up quark to this decay if their masses were equal to each other. As the rate was non-vanishing and the charm quark had not yet been observed experimentally, they concluded that the mass of the charm quark must be significantly larger than that of the up quark.

Their hunch was correct. In early 1974, months before its direct discovery, Mary K Gaillard and Benjamin Lee predicted the charm quark's mass by analysing another highly suppressed quantity, the mass difference in K^0–$\bar{K}^0$ mixing.

As modifications to the GIM mechanism by new heavy particles are still a hot prospect for discovering new physics in the 2020s, the details merit a closer look. Years earlier, Nicola Cabibbo had correctly guessed that weak interactions act between up quarks and a mixture ($d\cos\theta + s\sin\theta$) of the down and strange quarks. We now know that charm quarks interact with the mixture ($-d\sin\theta + s\cos\theta$). This is just a rotation of the down and strange quarks through this Cabibbo angle. The minus sign causes the destructive interference observed in the GIM mechanism.

With the discovery of a third generation of quarks, quark mixing is now described by the Cabibbo–Kobayashi–Maskawa (CKM) matrix – a unitary three-dimensional rotation with complex phases that parameterise CP violation. Understanding its parameters may prove central to our ability to discover new physics this decade.

On to the 1980s

The story of indirect discoveries continued in the late 1980s, when the magnitude of B^0_d–$\bar{B}^0_d$ mixing implied the existence of a heavy top quark, which was confirmed in 1995, completing the third generation of quarks. The W, Z and Higgs bosons were also predicted well in advance of their discoveries. It's only natural to expect that indirect searches for new physics will be successful at even shorter distance scales.

Rare weak decays of kaons and B mesons that are strongly suppressed by the GIM mechanism are expected to play a crucial role. Many channels of interest are predicted by the Standard Model to have branching ratios as low as 10^{-11}, often being further suppressed by small elements of the CKM matrix. If the GIM mechanism is violated by new-physics contributions, these branching ratios – the fraction of times

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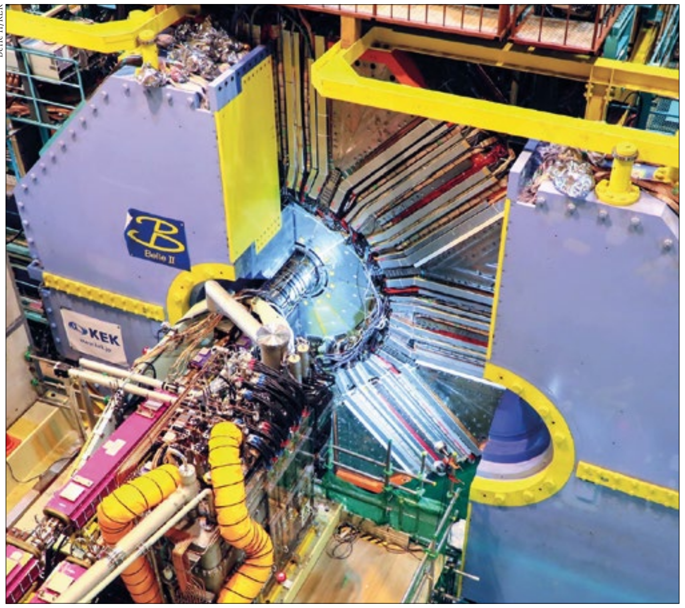


Belle II/KEK

Interesting excess *2023 data from the Belle II experiment at KEK moves the global average for the branching ratio of $B^+ \to K^+\nu\bar{\nu}$ to be a factor of 2.6 above the Standard Model.*

a particle decays that way – could be much larger.

Measuring suppressed branching ratios with respectable precision this decade is therefore an exciting prospect. Correlations between different branching ratios can be particularly sensitive to new physics and could provide the first hints of physics beyond the Standard Model. A good example is the search for the violation of lepton-flavour universality (*CERN Courier* May/June 2019 p33). Though hints of departures from muon–electron universality seem to be receding, hints that muon–tau universality may be violated still remain, and the measured branching ratios for $B \to K(K^*)\mu^+\mu^-$ differ visibly from Standard Model predictions.

The first step in this indirect strategy is to search for discrepancies between theoretical predictions and experimental observables. The main challenge for experimentalists is the low branching ratios for the rare decays in question. However, there are very good prospects for measuring many of these highly suppressed branching ratios in the coming years.

Six channels for the 2020s

Six channels stand out today for their superb potential to observe new physics this decade. If their decay rates defy expectations, the nature of any new physics could be identified by studying the correlations between these six decays and others.

The first two channels are kaon decays: the measurements of $K^+ \to \pi^+\nu\bar{\nu}$ by the NA62 collaboration at CERN (see "Needle in a haystack" image), and the measurement of $K_L \to \pi^0\nu\bar{\nu}$ by the KOTO collaboration at J-PARC in Japan. The branching ratios for these decays are predicted to be in the ballpark of 8×10^{-11} and 3×10^{-11}, respectively.

The second two are measurements of $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ by the Belle II collaboration at KEK in Japan. Branching ratios for these decays are expected to be much higher, in the ballpark of 10^{-5}.

The final two channels, which are only accessible at the LHC, are measurements of the dimuon decays $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ by the LHCb, CMS and ATLAS collaborations. Their branching ratios are about 4×10^{-9} and 10^{-10} in the Standard Model. Though the decays $B \to K(K^*)\mu^+\mu^-$ are also promising, they are less theoretically clean than these six.

The main challenge for theorists is to control quantum-chromodynamics (QCD) effects, both below 10^{-16} m, where strong interactions weaken, and in the non-perturbative region at distance scales of about 10^{-15} m, where quarks are confined in hadrons and calculations become particularly tricky. While satisfactory precision has been achieved at short-distance scales over the past three decades, the situation for non-perturbative computations is expected to improve significantly in the coming years, thanks to lattice QCD and analytic approaches such as dual QCD and chiral perturbation theory for kaon decays, and heavy-quark effective field theory for B decays.

Another challenge is that Standard Model predictions for the branching ratios require values for four CKM parameters that are not predicted by the Standard Model, and which must be measured using kaon and B-meson decays. These are the magnitude of the up-strange (V_{us}) and charm-bottom (V_{cb}) couplings and the CP-violating phases β and γ. The current precision on measurements of V_{us} and β is fully satisfactory, and the error on $\gamma = (63.8 \pm 3.5)°$ should be reduced to 1° by LHCb and Belle II in the coming years. The stumbling block is V_{cb}, where measurements currently disagree. Though experimental problems have not been excluded, the tension is thought to originate in QCD calculations. While measurements of exclusive decays to specific channels yield $39.21(62) \times 10^{-3}$, inclusive measurements integrated over final states yield $41.96(50) \times 10^{-3}$. This discrepancy makes the predicted branching ratios differ by 16% for the four B-meson decays, and by 25% and 35% for $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$. These discrepancies are a disaster for the theorists who had succeeded over many years of work to reduce QCD uncertainties in these decays to the level of a few percent.

One solution is to replace the CKM dependence of the branching ratios with observables where QCD uncertainties are under good control, for example: the mass differences in $B_s^0 - \bar{B}_s^0$ and $B_d^0 - \bar{B}_d^0$ mixing (ΔM_s and ΔM_d); a parameter that measures CP violation in $K^0 - \bar{K}^0$ mixing (ε_K); and the CP-asymmetry that yields the angle β. Fitting these observables to the experimental data avoids us being forced to choose between inclusive and exclusive values for the charm-bottom coupling, and avoids the 3.5° uncertainty on γ, which in this strategy is reduced to 1.6°. Uncertainty on the predicted branching ratios is thereby reduced to 6% and 9% for $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$, to 5% for the two kaon decays, and to 4% for $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$.

So what is the current experimental situation for the six channels? The latest NA62 measurement of $K^+ \to \pi^+\nu\bar{\nu}$ is 25% larger than the Standard Model prediction. Its 36% uncertainty signals full compatibility at present, and precludes any conclusions about the size of new physics contributing to this decay. Next year, when the full analysis has been completed, this could turn out to be possible. It is unfortunate that the HIKE proposal was not adopted (*CERN Courier* May/June 2024 p7), as NA62's expected precision of 15% could have been reduced to 5%. This could turn out to be crucial for the discovery of new physics in this decay.

The present upper bound on $K_L \to \pi^0\nu\bar{\nu}$ from KOTO is still two orders of magnitude above the Standard Model prediction. This bound should be lowered by at least one order of magnitude in the coming years. As this decay is fully governed by CP violation, one may expect that new physics will impact it significantly more than CP-conserving decays such as $K^+ \to \pi^+\nu\bar{\nu}$.

Branching out from Belle

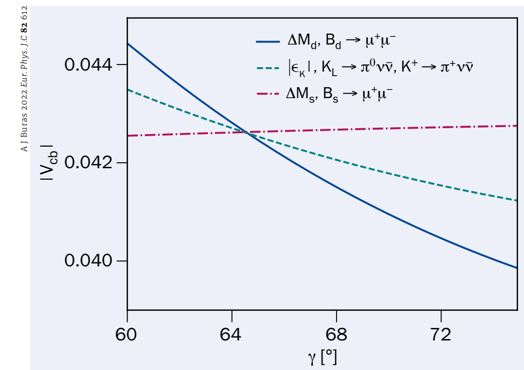
At present, the most interesting result concerns a 2023 update from Belle II to the measured branching ratio for $B^+ \to K^+\nu\bar{\nu}$ (see "Interesting excess" image). The resulting central value from Belle II and BaBar is currently a factor of 2.6 above the Standard Model prediction. This has sparked many theoretical analyses around the world, but the experimental error of 30% once again does not allow for firm conclusions. Measurements of other charge and spin configurations of this decay are pending.

Finally, both dimuon B-meson decays are at present consistent with Standard Model predictions, but significant improvements in experimental precision could still reveal new physics at work, especially in the case of B_d.

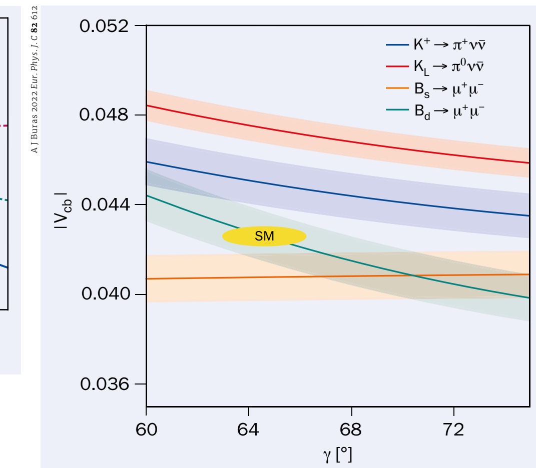
It will take a few years to conclude if new physics contributions are evident in these six branching ratios, but the fact that all are now predicted accurately means that we can expect to observe or exclude new physics in them before the end of the decade. This would be much harder if measurements of the V_{cb} coupling were involved.

So far, so good. But what if the observables that replaced V_{cb} and γ are themselves affected by new physics? How can they be trusted to make predictions against which rare decay rates can be tested?

Here comes some surprisingly good news: new physics does not appear to be required to simultaneously fit them using our new basis of observables ΔM_d, ε_K and ΔM_s, as they intersect at a single point in the V_{cb}–γ plane (see "No new physics" figure). This analysis favours the inclusive determination of V_{cb} and yields a value for γ that is consistent with the experimental world average and a factor of two more accurate. It's important to stress, though, that non-perturbative four-flavour lattice-QCD calculations of ΔM_s and ΔM_d by the HPQCD lattice collaboration played a key role here. It is crucial that another lattice QCD collaboration repeat these calculations, as the three curves cross at different points in three-flavour calculations that exclude charm.



No new physics *Independent observables ΔM_s, ΔM_d and ε_K intersect in the $V_{cb} - \gamma$ plane. No new physics is required to fit them simultaneously. Uncertainties are not shown in this illustrative Standard Model plot.*



New physics *The impact of hypothetical future measurements of branching ratios on a $V_{cb} - \gamma$ plot. Bands that do not intersect the Standard Model fit (yellow disc) would indicate the presence of new physics. 5% uncertainties are assumed.*

In this context, one realises the advantages of V_{cb}–γ plots compared to the usual unitarity-triangle plots, where V_{cb} is not seen and 1° improvements in the determination of γ are difficult to appreciate. In the late 2020s, determining V_{cb} and γ from tree-level decays will be a central issue, and a combination of V_{cb}-independent and V_{cb}-dependent approaches will be needed to identify any concrete model of new physics.

We should therefore hope that the tension between inclusive and exclusive determinations of V_{cb} will soon be conclusively resolved. Forthcoming measurements of our six rare decays may then reveal new physics at the energy frontier (see "New physics" figure). With a 1° precision measurement of γ on the horizon, and many V_{cb}-independent ratios available, interesting years are ahead in the field of indirect searches for new physics.

In 1676 Antonie van Leeuwenhoek discovered a microuniverse populated by bacteria, which he called animalcula, or little animals. Let us hope that we will, in this decade, discover new animalcula on our flavour expedition to the zeptouniverse. ●

Interesting years are ahead in the field of indirect searches for new physics

Further reading

A J Buras and E Venturini 2021 *Acta. Phys. Polon. B* **53** 6–A1 (arXiv:2109.11032).
A J Buras and E Venturini 2022 *Eur. Phys. J. C* **82** 615 (arXiv:2203.11960).
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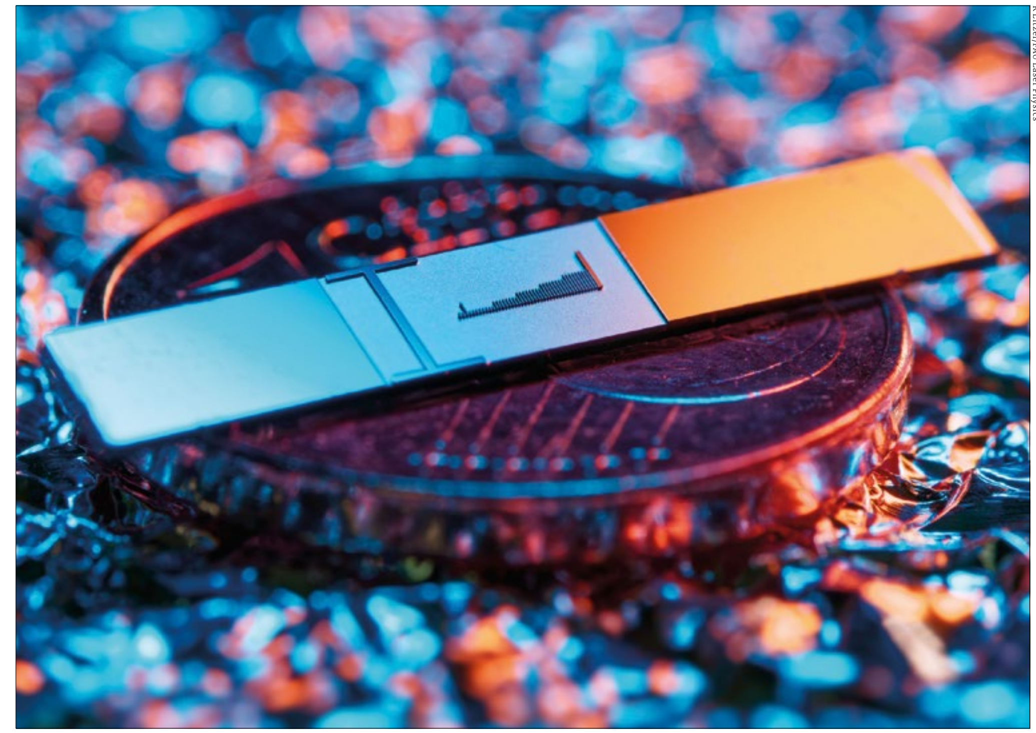
A J Buras 2023 *Eur. Phys. J. C* **83** 66 (arXiv:2209.03968).

ACCELERATION, BUT NOT AS WE KNOW IT



K Litzel/FAU Laser Physics

Accelerators on a chip *Forty long and thin mesas increase in length from 100 to 500 μm on a silicon chip the size of a cent coin. Each mesa supports a micron-wide dual colonnade of silicon pillars along its full length. Electrons passing between the pillars are accelerated when the colonnade is illuminated by a laser.*

On-chip acceleration pioneers Robert Byer, Joel England, Peter Hommelhoff and Roy Shiloh report on progress to miniaturise accelerators from centimetres to microns.

Metal cavities are at the heart of the vast majority of the world's 30,000 or so particle accelerators. Excited by microwaves, these resonant structures are finely tuned to generate oscillating electric fields that accelerate particles over many metres. But what if similar energies could be delivered 100 times more rapidly in structures a few tens of microns wide or less?

The key is to reduce the wavelength of the radiation powering the structure down to the optical scale of lasers. By combining solid-state lasers and modern nanofabrication, accelerating structures can be as small as a single micron wide. Though miniaturisation will never allow bunch charges as large as in today's science accelerators, field strengths can be much higher before structure damage sets in. The trick is to replace highly conductive structures with dielectrics like silicon, fused silica and diamond, which have a much higher damage threshold at optical wavelengths. The length of accelerators can thereby be reduced by orders of magnitude, with millions to billions of particle pulses accelerated per second, depending on the repetition rate of the laser.

Recent progress with "on chip" accelerators promises powerful, high-energy and high-repetition-rate particle sources that are accessible to academic laboratories. Applications may range from localised particle or X-ray irradiation in medical facilities to quantum communication and computation using ultrasmall bunches of electrons as qubits.

Laser focused

The inspiration for on-chip accelerators dates back to 1962, when Koichi Shimoda of the University of Tokyo proposed using early lasers – then called optical masers – as a way

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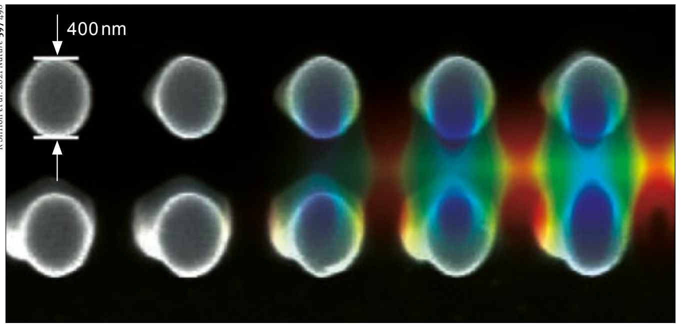


R Shiloh et al. 2021 *Nature* **597** 498

Continuous acceleration *A snapshot of the longitudinal electric field in a dual-pillar colonnade illuminated by a laser. Electrons pass through the accelerating channel from left to right. At this moment in time, they would be accelerated in the red regions and decelerated in the blue regions.*

On-chip accelerators promise powerful, high-energy and high-repetition-rate particle sources that are accessible to academic laboratories

to accelerate charged particles. The first experiments were conducted by shining light onto an open metal grating, generating an optical surface mode that could accelerate electrons passing above the surface. This technique was proposed by Yasutugu Takeda and Isao Matsui in 1968 and experimentally demonstrated by Koichi Mizuno in 1987 using terahertz radiation. In the 1980s, accelerator physicist Robert Palmer of Brookhaven National Laboratory proposed using rows of free-standing pillars of subwavelength separation illuminated by a laser – an idea that has propagated to modern devices.

In the 1990s, the groups of John Rosenzweig and Claudio Pellegrini at UCLA and Robert Byer at Stanford began to use dielectric materials, which offer low power absorption at optical frequencies. For femtosecond laser pulses, a simple dielectric such as silica glass can withstand optical field strengths exceeding 10 GV/m. It became clear that combining lasers with on-chip fabrication using dielectric materials could subject particles to accelerating forces 10 to 100 times higher than in conventional accelerators.

In the intervening decades, the dream of realising a laser-driven micro-accelerator has been enabled by major technological advances in the silicon-microchip industry and solid-state lasers. These industrial technologies have paved the way to fabricate and test particle accelerators made from silicon and other dielectric materials driven by ultrashort pulses of laser light. The dielectric laser accelerator (DLA) has been born.

The dream of realising a laser-driven micro-accelerator has been enabled by major advances in silicon microchips and solid-state lasers

Accelerator on a chip

Colloquially called an accelerator on a chip, a DLA is a miniature microwave accelerator reinvented at the micron scale using the methods of optical photonics rather than microwave engineering. In both cases, the wavelength of the driving field determines the typical transverse structure dimensions: centimetres for today's microwave accelerators, but between one and 10 μm for optically powered devices.

Other laser-based approaches to miniaturisation are available. In plasma-wakefield accelerators, particles gain energy from electromagnetic fields excited in an ionised gas by a high-power drive laser (*CERN Courier* May/June 2024 p25). But the details are starkly different. DLAs are powered by lasers with thousands to millions of times lower peak energy. They operate with more than a million times lower electron charges, but at millions of pulses per second. And unlike plasma accelerators, but similarly to their microwave counterparts, DLAs use a solid material structure with a vacuum channel in which an electromagnetic mode continuously imparts energy to the accelerated particles.

This mode can be created by a single laser pulse perpendicular to the electron trajectory, two pulses from opposite sides, or a single pulse directed downwards into the plane of the chip. The latter two options offer better field symmetry.

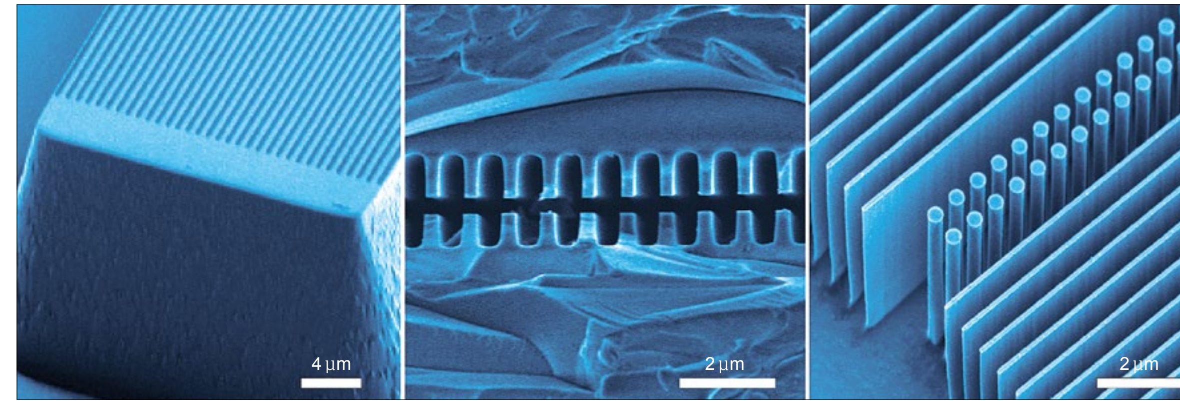
As the laser impinges on the structure, its electrons experience an electromagnetic force that oscillates at the laser frequency. Particles that are correctly matched in phase and velocity experience a forward accelerating force (see "Continuous acceleration" image). Just as the imparted force begins to change sign, the particles enter the next accelerating cycle, leading to continuous energy gain.

In 2013, two early experiments attracted international attention by demonstrating the acceleration of electrons using structured dielectric devices. Peter Hommelhoff's group in Germany accelerated 28 keV electrons inside a modified electron microscope using a single-sided glass grating (see "Evolution" image, left panel). In parallel, at SLAC, the groups of Robert Byer and Joel England accelerated relativistic 60 MeV electrons using a dual-sided grating structure, achieving an acceleration gradient of 310 MeV/m and 120 keV of energy gain (see "Evolution" image, middle panel).

Teaming up

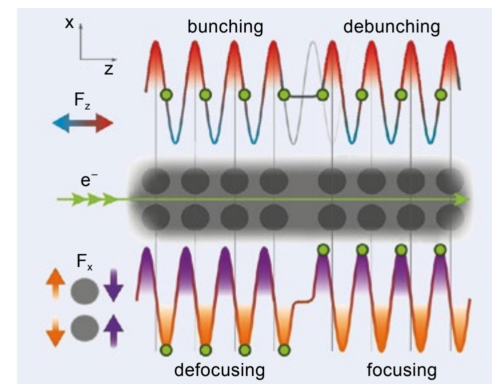
Encouraged by the experimental demonstration of accelerating gradients of hundreds of MeV/m, and the power efficiency and compactness of modern solid-state fibre lasers, in 2015 the Gordon and Betty Moore Foundation funded an international collaboration of six universities, three government laboratories and two industry partners to form the Accelerator on a Chip International Program (ACHIP). The central goal is to demonstrate a compact tabletop accelerator based on DLA technology. ACHIP has since developed "shoebox" accelerators on both sides of the Atlantic and used them to demonstrate nanophotonics-based particle control, staging, bunching, focusing and full on-chip electron acceleration by laser-driven microchip devices.

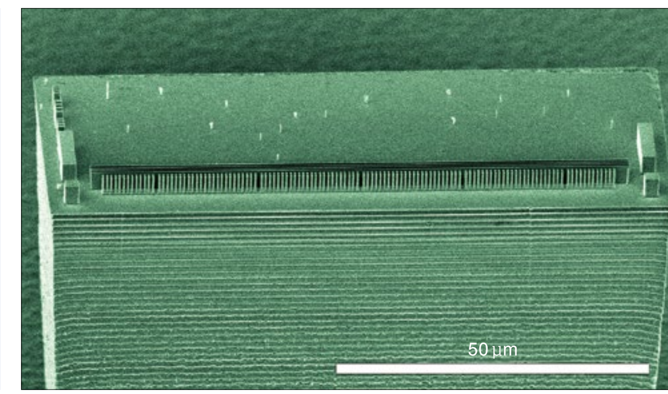
Silicon's compatibility with established nanofabrication processes makes it convenient, but reaching gradients of GeV/m requires materials with higher damage thresholds



J Breuer & P Hommelhoff/FAU Erlangen; E Peralta/Stanford Univ.; P Hommelhoff/FAU Erlangen

Evolution *Dielectric structures have evolved from single-sided gratings (left) to dual-sided fused silica gratings (middle) and dual-pillar silicon structures (right).*





T Chlouba et al. 2023 *Nature* **622** 476; R Shiloh et al. 2021 *Nature* **597** 498

Beam control *Longitudinal and transverse beam control (left) is achieved by introducing gaps into the dual colonnade (right).*

such as fused silica or diamond. In 2018, ACHIP research at UCLA accelerated electrons from a conventional microwave linac in a dual-sided fused silica structure powered by ultrashort (45 fs) pulses of 800 nm wavelength laser light. The result was an average energy gain of 850 MeV/m and accelerating fields up to 1.8 GV/m – more than double the prior world best in a DLA, and still a world record.

Since DLA structures are non-resonant, the interaction time and energy gain of the particles is limited by the duration of the laser pulse. However, by tilting the laser's pulse front, the interaction time can be arbitrarily increased. In a separate experiment at UCLA, using a laser pulse tilted by 45°, the interaction distance was increased to more than 700 μm – or 877 structure periods – with an energy gain of 0.315 MeV. The UCLA group has further extended this approach using a spatial light modulator to "imprint" the phase information onto the laser pulse, achieving more than 3 mm of interaction at 800 nm, or 3761 structure periods.

Under ACHIP, the structure design has evolved in several directions, from single-sided and double-sided gratings etched onto substrates to more recent designs with colonnades of free-standing silicon pillars forming the sides of the accelerating channel, as originally proposed by Robert Palmer some 30 years earlier. At present, these dual-pillar structures (see "Evolution" image, right panel) have proven to be the optimal trade-off between cleanroom fabrication complexity and experimental technicalities. However, due to the lower damage threshold of silicon as compared with fused silica, researchers have yet to demonstrate gradients above 350 MeV/m in silicon-based devices.

With the dual-pillar colonnade chosen as the fundamental nanophotonic building block, research has turned to making DLAs into viable accelerators with much longer acceleration lengths. To achieve this, we need to be able to control the beam and manipulate it in space and time, or electrons quickly diverge inside the narrow acceleration channel and are lost on impact with the accelerating structure. The ACHIP collaboration has made substantial progress here in recent years.

Focusing on nanophotonics

In conventional accelerators, quadrupole magnets focus electron beams in a near perfect analogy to how concave and convex lens arrays transport beams of light in optics. In laser-driven nanostructures it is necessary to harness the intrinsic focusing forces that are already present in the accelerating field itself.

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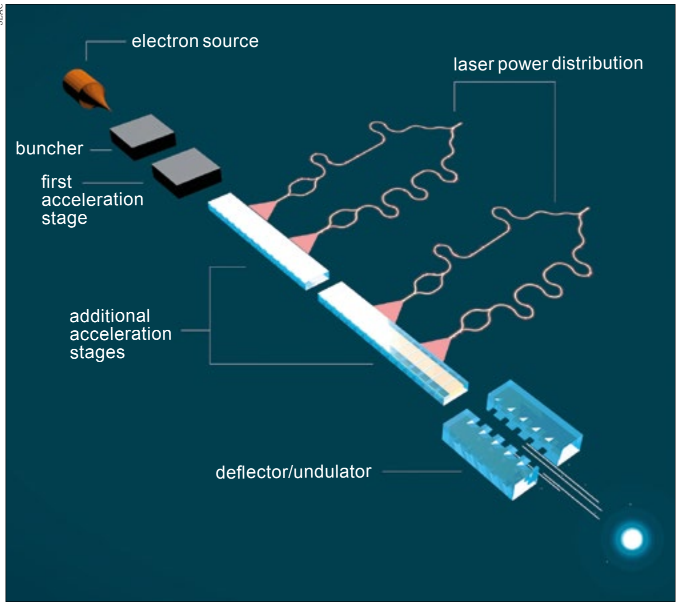

Compact light source *The concept for a fully on-chip accelerator light source to produce coherent radiation.*

In 2021, the Hommelhoff group guided an electron pulse through a 200 nm-wide and 80 µm-long structure based on a theoretical lattice designed by ACHIP colleagues at TU Darmstadt three years earlier. The lattice's alternating-phase focusing (APF) periodically exchanges an electron bunch's phase-space volume between the transverse dimension across the narrow width of the accelerating channel and the longitudinal dimension along the propagation direction of the electron pulse. In principle this technique could allow electrons to be guided through arbitrarily long structures.

Guiding is achieved by adding gaps between repeating sets of dual-pillar building-blocks (see "Beam control" image). Combined guiding and acceleration has been demonstrated within the past year. To achieve this, we select a design gradient and optimise the position of each pillar pair relative to the expected electron energy at that position in the structure. Initial electron energies are up to 30 keV in the Hommelhoff group, supplied by electron microscopes, and from 60 to 90 keV in the Byer group, using laser-assisted field emission from silicon nanotips. When accelerated, the electrons' velocities change dramatically from 0.3 to 0.7 times the speed of light or higher, requiring the periodicity of the structure to change by tens of nanometres to match the velocity of the accelerating wave to the speed of the particles.

We expect on-chip accelerators to become ubiquitous devices with wide-ranging and unexpected applications

Although focusing in the narrow dimension of the channel is the most critical requirement, an extension of this method to focus beams in the transverse vertical dimension out of plane of the chip has been proposed, which varies the geometry of the pillars along the out-of-plane dimension. Without it, the natural divergence of the beam in the vertical direction eventually becomes dominant. This approach is awaiting experimental realisation.

Acceleration gradients can be improved by optimising material choice, pillar dimensions, peak optical field strength and the duration of the laser pulses. In recent demonstrations, both the Byer and Hommelhoff groups have kept pillar dimensions constant to ease difficulties in uniformly etching the structures during nanofabrication. The complete structure is then a series of APF cells with tapered cell lengths and tapered dual-pillar periodicity. The combination of tapers accommodates both the changing size of the electron beam and the phase matching required due to the increasing electron energy.

In these proof-of-principle experiments, the Hommelhoff group has designed a nanophotonic dielectric laser accelerator for an injection energy of 28.4 keV and an average acceleration gradient of at least 22.7 MeV/m, demonstrating a 43% energy increase over a 500 µm-long structure. The Byer group recently demonstrated the acceleration of a 96 keV beam at average gradients of 35 to 50 MeV/m, reaching a 25% energy increase over 708 µm. The APF periods were in the range of tens of microns and were tapered along with the energy-gain design curve. The beams were not bunched, and by design only 4% of the electrons were captured and accelerated.

One final experimental point has important implications for the future use of DLAs as compact tabletop tools for ultrafast science. Upon interaction with the DLA, electron pulses have been observed to form trains of evenly spaced sub-wavelength attosecond-scale bunches. This effect was shown experimentally by both groups in 2019, with electron bunches measured down to 270 attoseconds, or roughly 4% of the optical cycle.

From demonstration to application

To date, researchers have demonstrated high gradient (GeV/m) acceleration, compatible nanotip electron sources, laser-driven focusing, interaction lengths up to several millimetres, the staging of multiple structures, and attosecond-level control and manipulation of electrons in nanophotonic accelerators. The most recent experiments combine these techniques, allowing the capture of an accelerated electron bunch with net acceleration and precise control of electron dynamics for the first time.

These milestone experiments demonstrate the viability of the nanophotonic dielectric electron accelerator as a scalable technology that can be extended to arbitrarily long structures and ever higher energy gains. But for most applications, beam currents need to increase.

A compelling idea proposes to "copy and paste" the accelerator design in the cleanroom and make a series of parallel accelerating channels on one chip. Another option is to increase the repetition rate of the driving laser by orders of magnitude to produce more electron pulses per second. Optimising the electron sources used by DLAs would also allow for more electrons per pulse, and parallel arrays of emitters on multi-channel devices promise tremendous advantages. Eventually, active nanophotonics can be employed to integrate the laser and electron sources on a single chip.

Once laser and electron sources are combined, we expect on-chip accelerators to become ubiquitous devices with wide-ranging and unexpected applications, much like the laser itself. Future applications will range from medical treatment tools to electron probes for ultrafast science. According to the International Atomic Energy Agency statistics, 13% of major accelerator facilities around the world power light sources. On-chip accelerators may follow a similar path.

Illuminating concepts

A concept has been proposed for a dielectric laser-driven undulator (DLU) which uses laser light to generate deflecting forces that wiggle the electrons so that they emit coherent light. Combining a DLA and a DLU could take advantage of the unique time structure of DLA electrons to produce ultrafast pulses of coherent radiation (see "Compact light source" image). Such compact new light sources – small enough to be accessible to individual universities – could generate extremely short flashes of light in ultraviolet or even X-ray wavelength ranges, enabling tabletop instruments for the study of material dynamics on ultrafast time scales. Pulse trains of attosecond electron bunches generated by a DLA could provide excellent probes of transient molecular electronic structure.

The generation of intriguing quantum states of light might also be possible with nanophotonic devices. This quantum light results from shaping electron wavepackets inside the accelerator and making them radiate, perhaps even leading to on-chip quantum-communication light sources.

In the realm of medicine, an ultracompact self-contained multi-MeV electron source based on integrated photonic particle accelerators could enable minimally invasive cancer treatments with improved dose control.

One day, instruments relying on high-energy electrons produced by DLA technology may bring the science of large facilities into academic-scale laboratories, making novel science endeavours accessible to researchers across various disciplines and minimally invasive medical treatments available to those in need. These visionary applications may take decades to be fully realised, but we should expect developments to continue to be rapid. The biggest challenges will be increasing beam power and transporting beams across greater energy gains. These need to be addressed to reach the stringent beam quality and machine requirements of longer term and higher energy applications. ●

The generation of intriguing quantum states of light might also be possible with nanophotonic devices

Further reading
R Shiloh *et al.* 2021 *Nature* **597** 498.
R Shiloh *et al.* 2022 *Adv. Opt. Phot.* **14** 862.
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A GOLD MINE FOR NEUTRINO PHYSICS

The DUNE experiment is taking shape deep in the same mine where physicists got the first hint that something was amiss with the neutrino.

Vertical drift *A physicist studies the field cage of a prototype liquid–argon time-projection chamber at CERN.* M Cavazza/CERN-PHOTO-202308-195-28

In 1968, deep underground in the Homestake gold mine in South Dakota, Ray Davis Jr. observed too few electron neutrinos emerging from the Sun. The reason, we now know, is that many had changed flavour in flight, thanks to tiny unforeseen masses.

At the same time, Steven Weinberg and Abdus Salam were carrying out major construction work on what would become the Standard Model of particle physics, building the Higgs mechanism into Sheldon Glashow's unification of the electromagnetic and weak interactions. The Standard Model is still bulletproof today, with one proven exception: the nonzero neutrino masses for which Davis's observations were in hindsight the first experimental evidence.

Today, neutrinos are still one of the most promising windows into physics beyond the Standard Model, with the potential to impact many open questions in fundamental science (*CERN Courier* May/June 2024 p29). One of the most ambitious experiments to study them is currently taking shape in the same gold mine as Davis's experiment more than half a century before.

Deep underground

In February this year, the international Deep Underground Neutrino Experiment (DUNE) completed the excavation of three enormous caverns 1.5 kilometres below the surface at the new Sanford Underground Research Facility (SURF) in the Homestake mine. 800,000 tonnes of rock have been excavated over two years to reveal an underground campus the size of eight soccer fields, ready to house four 17,500 tonne liquid–argon time-projection chambers

THE AUTHORS

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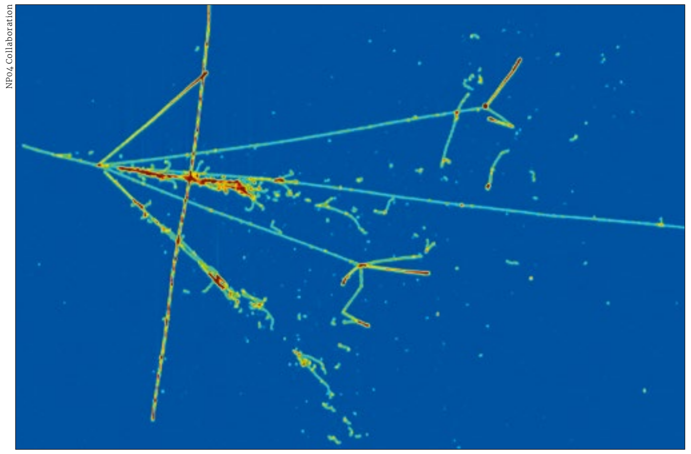
Kate Shaw *University of Sussex.*

NP04 Collaboration



Millimetre precision *A 6 GeV charged pion (left) ejects a proton (top) from an argon nucleus in the single-phase ProtoDUNE detector at CERN. Three charged pions and two photons also emerge from the vertex, and a stopping cosmic-ray muon is seen crossing the event.*

CERN

Cryostat creation *The pre-assembly of a section of the second cryostat for DUNE at the factory in Arteixo, Spain.*

(LArTPCs). As part of a diverse scientific programme, the new experiment will tightly constrain the working model of three massive neutrinos, and possibly even disprove it.

DUNE will measure the disappearance of muon neutrinos and the appearance of electron neutrinos over 1300 km and a broad spectrum of energies. Given the long journey of its accelerator-produced neutrinos from the Long Baseline Neutrino Facility (LBNF) at Fermilab in Illinois to SURF in South Dakota, DUNE will be uniquely sensitive to asymmetries between the appearance of electron neutrinos and antineutrinos. One predicted asymmetry will be caused by the presence of electrons and the absence of positrons in the Earth's crust. This asymmetry will probe neutrino mass ordering – the still unknown ordering of narrow and broad mass splittings between the three tiny neutrino masses. In its first phase of operation, DUNE will definitively establish the neutrino mass ordering regardless of other parameters.

If CP symmetry is violated, DUNE will then observe a second asymmetry between electron neutrinos and antineutrinos, which by experimental design is not degenerate with the first asymmetry. Potentially the first evidence for CP violation by leptons, this measurement will be an important experimental input to the fundamental question of how a matter–antimatter asymmetry developed in the early universe.

If CP violation is near maximal, DUNE will observe it at 3σ (99.7% confidence) in its first phase. In DUNE and LBNF's recently reconceptualised second phase, which was strongly endorsed by the US Department of Energy's Particle Physics Project Prioritization Panel (P5) in December (*CERN Courier* January/February 2024 p7), 3σ sensitivity to CP violation will be extended to more than 75% of possible values of δ_{CP}, the complex phase that parameterises this effect in the three-massive-neutrino paradigm.

Combining DUNE's measurements with those by fellow next-generation experiments JUNO and Hyper-Kamiokande will test the three-flavour paradigm itself. This paradigm rotates three massive neutrinos into the mixtures that interact with charged leptons via the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix, which features three angles in addition to δ_{CP}.

As well as promising world-leading resolution on the PMNS angle θ_{23}, DUNE's measurements of θ_{13} and the Δm^2_{32} mass splitting will be different and complementary to those of JUNO in ways that could be sensitive to new physics. JUNO, which is currently under construction in China, will operate in the vicinity of a flux of lower-energy electron antineutrinos from nuclear reactors. DUNE and Hyper-Kamiokande, which is currently under construction in Japan, will both study accelerator-produced sources of muon neutrinos and antineutrinos, though using radically different baselines, energy spectra and detector designs.

Innovative and impressive

DUNE's detector technology is innovative and impressive, promising millimetre-scale precision in imaging the interactions of neutrinos from accelerator and astrophysical sources (see "Millimetre precision" image). The argon target provides unique sensitivity to low-energy electron neutrinos from supernova bursts, while the detectors' imaging capabilities will be pivotal when searching for beyond-the-Standard-Model physics such as dark matter, sterile-neutrino mixing and non-standard neutrino interactions.

First proposed by Nobel laureate Carlo Rubbia in 1977, LArTPC technology demonstrated its effectiveness as a neutrino detector at Gran Sasso's ICARUS T600 detector more than a decade ago, and also more recently in the MicroBooNE experiment at Fermilab. Fermilab's short-baseline neutrino programme now includes ICARUS and the new Short Baseline Neutrino Detector, which is due to begin taking neutrino data this year.

The first phase of DUNE will construct one LArTPC in

DUNE's detector technology is innovative and impressive, promising millimetre-scale precision in imaging the interactions of neutrinos

each of the two detector caverns, with the second phase adding an additional detector in each. A central utility cavern between the north and south caverns will house infrastructure to support the operation of the detectors.

Following excavation by Thyssen Mining, final concrete work was completed in all the underground caverns and drifts, and the installation of power, lighting, plumbing, heating, ventilation and air conditioning is underway. 90% of the subcontracts for the installation of the civil infrastructure have already been awarded, with LBNF and DUNE's economic impact in Illinois and South Dakota estimated to be $4.3 billion through fiscal years 2022 to 2030.

Once the caverns are prepared, two large membrane cryostats will be installed to house the detectors and their liquid argon. Shipment of material for the first of the two cryostats being provided by CERN is underway, with the first of approximately 2000 components having arrived at SURF in January; the remainder of the steel for the first cryostat was due to have been shipped from its port in Spain by the end of May. The manufacture of the second cryostat by Horta Coslada is ongoing (see "Cryostat creation" image).

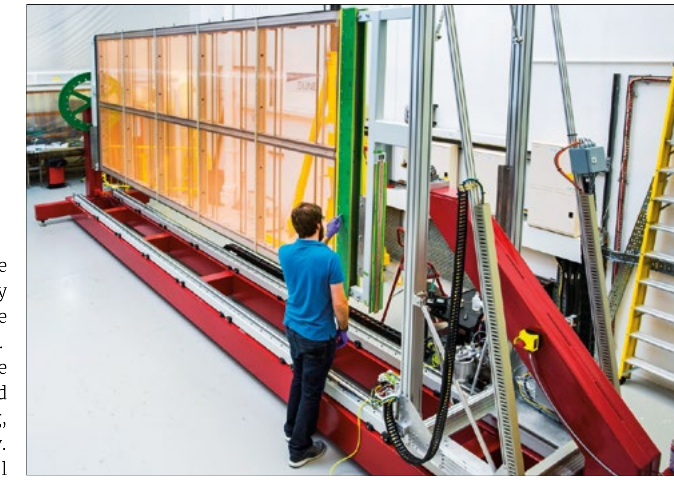
Procedures for lifting and manipulating the components will be tested in South Dakota in spring 2025, allowing the collaboration to ensure that it can safely and efficiently handle bulky components with challenging weight distributions in an environment where clearances can reach as little as 3 inches on either side. Lowering detector components down the Homestake mine's Ross shaft will take four months.

Two configurations

The two far-detector modules needed for phase one of the DUNE experiment will use the same LArTPC technology, though with different anode and high-voltage configurations. A "horizontal-drift" far detector will use 150 6 m-by-2.3 m anode plane assemblies (APAs). Each will be wound with 4000 150 μm diameter copper-beryllium wires to collect ionisation signals from neutrino interactions with the argon.

A second "vertical-drift" far detector will instead use charge readout planes (CRPs) – printed circuit boards perforated with an array of holes to capture the ionisation signals. Here, a horizontal cathode plane will divide the detector into two vertically stacked volumes. This design yields a slightly larger instrumented volume, which is highly modular in design, and simpler and more cost-effective to construct and install. A small amount of xenon doping will significantly enhance photo detection, allowing more light to be collected beyond a drift length of 4 m.

Daresbury laboratory



Wind it up *A winding machine producing a ProtoDUNE anode plane assembly at Daresbury Laboratory in the UK.*

The construction of the horizontal-drift APAs is well underway at STFC Daresbury Laboratory in the UK and at the University of Chicago in the US. Each APA takes several weeks to produce, motivating the parallelisation of production across five machines in Daresbury and one in Chicago. Each machine automates the winding of 24 km of wire onto each APA (see "Wind it up" image). Technicians then solder thousands of joints and use a laser system to ensure the wires are all wound to the required tension.

Two large ProtoDUNE detectors at CERN are an essential part of developing and validating DUNE's detector design. Four APAs are currently installed in a horizontal-drift prototype that will take data this summer as a final validation of the design of the full detector. A vertical-drift prototype (see "Vertical drift" image) will then validate the production of CRP anodes and optimise their electronics. A full-scale test of vertical-drift-detector installation will take place at CERN later this year.

Phase transition

Alongside the deployment of two additional far-detector modules, phase two of the DUNE experiment will include an increase in beam power beyond 2 MW and the deployment of a more capable near detector (MCND) featuring a magnetised high-pressure gaseous-argon TPC. These enhancements pursue increased statistics, lower energy thresholds, better energy resolution and lower intrinsic backgrounds. They are key to DUNE's measurement of the parameters governing long-baseline neutrino oscillations, and will expand the experiment's physics scope, including searches for anomalous tau-neutrino appearance, long-lived particles, low-mass dark matter and solar neutrinos.

Phase-one vertical-drift technology is the starting point for phase-two far-detector R&D – a global programme under ECFA in Europe and CPAD in the US that seeks to reduce costs and improve performance. Charge-readout R&D includes improving charge-readout strips, 3D pixel readout and 3D readout using high-performance fast cam-

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eras. Light-readout R&D seeks to maximise light coverage by integrating bare silicon photomultipliers and photoconductors into the detector's field-cage structure.

A water-based liquid scintillator module capable of separately measuring scintillation and Cherenkov light is currently being explored as a possible alternative technology for the fourth "module of opportunity". This would require modifications to the near detector to include corresponding non-argon targets.

Intense work

At Fermilab, site preparation work is already underway for LBNF, and construction will begin in 2025. The project will produce the world's most intense beam of neutrinos. Its wide-band beam will cover more than one oscillation period, allowing unique access to the shape of the oscillation pattern in a long-baseline accelerator-neutrino experiment.

The next generation of big neutrino experiments promises to bring new insights into the nature of our universe

LBNF will need modest upgrades to the beamline to handle the 2 MW beam power from the upgrade to the Fermilab accelerator complex, which was recently endorsed by P5. The bigger challenge to the facility will be the proton-target upgrades needed for operation at this beam power. R&D is now taking place at Fermilab and at the Rutherford Appleton Laboratory in the UK, where DUNE's phase-one 1.2 MW target is being designed and built.

DUNE highlights the international and collaborative nature of modern particle physics, with the collaboration boasting more than 1400 scientists and engineers from 209 institutions in 37 countries. A milestone was achieved late last year when the international community came together to sign the first major multi-institutional memorandum of understanding with the US Department of Energy, affirming commitments to the construction of detector components for DUNE and pushing the project to its next stage. US contributions are expected to cover roughly half of what is needed for the far detectors and the MCND, with the international community contributing the other half, including the cryostat for the third far detector.

DUNE is now accelerating into its construction phase. Data taking is due to start towards the end of this decade, with the goal of having the first far-detector module operational before the end of 2028.

The next generation of big neutrino experiments promises to bring new insights into the nature of our universe – whether it is another step towards understanding the preponderance of matter, the nature of the supernovae explosions that produced the stardust of which we are all made, or even possible signatures of dark matter… or something wholly unexpected! ●

Further reading

DUNE Collab. 2022 *JINST* **17** P01005.

The next 10 years in astroparticle theory

Newly appointed EuCAPT director Silvia Pascoli sets out her vision for disentangling fundamental questions involving dark matter, the baryon asymmetry, neutrinos, cosmic rays, gravitational waves, dark energy and other cosmic relics.

T Klein/NANOGrav

Unknown origin *Pulsar timing arrays indicate the presence of a stochastic background of gravitational waves.*

University & INFN Bologna

Silvia Pascoli, *University of Bologna and INFN, is director of the European Consortium for Astroparticle Theory (EuCAPT).*

Astroparticle physics connects the extremely small with the extremely large. At the interface of particle physics, cosmology and astronomy, the field ties particles and interactions to the hot Big Bang cosmological model. This synergy allows us to go far beyond the limitations of terrestrial probes in our quest to understand nature at its most fundamental level. A typical example is neutrino masses, where cosmological observations from large-scale structure formation far exceed current bounds from terrestrial experiments. Astroparticle theory (APT) has accelerated quickly in the past 10 years. And this looks certain to continue in the next 10.

Today, neutrino masses, dark matter and the baryon asymmetry of the universe are the only evidence we have of physics beyond the Standard Model (BSM) of particle physics. Astroparticle theorists study how to extend the theory towards a new Standard Model – and the cosmological consequences of doing so.

New insights

For a long time, work on dark matter focused on TeV-scale models parallel to searches at the LHC and in ultra-low-noise detectors. The scope has now broadened to a much larger range of masses and models, from ultralight dark matter and axions to sub-GeV dark matter and WIMPs. Theoretical developments have gone hand-in-hand with new experimental opportunities. In the next 10 years, much larger detectors are planned for WIMP searches aiming towards the neutrino floor. Pioneering experimental efforts, even borrowing techniques from atomic and condensed-matter physics, test dark matter with much lower masses, providing new insights into what dark matter may be made of.

I strongly welcome efforts to broaden the reach in mass scales to efficiently hunt for any hint of what the new physics BSM may be

Neutrinos provide a complementary window on BSM physics. It is just over 25 years since the discovery of neutrino oscillation provided evidence that neutrinos have mass – a fact that cannot be accounted for in the SM (*CERN Courier* May/June 2024 p29). But the origin of neutrino masses remains a mystery. In the coming decade, neutrinoless double-beta decay experiments and new large experiments, such as JUNO, DUNE (p41) and Hyper-Kamiokande, will provide a much clearer picture, determining the mass ordering and potentially discovering the neutrino's nature and whether it violates CP symmetry. These results may, via leptogenesis, be related to the origin of the matter–antimatter asymmetry of the universe.

Recently, there has been renewed interest in models with scales accessible to current particle-physics experiments. These will exploit the powerful beams and capable detectors of the current and future experimental neutrino programme, and collider-based searches for heavy neutral leptons with MeV-to-TeV masses.

Overall, while the multi-TeV scale should continue to be a key focus for both particle and astroparticle physics experiments, I strongly welcome the theoretical and experimental efforts to broaden the reach in mass scales to efficiently hunt for any hint of what the new physics BSM may be.

Astroparticle physics also studies the particles that arrive on Earth from all around our universe. They come from extreme astrophysical environments, such as supernovae and active galactic nuclei, where they may be generated and accelerated to the highest energies. Thanks to their detection we can study the processes that fuel these astrophysical objects and gain an insight into their evolution (p24).

The discovery of gravitational waves (GWs) just a few years ago has shed new light on this field. Together with gamma rays, cosmic rays and the high-energy neutrinos detected at IceCube, the field of multi-messenger astronomy is in full bloom. In the coming years it will get a boost from the results of new, large experiments such as KM3Net, the Einstein Telescope, LISA and the Cherenkov Telescope Array – as well as many new theoretical developments, such as advanced particle-theory techniques for GW predictions.

In the field of GWs, last year's results from pulsar timing arrays indicate the presence of a stochastic background of GWs. What is its origin? Is it of astrophysical nature or does it come from some dramatic event in the early universe, such as a strong first-order phase transition? In this latter case, we would be getting a glimpse of the universe when it was just born, opening up a new perspective on fundamental particles and interactions. Could it be that we have seen a new GeV-scale dark sector at work? It is too early to tell. But this is very exciting.

OPINION INTERVIEW

How to democratise radiation therapy

Only 10% of patients in low- or middle-income countries have access to radiation therapy. Manjit Dosanjh and Steinar Stapnes tell the *Courier* about the need to disrupt the market for a technology that is indispensable when treating cancer.


IAI


S Stapnes

Science for society *A leader in medical applications of physics for cancer treatment, Manjit Dosanjh (left) is Smart Technology to Extend Lives with Linear Accelerators (STELLA) project leader for the International Cancer Expert Corps and visiting professor at the University of Oxford. Longstanding linear-collider study leader at CERN Steinar Stapnes (right) is responsible for design studies for the STELLA radiation-therapy system.*

How important is radiation therapy to clinical outcomes today?
Manjit Fifty to 60% of cancer patients can benefit from radiation therapy for cure or palliation. Pain relief is also critical in low- and middle-income countries (LMICs) because by the time tumours are discovered it is often too late to cure them. Radiation therapy typically accounts for 10% of the cost of cancer treatment, but more than half of the cure, so it's relatively inexpensive compared to chemotherapy, surgery or immunotherapy. Radiation therapy will be tremendously important for the foreseeable future.

What is the state of the art?
Manjit The most precise thing we have at the moment is hadron therapy with carbon ions, because the Bragg peak is very sharp. But there are only 14 facilities in the whole world. It's also hugely expensive, with each machine costing around $150 million (M). Proton therapy is also attractive, with each proton delivering about a third of the radiobiological effect of a carbon ion. The first proton patient was treated at Berkeley in September 1954, in the same month CERN was founded. Seventy years later, we have about 130 machines and we've treated 350,000 patients. But the reality is that we have to make the machines more affordable and more widely available. Particle therapy with protons and hadrons probably accounts for less than 1% of radiation-therapy treatments whereas roughly 90 to 95% of patients are treated using electron linacs. These machines are much less expensive, costing between $1M and $5M, depending on the model and how good you are at negotiating.

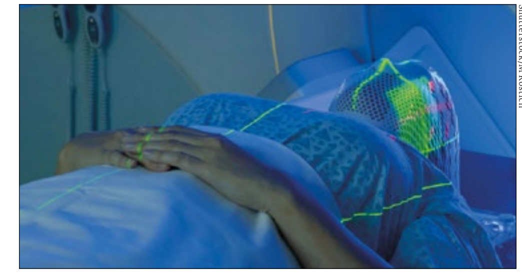
Most radiation therapy in the developing world is delivered by cobalt-60 machines. How do they work?
Manjit A cobalt-60 machine treats patients using a radioactive source. Cobalt has a half-life of just over five years, so patients have to be treated longer and longer to be given the same dose as the cobalt-60 gets older, which is a hardship for them, and slows the number of patients who can be treated. Linacs are superior because you can take advantage of advanced treatment options that target the tumour using focusing, multi-beams and imaging. You come in from different directions and energies, and you can paint the tumour with precision. To the best extent possible, you can avoid damaging healthy tissue. And the other thing about linacs is that once you turn it off there's no radiation anymore, whereas cobalt machines present a security risk. One reason we've got funding from the US Department of Energy (DOE) is because our work supports their goal of reducing global reliance on high-activity radioactive sources through the promotion of non-radioisotopic technologies. The problem was highlighted by the ART (access to radiotherapy technologies) study I led for International Cancer Expert Corps (ICEC) on the state of radiation therapy in former Soviet Union countries. There, the legacy has always been cobalt. Only three of the 11 countries we studied have had the resources and knowledge to be able to go totally to linacs. Most still have more than 50% cobalt radiation therapy.

The kick-off meeting for STELLA took place at CERN from 29 to 30 May. How will the project work?
Manjit STELLA stands for Smart Technology to Extend Lives with Linear Accelerators. We are an international collaboration working to increase access to radiation therapy in LMICs, and in rural regions in high-income countries. We're working to develop a linac that is less expensive, more robust and, in time, less costly to operate, service and maintain than currently available options.
Steinar $1.75M funding from the DOE has launched an 18 month "pre-design" study. ICEC and CERN will collaborate with the universities of Oxford, Cambridge and Lancaster, and a network of 28 LMICs who advise and guide us, providing vital input on their needs. We're not going to build a radiation-therapy machine, but we will specify it to such a level that we can have informed discussions with industry partners, foundations, NGOs and governments who are interested in investing in developing lower cost and more robust solutions. The next steps, including prototype construction, will require a lot more funding.

> **We're working to develop a linac that is less expensive, more robust and less costly to operate, service and maintain than currently available options**

What motivates the project?
Steinar The basic problem is that access to radiation therapy in LMICs is embarrassingly limited. Most technical developments are directed towards high-income countries, ultimately profiting the rich people in the world – in other words, ourselves. At present, only 10% of patients in LMICs have access to radiation therapy.
Manjit The basic design of the linac hasn't changed much in 70 years. Despite that, prices are going up, and the cost of service contracts and software upgrades is very high. Currently, we have around 420 machines in Africa, many of which are down for long intervals, which often impacts treatment outcomes. Often, a hospital can buy the linac but they can't afford the service contract or repairs, or they don't have staff with the skills to maintain them. I was born in a small village with no gas, electricity or water. I wasn't supposed to go to school because girls didn't. I was fortunate to have got an education that enabled me to have a better life with access to the healthcare treatments that I need. I look at this question from the perspective of how we can make radiation therapy available around the world in places such as where I'm originally from.

What's your vision for the STELLA machine?
Steinar We want to get rid of the cobalt machines because they are not as effective as linacs for cancer treatment and they are a security risk. Hadron-therapy machines are more costly, but they are more precise, so we need to make them more affordable in the future. As Manjit said, globally 90 or 95% of radiation treatments are given by an electron linac, most often running at 6 MeV. In a modern radiation therapy facility today, such linacs are not developing so fast. Our challenge is to make them more reliable and serviceable. We want to develop a workhorse radiation therapy system that can do high-quality treatment. The other, perhaps more important, key parts are imaging and software. CERN has valuable experience here because we build and integrate a lot of detector systems including readout and data-analysis. From a certain perspective, STELLA will be an advanced detector system with an integrated linac.


Shutterstock/M Kostich

Treatment for all *The STELLA collaboration is working hard to ensure that radiation therapy can be made available to everyone, regardless of their location in the world.*

Are any technical challenges common to both STELLA and to projects in fundamental physics?
Steinar The early and remote prediction of faults is one. This area is developing rapidly, and it would be very interesting for us to deploy this on a number of accelerators. On the detector and sensor side, we would like to make STELLA easily upgradeable, and some of these upgrades could be very much linked to what we want to do for our future detectors. This can increase the industrial base for developing these types of detectors as the medical market is very large. Software can also be interesting, for example for distributed monitoring and learning.

Where are the biggest challenges in bringing STELLA to market?
Steinar We must make medical linacs open in terms of hardware. Hospitals with local experts must be able to improve and repair the system. It must have a long lifetime. It needs to be upgradeable, particularly with regard to imaging, because detector R&D and imaging software are moving quickly. We want it to be open in terms of software, so that we can monitor the performance of the system, predict faults, and do treatment planning off site using artificial intelligence. Our biggest contribution will be to write a specification for a system where we "enforce" this type of open hardware and open software. Everything we do in our field relies on that open approach, which allows us to integrate the expertise of the community. That's something we're good at at CERN and in our community. A challenge for STELLA is to build in openness while ensuring that the machines can remain medically qualified and operational at all times.

How will STELLA disrupt the model of expensive service contracts and lower the cost of linacs?
Steinar This is quite a complex area, and we don't know the solution yet. We need to develop a radically different service model so that developing countries can afford to maintain their machines. Deployment might also need a different approach. One of the work packages of this project is to look at different models and bring in expertise on new ideas. The challenges are not unique to radiation therapy. In the next 18 months we'll get input from people who've done similar things.
Manjit Gavi, the global alliance for vaccines, was set up 24 years ago to save millions of children who died every year from vaccine-preventable diseases such as measles, TB, tetanus and rubella using vaccinations that were not available to millions of children in poorer parts of the world, especially Africa. Before, people were dying of these diseases, but now they get a vaccination and live. Vaccines and radiation therapy are totally different technologies, but we may need to think that way to really make a critical difference.
Steinar There are differences with respect to vaccine development. A vaccine is relatively cheap, whereas a linac costs millions of dollars. The diseases addressed by vaccines affect a lot of children, more so than cancer, so the patients have a different demographic. But nonetheless, the fact is that there was a group of countries and organisations who took this on as a challenge, and we can learn from their experiences.
Manjit We would like to work with the UN on their efforts to get rid of the disparities and focus on making radiation therapy available to the 70% of the world that doesn't have access. To accomplish that, we need global buy-in, especially from the countries who are really suffering, and we need governmental, private and philanthropic support to do so.

What's your message to policymakers reading this who say that they don't have the resources to increase global access to radiation therapy?
Steinar Our message is that this is a solvable problem. The world needs roughly 5000 machines at $5M or less

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each. On a global scale this is absolutely solvable. We have to find a way to spread out the technology and make it available for the whole world. The problem is very concrete. And the solution is clear from a technical standpoint.

Manjit The International Atomic Energy Agency (IAEA) have said that the world needs one of these machines for every 200 to 250 thousand people. Globally, we have a population of 8 billion. This is therefore a huge opportunity for businesses and a huge opportunity for governments to improve the productivity of their workforces. If patients are sick they are not productive. Particularly in developing countries, patients are often of a working economic age. If you don't have good machines and early treatment options for these people, not only are they not producing, but they're going to have to be taken care of. That's an economic burden on the health service and there is a knock-on effect on agriculture, food, the economy and the welfare of children. One example is cervical cancer. Nine out of 10 deaths from cervical cancer are in developing countries. For every 100 women affected, 20 to 30 children die because they don't have family support.

We need to develop a good business model and find government and private partners who are willing to invest

How can you make STELLA attractive to investors?

Steinar Our goal is to be able to discuss the project with potential investor partners – and not only in industry but also governments and NGOs, because the next natural step will be to actually build a prototype. Ultimately, this has to be done by industry partners. We likely cannot rely on them to completely fund this out of their own pockets, because it's a high-risk project from a business point of view. So we need to develop a good business model and find government and private partners who are willing to invest. The dream is to go into a five-year project after that.

Manjit It's important to remember that this opportunity is not only linked to low-income countries. One in two UK citizens will get cancer in their lifetime, but according to a study that came out in February, only 25 to 28% of UK citizens have adequate access to radiation therapy. This is also an opportunity for young people to join an industrial system that could actually solve this problem. Radiation therapy is one of the most multidisciplinary fields there is, all the way from accelerators to radio-oncology and everything in between. The young generation is altruistic. This will capture their spirit and imagination.

Can STELLA help close the radiation-therapy gap?

Manjit When the IAEA first visualised radiation-therapy inequalities in 2012, it raised awareness, but it didn't move the needle. That's because it's not enough to just train people. We also need more affordable and robust machines. If in 10 or 20 years people start getting treatment because they are sick, not because they're dying, that would be a major achievement. We need to give people hope that they can recover from cancer.

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

High time for holographic cosmology

On the Origin of Time: Stephen Hawking's Final Theory

By Thomas Hertog

Penguin

On the Origin of Time is an intellectually thrilling book and a worthy sequel to Stephen Hawking's bestsellers. Thomas Hertog, who was a student and collaborator of Hawking, suggests that it may be viewed as the next book the famous scientist would have written if he were still alive. While addressing fundamental questions about the origin of the cosmos, Hertog sprinkles the text with anecdotes from his interactions with Hawking, easing up on the otherwise intense barrage of ideas and concepts. But despite its relaxed and popular style, the book will be most useful for physicists with a basic education in relativity and quantum theory.

S Zaklin/Keystone

Unwritten sequel? On the Origin of Time *is the next book Stephen Hawking would have written, says author Thomas Hertog.*

Expanding universes

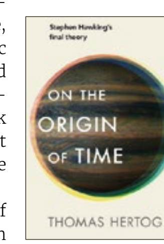
The book starts with an exhaustive journey through the history of cosmology. It reviews the ancient idea of an eternal mathematical universe, passes through the ages of Copernicus and Newton, and then enters the modern era of Einstein's universe. Hertog thoroughly explores static and expanding universes, Hoyle's steady-state cosmos, Hartle and Hawking's no-boundary universe, Guth's inflationary universe and Linde's multiverse with eternal inflation. Everything culminates in the proposal for holographic quantum cosmology that the author developed together with the late Hawking.

What makes the book especially interesting is its philosophical reflections on the historical evolution of various underlying scientific paradigms. For example, the old Greeks developed the Platonic view that the workings of the world should be governed by eternal mathematical laws. This laid the groundwork for the reductionistic worldview that many scientists – especially particle physicists – subscribe to today.

Hertog argues that this way of thinking is flawed, especially when confronted with a Big Bang followed by a burst of inflation. Given the supremely fine-tuned structure of our universe, as is necessitated by the existence of atoms, galaxies and ultimately us, how could the universe "know" back at the time of the Big Bang that this fine-tuned world would emerge after inflation and phase transitions?

The quest to scientifically understand this apparent intelligent design has led to physical scenarios such as eternal inflation, which produces an infinite collection of pocket universes with their own laws. These ideas blend the anthropic principle – that only a life-friendly universe can be observed – into the narrative of a multiverse.

However, for anthropic reasoning to make sense, one needs to specify what a typical observer would be, observes Hertog, because otherwise the statement is circular. Instead, he argues that one should interpret the history of the universe as an evolutionary process. Not only would physical objects continuously evolve, but also the laws that govern them, thereby building up an enormous chain of frozen accidents analogous to the evolutionary tree of biological species on Earth.



Penguin

This represents a major paradigm shift as it introduces a retrospective element: one can only understand evolution by looking at it backwards in time. Deterministic and causal explanations apply only at a crude, coarse-grained level, while the precise way that structures and laws play out is governed by accumulated accidents. Essentially the question "how did everything start?" is superseded by the question "how did our universe become as it is today?" This may be seen as adopting a top-down view (into the past) instead of a bottom-up view (from the past).

Hawking criticised traditional cosmology for hiding certain assumptions, in particular the separation of the fundamental laws from initial boundary conditions and from the role of the observer. Instead, one should view the universe, at its most fundamental level, as a quantum superposition of many possible spacetimes, of which the observer is an intrinsic part.

From this Everettian viewpoint, wavefunctions behave like separate branches of reality. A measurement is like a fork in the road, where history divides into different outcomes. This line of thought has significant consequences. The author presents an illuminating analogy with the so-called delayed double-slit experiment, which was first conceived by John Archibald Wheeler. Here the measurement that determines whether an electron behaves as particle or wave is delayed until after the electron has already passed the slit. This demonstrates that the process of observation inflicts a retroactive component which, in a sense, creates the past history of the electron.

The fifth dimension

Further ingredients are needed to transform this collection of ideas to a concrete proposal, argues Hertog. In short, these are quantum entanglement and holography. Holography has been recognised as a key property of quantum gravity, following Maldacena's work on quantum black holes. It posits that all the information about the interior of a black hole is encoded at its horizon, which acts like a holographic screen. Inside, a fictitious fifth dimension emerges that plays the role of an energy scale.

In Hawking and Hertog's holo- ▷

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graphic quantum universe, one considers a Euclidean universe where the role of the holographic screen is played by the surface of our observations. The main idea is that the emergent dimension is time itself! In essence, the observed universe, with all its complexity, is like a holographic screen whose quantum bits encode its past history. Moving from the screen to the interior is equivalent to going back in time, from a highly entangled complex universe to a gradually less structured universe with fading physical laws and less entangled qubits. Eventually no entangled qubits remain. This is the origin of time as well as of the physical laws. Such a holographic universe would be the polar opposite of a Platonic universe with eternal laws.

A holographic universe would be the polar opposite of a Platonic universe with eternal laws

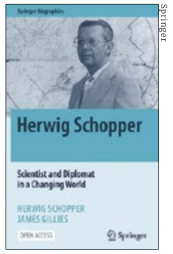
Could these ideas be tested? Hertog argues that an observable imprint in the spectrum of primordial gravitational waves could be discovered in the future. For now, *On the Origin of Time* is delightful food for thought.

Wolfgang Lerche *CERN.*

Herwig Schopper: Scientist and Diplomat in a Changing World

By Herwig Schopper and James Gillies

Springer Biographies



Springer

It is rare and inspiring to be able to read the memoirs of a person who has celebrated their 100th birthday and yet is still exceptionally inquisitive and reflective. Herwig Schopper, director-general of CERN from 1981 to 1988, is one such person. In *Scientist and Diplomat in a Changing World*, he takes stock of his personal life, the development of physics, the political challenges he has faced, and the human interactions that knit each of these subjects together.

Schopper told the story of his life to co-author James Gillies, a particle physicist and former head of communications at CERN. Their interviews shed a brilliant light on his life. Starting work as a physicist in the field of optics, he moved first to study beta decays and parity violation, and then to nuclear and particle physics, accelerator physics and detector development more generally. Initial chapters cover his early years in what is today the Czech Republic, the dark years of war, and his studies in Hamburg from 1945 to 1954.

But though he loved to work hands on, Schopper was soon asked to found and direct institutes. His impact on nuclear and particle physics in Germany becomes eminently clear when he describes his career at the universities of Erlangen, Mainz, Karlsruhe and Hamburg. The book therefore next turns to time spent as a university professor establishing and directing institutes from 1954 to 1973, including productive sabbaticals in Stockholm, Cambridge and Cornell, and his journey to DESY via CERN between 1973 and 1980. It then explores his time as director-general of CERN from 1981 to 1988, his transition from science to diplomacy, his travels east and his impact on LEP and the LHC. These chapters are captivating, as they describe not only the life story of a remarkably active and productive scientist, but also the historical, scientific and political context in which the work was done.

Many people are happy to take life a little easier when they retire. Not so Herwig Schopper. For him, science is centre stage, and given his vast knowledge in science and science policy, his advice and help are still in high demand. A chapter on science for peace illustrates the rocky path he and dedicated colleagues took to create a science project in the Middle East, SESAME, with the goal to bring scientists from hostile countries to work together on excellent scientific projects.

While the main part of this very readable text describes the life and work of Schopper in the words of his co-author Gillies, each chapter ends with a section in Schopper's own words in which he shares some very personal memories with the reader, speaking about his family and friends, and his deep love for music. The book also ends with an epilogue and some reflections by the man himself. Building on 100 years of experience, these words provide much food for thought.

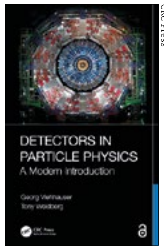
Many of Herwig Schopper's colleagues and friends have encouraged him to write about his life, as he has seen and done so many things. The result of those requests, this biography is a captivating documentation of an exemplary life in particle physics. But more than the story of a fulfilled life, this biography is a textbook about how scientific progress depends on individuals, scientific excellence, inspiration, perseverance and the *fortune* needed to bring it all off, as the French say.

Albrecht Wagner *DESY.*

Detectors in Particle Physics: A Modern Introduction

By Georg Viehhauser and Tony Weidberg

CRC Press



CRC Press

Progress in elementary particle physics is driven by the development of radiation-detection technologies. From early photographic emulsions to the gargantuan modern systems that are deployed at particle accelerators and astrophysics experiments, radiation detectors use extraordinary means to disclose the nature and fundamental interactions of elementary particles.

In *Detectors in Particle Physics*, Georg Viehhauser and Tony Weidberg offer an accessible and comprehensive introduction to this intricate world. Addressed to graduate students in particle and nuclear physics, and more advanced researchers, this book provides the knowledge needed to understand and appreciate these indispensable tools. Building on their personal contributions to the conception, construction and operation of major detector systems at the DELPHI and ATLAS detectors at CERN, the authors review basic physics principles to enable the reader to grasp the fundamental operating mechanisms of gaseous, liquid and semiconductor detectors, as well as systems for particle identification and calorimetry.

In addition to exploring core concepts in detector physics, another objective of the book is to introduce the reader to case studies of applications in particle physics and astrophysics. From the Large Hadron Collider to neutrino experiments, the University of Oxford-based authors connect theoretical physics to practical applications and present real-world examples of modern detectors, bridging the gap between theory and experimentation. The book describes key practical aspects of particle detectors, including electronics, alignment, calibration and simulation. These practical insights enhance the reader's understanding of how detectors operate in experiments, and each chapter includes practical exercises to help further the reader's understanding of the subject.

Detectors in Particle Physics offers a unique blend of theoretical foundations and practical considerations. Whether you're fascinated by the mysteries of the universe or planning a career in experimental physics, Viehhauser and Weidberg will undoubtedly prove to be a valuable resource.

Fabio Sauli *CERN.*

How skills pursue diversity and inclusion

Sudhir Malik reports on an initiative by the US CMS collaboration to increase opportunities for under-represented students in high-energy physics.

Students from under-represented populations, including those at institutions serving minorities, have traditionally faced barriers to participating in high-energy physics (HEP). These include a lack of research infrastructure and opportunities, insufficient mentoring, lack of support networks, and financial hardship, among many others.

To help overcome these barriers, in 2022 the US CMS collaboration designed a pilot programme called PURSUE – the Program for Undergraduate Research Summer Experience. Due to the COVID pandemic, the collaboration initially worked virtually with 16 students, before an in-person pilot was launched in 2023. The programme has changed the career paths of several students, and a third edition with 20 undergraduates is now underway.

The power of collaboration

Two thirds of the HEP workforce go on to develop careers outside the field. The skills developed in HEP can lead to careers in many sectors, from software and electronics to health and finance. With skills-based labour markets currently a hot topic in business, a more guided and organised approach towards skills has the potential to reinforce the workforce pipeline for both HEP and industry, and benefit the many young researchers who look for jobs outside of academia.

The LHC experiments are a perfect seedbed for this. Comprising some 1200 physicists, graduate students, engineers, technicians and computer scientists from 55 universities and institutes, the US CMS collaboration each year trains about 200 students, 100 postdocs and produces 45 PhDs. It is therefore in a strong position to provide pathways to involve many young researchers in every aspect of the experiment and to prepare hundreds of next-generation scientists for careers in physics and industry alike.

The PURSUE undergraduate internship offers opportunities in state-of-art detector design and upgrades, operations, novel techniques in data taking and analysis, scientific presentations and international partnerships. It doesn't matter if you are a US citizen or not. The basic requirement is that you are a student inside the US. This year's cohort comprises students from Africa, South and Central America, and Asia.

Fermilab

Equipped for the future *The 2024 PURSUE cohort at Fermilab.*

This one-of-its-kind programme relies on a large team of dedicated collaborators

At the start of each year, invitations are sent out to all US CMS institutes asking them to propose projects and mentors. This year almost 30 applications were received, which were then matched as closely as possible to the individual interests of the students. Being a diverse and sprawling collaboration – rather than a single institution – is an attractive part of the programme.

At the beginning of the internship, all students meet at the LHC Physics Center at Fermilab for two weeks of software training, during which they gain skills in Unix, Python, machine learning and other areas that will equip them in any research area and throughout industry. This part of PURSUE was developed within the framework of the IRIS-HEP project, which is funded by the US National Science Foundation to address the computing challenges of the High-Luminosity LHC, and the CERN-based HEP Software Foundation. These skills are also key requirements for industry, with 42% of companies identifying AI and big data as a strategic priority for the next five years, according to the World Economic Forum's *Future of Jobs Report 2023*.

During the remaining eight weeks of their internship, students travel to the US institution where their mentor is located. The students stay connected throughout this period via meetings and Zoom talks on physics and careers topics, and at the end of the programme they come together to produce a final presentation and poster. Some continue their research during the following semester, enabling a deeper dive into the field.

Success story

This one-of-its-kind programme relies on a large team of dedicated collaborators who take precious time out of their routines to battle the lack of diversity in HEP. And PURSUE's interns are already succeeding. For example, from the 2022 cohort, Sneha Dixit has been admitted to graduate school at the University of Nebraska–Lincoln to pursue doctoral research on the CMS experiment, and Gabriel Soto has taken up a PhD in accelerator physics at the University of California Davis.

PURSUE also provides a way to engage new institutes with HEP. The initial funding for the programme was provided by a US Department of Energy grant awarded to Tougaloo College in Mississippi along with Brown University, the University of Puerto Rico and the University of Wisconsin. Tougaloo College had no previous connection to particle physics, but it is now hoped that it will become a member of the US CMS collaboration.

The driving force behind PURSUE was Meenakshi Narain of Brown University, an inspirational leader and champion of diversity in CMS and beyond, who passed away in January last year. We hope that the programme inspires similar initiatives in other experiments, fields and regions.

Sudhir Malik *University of Puerto Rico–Mayaguez.*

Further reading

S Banerjee *et al.* 2024 arXiv:2401.16217.

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Appointments and awards

S Mertens/TU Munich

New director at MPIK

Experimental particle physicist Susanne Mertens has been appointed director of the Max Planck Institute for Nuclear Physics (MPIK), and will succeed Manfred Lindner on a full-time basis in March 2025. After obtaining her PhD from Karlsruhe Institute of Technology on electrostatic background processes for KATRIN, she was a postdoc at LBNL, started an independent research group at MPIK and has been associate professor at the Technical University of Munich since 2022. She is co-spokesperson of the KATRIN experiment, which aims to measure the mass of the neutrino, member of the IAXO solar axion experiment, and principal investigator of both the TRISTAN project, a future upgrade to KATRIN to search for sterile neutrinos, and ComPol, a proposed CubeSat mission to measure the polarisation of the X-ray binary Cygnus X-1.

Heading MIT fusion

Theoretical physicist and fusion scientist Nuno Loureiro has been appointed director of MIT's plasma science and fusion centre (PSFC). Founded in 1976, the multidisciplinary laboratory researches topics such as fusion energy, plasma physics and its applications, superconducting magnet technology and magnetic resonance spectroscopy. Loureiro is cited for advancing the understanding of multiple aspects of plasma behaviour, particularly turbulence and the physics underpinning solar flares and other astronomical phenomena, as well as working on devices that can more efficiently control and harness energy for clean, sustainable energy. Alongside his mandate, PSFC is launching a technological development project, LIBRA, which uses a blanket of lithium or beryllium salts to absorb neutrons on the inside of fusion vessels. The neutrons then interact with Li-6 to form tritium, which acts as the fuel needed to power deuterium–tritium fusion.

SRF advancements honoured

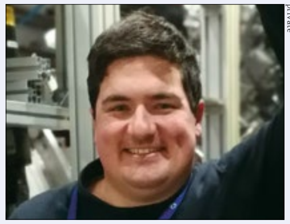
In March, at the spring conference of the German Physical Society (DPG) in Berlin, Sebastian Keckert

HZB/ S Zerbe

(Helmholtz-Zentrum Berlin) was presented with the 2023 DPG young scientist award for accelerator physics. He is honoured for achievements during his doctorate and first research phase, when he worked on new advancements to quadrupole resonators for testing superconducting materials in superconducting radiofrequency applications. This improved the measurement capabilities, enabling precise characterisation of multilayer superconductors. Now used in labs around the world, Keckert's work is relevant to efforts to make accelerators more sustainable. In 2022 he became a researcher at the centre's science and technology of accelerating systems institute. The €5000 award aims to support early-career research in accelerator physics.

Caravita wins EPS award

Cited for his excellent experimental work on the interactions between gravity and antimatter, Ruggero Caravita



private

(INFN-TIFPA) is the winner of the 2024 European Physical Society (EPS) early-career award. Caravita is a member of the AEgIS collaboration at CERN, which studies the gravitational behaviour of antihydrogen atoms, where his research focuses on experimental aspects of producing cold antiatoms in the laboratory. During his 12 years with the collaboration, he has served as physics coordinator and was recently elected spokesperson.

2024 Guido Altarelli awards

During the 31st international workshop on deep inelastic scattering (held on 8–12 April in Grenoble), young scientists working on quantum chromo-dynamics (QCD) were recognised with this year's Guido Altarelli awards. The experimental prize goes to Holly Szumila-Vance (JLab, left) for her investigations

JLab/A Devlin

PSI

of colour transparency and other nuclear manifestations of QCD. Having graduated with a double major in aerospace and space engineering, Szumila-Vance worked briefly as a medevac pilot before deciding to pursue a nuclear-physics degree in 2012. The theory award goes to Javier Mazzitelli (PSI, right) for contributions to precision calculations in Higgs-boson and top-quark production at the LHC. Mazzitelli obtained his PhD from the University of Buenos Aires and has held positions at the University of Zurich and MPI.

Röntgen Medal to Feidenhans'l

The 2024 Röntgen Medal is awarded to Danish physicist Robert Feidenhans'l, a senior scientist at the European XFEL located close to its main shareholder DESY. His long career spans nanophysics, the development of X-ray techniques for materials analysis, X-ray imaging and tomography of biological tissues, materials (such as metals and semiconductors) and medical applications. Feidenhans'l is a co-founder of surface crystallography and was the first person to succeed in precisely determining surface structures experimentally. He began work at Risø National Laboratory in 1986 as a scientist and was head of the materials department in 2001–2005. This was followed by an appointment as professor at the Niels Bohr Institute in 2007, where he was first deputy-director in 2007 and director in 2012. Feidenhans'l has held other leading positions, such as chairman of the management board of the European XFEL between 2017–2023. The medal has been awarded every year since 1951 to researchers who make seminal contributions using X-rays in astronomy, radiology, medicine and biochemistry; amongst the early winners were Rolf Widerøe and William Lawrence Bragg.

Gruber cosmology prize

This year's Gruber cosmology prize is awarded to Marcia Rieke (University of Arizona) for making a "lasting impact on our understanding of the universe". Rieke has made major contributions to the sensitivity of infrared instruments including those on the James Webb Space

IAU

Telescope, Hubble Space Telescope and Spitzer Space Telescope. Rieke obtained her PhD from MIT in 1976 and then joined the Steward Observatory at the University of Arizona. She was appointed principal investigator for Webb's near-infrared camera in 2002. Rieke will receive the $500,000 award at the 32nd general assembly of the International Astronomical Union in Cape Town in August.

RECRUITMENT

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PEOPLE OBITUARIES

Yves Baconnier 1934–2024

A fruitful trip through CERN's accelerators

Yves Baconnier, who made important technical and managerial contributions to a surprising number of CERN accelerators, passed away on 21 January 2024.

Born in 1934 in the Ardèche in the South of France, Yves completed his studies at the Institut Polytechnique de Grenoble. He joined CERN in 1963 as engineer-in-charge of the Proton Synchrotron (PS) and quickly took a strong interest in analysing and improving the slow-ejection procedure. He became leader of the machine study team before moving to the Super Proton Synchrotron (SPS) project in the early 1970s, where his experience with beam extraction was very welcome.

Once the SPS extraction was operational at the end of the 1970s, Yves moved on to the Large Electron Positron (LEP) collider and, in particular, its injection system, which at the beginning was imagined as a new system without a link to the existing accelerators. His decisive idea to use the deadtime between the proton cycles of the SPS – dictated by limited cooling power – to insert the low-dissipation e^+e^- acceleration cycles from 3.5 to 20 GeV was the key element for accepting the existing accelerator chain PS and SPS with all its infrastructure as the LEP injector. This cut short all discussions on other possible LEP sites in Europe.

After this memorable success with LEP, Yves moved back to his first love, the PS, and took responsibility for the PS ring proper to define and oversee an upgrade programme enabling the elderly machine to accelerate electrons and positrons from 0.6 to 3.5 GeV. The complete vacuum system had to be modified to withstand the beams, and the campaign reached its climax during a very long shutdown in 1987, during which a stainless-steel vacuum chamber was installed around the ring. Since the PS magnets had combined-focussing, i.e. a quadrupole magnetic field on top of the dipole field, the synchrotron radiation would not allow for stable operation. To counter this, two Robinson-type wiggler magnets had to be inserted. Yves and his team designed this unique magnet, tested the prototype in the PS and at the DCI ring at LAL in Orsay and, finally, introduced it successfully in the PS.


Yves Baconnier (left) in discussion with Ewan Paterson of SLAC.

In the early 1990s, Yves went on to join the teams designing a beauty factory to be housed in the tunnel of the former Intersecting Storage Rings, and took the lead in the design of a tau–charm factory to be built on a green-field site in Spain. However, since these projects did not then materialise, he continued his work at the CLIC test facility to which the linear accelerator of LEP had to be converted. In 1984, in parallel with his other widespread activities, Yves took an active interest in the LHC design study, leading to the project's official approval in 1994. He moved into project management in the mid-1990s and was entrusted with chairing the influential LHC parameter committee until his retirement in 1999.

Yves will be remembered for his thorough and well-thought approach to his work, always seeking to understand *ab initio*, and for his meticulous insistence on checking hardware through prototyping and extended testing. Unassuming but sharp and exacting, he was a well-respected colleague, an appreciated lecturer and a leader with wide-ranging interests.

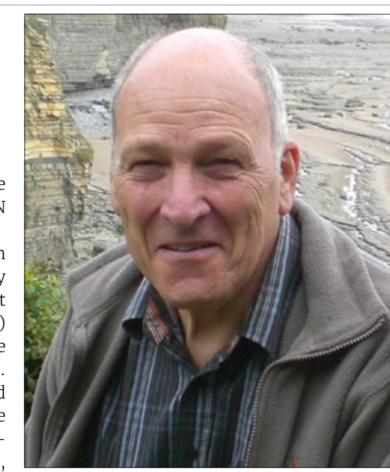
His friends and colleagues.

Philip John Bryant 1942–2024

From the ISR to medical physics

Accelerator physicist Phil Bryant, who made significant contributions to machines at CERN and beyond, passed away on 15 April 2024.

Just married, and fresh from his PhD from University College London, Phil was recruited by CERN in November 1968 to work in the magnet group of the Intersecting Storage Rings (ISR) division, where his first task was to oversee the manufacture of the skew quadrupoles. The group, later renamed the beam optics and magnets group, was strongly involved in the commissioning and development of the collider. Phil set up and tested a low-beta scheme, built from recuperated iron-core magnets, to validate this technology for the ISR, paving the way for the first superconducting low-beta insertion in a working accelerator. Later, he led the design and construction of the beamline from the PS that enabled $p\bar{p}$ collisions at the ISR, a development with which he became deeply involved. His name is also associated with coupling compensation, and generally with the smooth operation of the collider until it closed in 1983.


Family photo
Phil Bryant was director of the CERN Accelerator School from 1985 to 1991.

In addition to his managerial competence, Phil brought a contagious enthusiasm to the table

A skilled communicator, Phil moved on to assist Kjell Johnsen with setting up the CERN Accelerator School (CAS). He served as direc- ▷

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tor of the school from 1985 to 1991, delivering many lectures himself, and laying the foundations for it to become the valued institution that it is today. He then participated in a study of a B-meson factory for CERN before turning his attention to medical accelerators. Under his leadership this culminated in the Proton-Ion Medical Machine Study (PIMMS) of a synchrotron and its beamlines, which became the basis of the now operating medical centres for cancer treatment in Italy (CNAO) and Austria (MedAustron).

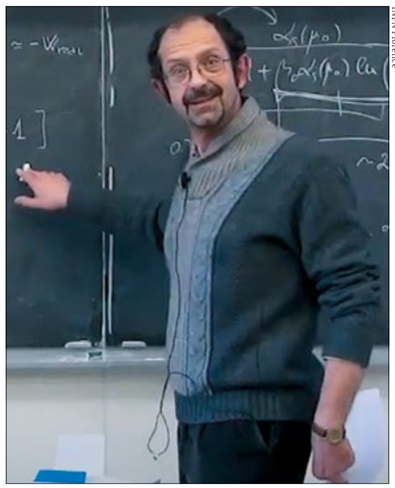
In the early 2000s, Phil joined the LHC effort, serving as chair of the specification committee and taking responsibility for the contract office. Having to navigate deadlines, he shuttled between physicists, engineers, procurement officers and CERN's legal team. In addition to his managerial competence, Phil brought a contagious enthusiasm to the table, and would apply diplomatic skill in the conclusion of protocols with funding agencies and institutes. On his official retirement from CERN in 2007, Phil moved to Austria to be available for the medical facility under construction there. As this activity wound down, he increased his collaboration with the Vienna-based company Cividec, developing diamond radiation detectors, as well as continuing to improve the WinAgile program that he had developed for accelerator design, and lecturing – notably for CAS and the Joint Universities Accelerator School.

Phil enjoyed scientific work, developing new ideas and writing. The author of numerous papers, his 2012 report on the advancement of colliders due to work done at the ISR is exemplary. A prodigious worker, he was nevertheless modest and always anxious to acknowledge the contribution of collaborators. Besides being a talented physicist and engineer, Phil was also good at drawing, his cartoons being especially appreciated. An inveterate "bricoleur", when not busy advancing accelerator technology he was active with his hands at home. Phil will be sorely missed.

His friends and colleagues.

STEFANO CATANI 1958–2024

Remembering a QCD pioneer


INFN Florence

Stefano Catani helped turn QCD into a precision tool.

Stefano Catani, a theoretical particle physicist in the Florence section of Istituto Nazionale di Fisica Nucleare (INFN), passed away on 16 January 2024. Stefano was one of the world's leading experts in quantum chromodynamics (QCD) and its phenomenological application to high-energy collider physics, leaving an irreplaceable void among his colleagues, friends and family.

Stefano studied physics at the University of Florence and obtained his PhD in 1987 under the supervision of Marcello Ciafaloni, who passed away in September 2023. He was a postdoctoral fellow at the University of Cambridge from 1989 to 1991, and a member of CERN's theory division from 1991 to 1993. After 1993 he developed his scientific career at INFN Florence, with a period as a CERN staff member between 1997 and 2002.

Discussing physics with Stefano was a fantastic experience. His depth and vision were simply unique. He was one of the great pioneers in the development of QCD as a precision science, thanks to his extraordinary ability to embrace the entire field without interruption, from the physics of "soft" gluons and their resummation to the perturbative regime. His research achievements are internationally recognised as being fundamental to the success of the high-energy collider physics programme, in particular for precision studies of the Higgs boson and the top quark.

> **His work is recognised as fundamental to the success of the high-energy collider physics programme**

Among his most important contributions are the formulation of jet clustering algorithms at lepton and hadron colliders (a key component of most experimental analyses), a general expression for the determination of the infrared singularities of scattering amplitudes (the so-called Catani formula), the design of general algorithms for the perturbative calculation of cross sections and differential observables, which have become a standard in the community (the well-known Catani–Seymour dipole subtraction and the q_T subtraction schemes), and the innovative Catani–Krauss–Kuhn–Webber algorithm for Monte Carlo simulations of many-jet processes.

Stefano's work was especially motivated by the application of QCD to collider data. He was convinced that our understanding of QCD singularities could be formulated in a way that any user could make a next-to-leading-order calculation of any suitable observable, not just dedicated calculations by experts. He also studied factorisation properties and coherence effects in the high-energy limit (the Catani–Ciafaloni–Fiorani–Marchesini equation) and proposed a generalisation of collinear factorisation that accounts for potential factorisation breaking effects at very high perturbative orders. The countless messages received from collaborators and colleagues all over the world, affected by the premature loss of a dear friend and extraordinary colleague, highlight Stefano's great qualities of generosity, human warmth and scientific rigour that will be sorely missed by all.

His friends and colleagues.

JACQUES HAISSINSKI 1935–2024

Expertise and leadership in colliding rings

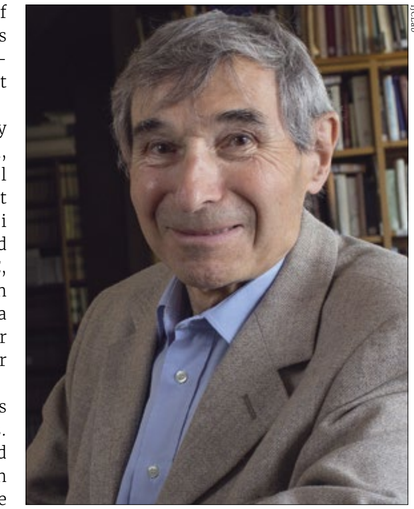
Jacques Haissinski, who played an important role in major particle-physics experiments, passed away on 25 March 2024 at the age of 89. His father Moïse worked with Marie Curie and had been a long-time collaborator of her daughter Irène Joliot-Curie.

Jacques entered Ecole Normale Supérieure in 1954 and later went to Stanford, where he worked under Burton Richter on the pioneering Colliding Beam machine to collide electrons in flight using two storage rings. After his military service, Jacques joined the Laboratoire de l'Accélérateur Linéaire in Orsay, to undertake a doctorate on the AdA (Anello di Accumulazione) ring. Built in Frascati from an idea of Bruno Touschek to collide in-flight electrons and positrons stored in the same vacuum chamber, AdA had been brought to Orsay by Pierre ▷

Marin to take advantage of the high intensity of the linac beams. Jacques mastered all aspects of the ground-breaking experiment and succeeded in detecting the very first time-in-flight collisions in 1963.

In accelerator physics, following a discovery on the ACO ring at Orsay, Jacques published, in 1967, a basic paper on the longitudinal equilibrium of particles in a storage ring that contained the now widely used "Haïssinski equation". He also collaborated with Stanford on the commissioning of SPEAR and later SLC, the very first and so-far only linear collider. In phenomenology, following Touschek, he led a programme on radiative corrections and later gave lectures on this subject in preparation for LEP at Ecole de Gif in 1989.

But the main scientific activity of Jacques Haïssinski was experimental particle physics. He took part in many experiments, directed theses in Orsay on ACO, and was spokesperson of the CELLO experiment at DESY. During the construction of LEP, Jacques served as chairperson of the LEP committee at CERN.


IJCLab

Jacques Haissinski was an outstanding physicist and mentor.

After LEP, Jacques turned his interests to astroparticle physics and cosmology, notably giving courses on the subject and collaborating on the EROS experiment and the Planck mission. During that time, he also took responsibilities in the management of Paris-Sud University (at Orsay), and later as a leader in IN2P3 and in the Saclay Laboratory DAPNIA (now IRFU). His leadership was greatly appreciated by the French high-energy physics community.

An outstanding teacher, Jacques also campaigned for the dissemination of knowledge to the public. He was a great humanist who was deeply concerned with social injustice and criminal wars. He presented his views publicly and believed that other physicists should do so. Generous with his precious time, he was always available to pass on his knowledge and vast scientific culture. He marked and inspired several generations of particle and accelerator physicists.

His friends and colleagues.

MATS LINDROOS 1961–2024

A driving force for accelerators

Mats Lindroos, who made major contributions to accelerator technology, passed away on 2 May 2024 aged just 62.

Mats received his PhD in subatomic physics from Chalmers University of Technology in Gothenburg, Sweden in 1993 under the supervision of Björn Jonson. As a PhD student he studied decay properties and hyperfine interactions from oriented nuclei, making use of the low-temperature nuclear orientation facilities at ISOLDE, Daresbury and Studsvik. He joined CERN as a research fellow in 1993 and became a staff member in 1995.

While at CERN, Mats filled a number of diverse roles including being responsible for PS Booster operation and the technical coordination of the ISOLDE facility. He was one of the driving forces behind the HIE-ISOLDE project that commenced construction in 2009 and is now one of the major accelerated radioactive beam facilities worldwide. While at CERN he also played leading roles in several European Union-supported design studies for future conceptual accelerator facilities: the nuclear-physics radioactive beam facility EURISOL and the beta-beam neutrino factory.

In 2009, when Sweden and Denmark were selected to be the host countries for the European Spallation Source (ESS), Mats returned to his roots in Sweden on secondment from CERN, formally joining the ESS in 2015. As one of the earliest members of the ESS organisation, he was responsible for establishing the nascent accelerator organisation as well as the accelerator collaboration, set up as a CERN-like collaboration, between major European accelerator laboratories across 10 countries to undertake the technical design of this important part of the facility. Mats led the technical design for the 5 MW proton linac of the ESS, and from 2013 as head of the 100-strong accelerator division he led the linac project that is now in the late stages of construction and installation. Even after stepping down from his leadership roles because of illness, he enthusiastically accepted a new one to advise the ESS management. He was fully involved in the process, and undoubtedly would have been instrumental in guiding the future evolution of the facility.


ESS

Mats Lindroos leaves a lasting legacy at the European Spallation Source.

> **He set up a CERN-like collaboration between major European accelerator laboratories across 10 countries**

As a globally recognised expert on accelerator technology, Mats served on many committees in an advisory role, such as the IJC Lab strategic advisory board (France), IN2P3 scientific committee (France), J-PARC technical advisory committee (Japan), PIP-II Fermilab technical advisory committee (US) and CERN's scientific policy committee. As an adjunct professor at Lund University he enjoyed teaching and supervising students in addition to his numerous research, management and committee roles. Despite all these work activities, Mats found time to oversee, together with his partner Anette, the construction of a house on the south Swedish coast, where they enjoyed walking, gardening and being active in the local community.

Mats has touched all our lives with his energy and passion for research, his creativity for new ideas, his worldly knowledge, his sense of humour, and most importantly, his humanity and kindness. He will be greatly missed by all of us who had the privilege to count him as a friend and colleague.

His friends and colleagues.

BACKGROUND

Notes and observations from the high-energy physics community

Gotta catch ‘em all

DUNE PhD student Camille Sironneau has produced a set of Pokémon cards as an outreach tool for the Yggdrasil festival in February. “When you think about it, particles are a bit like Pokémon that we want to catch,” she says. “They have different types, different abilities and some are rarer than others.” Sironneau created the designs using AI. *Boson de Higgs*, *Boson Z*, *Muon* and *Muonique Neutrino* are pictured clockwise from top left. The Pokémons’ powers are inspired by physics, for example *Matière Noire* (dark matter) has the ability *lentille gravitationelle* (gravitational lensing), which allows the player to deviate an attack. “As particle physicists it’s really hard to illustrate what we talk about when doing outreach,” she notes. The cards were inspired by KM3NeT student Théophile Cartraud. “We’re both nerds I guess,” she observes.

Tunnel congress identifies icons

The LEP and later LHC tunnel has been recognised as one of the 50 most iconic in the world at the 50th anniversary bash of the International Tunnelling and Underground Space Association. Fellow nominees include the Gotthard Base Tunnel and the Channel Tunnel. The roster was revealed at the annual World Tunnel Congress in Shenzhen in April, where plans for the proposed Future Circular Collider attracted great interest from the global tunnelling community. In February 1985, three tunnel-boring machines began crunching through the deep molasse of the Geneva basin. Three years and numerous geological hiccoughs later, the two ends of the 27 km ring came together with just 1 cm of error.

Media corner

“Their approach to the challenges is not much different from CERN’s, so I am confident that Chinese scientists can do it.”
CERN Council president **Eliezer Rabinovici** talking to *South China Morning Post* (6 May) about the proposed Circular Electron Positron Collider.

“The questions and concerns he raised about the FCC are not new to us and they are all being addressed in the FCC feasibility study.”
CERN director for research and computing **Joachim Mnich** responding to concerns about the FCC raised by **Eckart Lilienthal** of Germany’s Federal Ministry of Education and Research (*Nature*, 6 June).

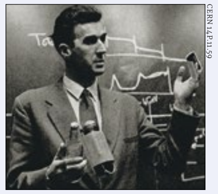
“Full membership of CERN is important for Estonia since it will mean that there will no longer be any financial ceiling when it comes to us taking part in tenders and entering into employment contracts.”
Tiit Riisalo, Estonia’s minister of economic affairs and information technology, on the country’s bid to become a CERN member state (*AP*, 1 June).

“The existence of light axion-like particles is strongly motivated by many kinds of string compactifications… and it’s something that we should take seriously.”
Theorist **Jessie Shelton** (University of Illinois) talking to *Quanta Magazine* (7 May) about the hunt for ultra-light dark matter.

From the archive: July/August 1984

What goes around comes around

In April 1984 CERN’s Main Auditorium was packed as tributes were paid to Sir John Adams, former CERN DG, who died in March. Adams, one of the main architects of CERN’s big machines, was appointed Proton Synchrotron PS Director in 1954, and in 1968 CERN Council invited him to lead the building of a ‘300 GeV machine’, the Super Proton Synchrotron. The SPS reached its nominal energy at noon on 17 June 1976 and accelerated protons to 400 GeV at half past three. Adams has left his indelible imprint on European science and has made a major contribution towards setting up the high energy physics infrastructure for the remainder of this century.



CERN PS Director John Adams holds an empty vodka bottle and a photograph of one of the first 24 GeV pulses produced by the newly completed machine. The vodka was supplied by JINR Dubna, for consumption if CERN surpassed the synchrophasotron’s world energy record of 10 GeV. The empty bottle served to send the photograph to the USSR as proof of CERN’s achievement.

The UA1 ‘Monojets’ were first past the post in this year’s traditional 3.9 km relay race around the CERN site. Last year, with all the panic about the W and Z particles, the experiment’s first team could only manage second place. This year UA1 fielded no less than seven teams, meriting some additional award for mass participation, with the aptly named ‘Missing Energy’ sextet finishing near the other end of the spectrum of results.

In 1984, over 60 runners lined up at the start of the traditional annual relay race round the CERN site.

● Text adapted from *CERN Courier* July/August 1984 pp232–236, 244.

Compiler’s note

CERN’s SPS will supply high-intensity proton beams to the SHiP experiment, an international collaboration between 54 institutes in 18 countries to search for hidden particles, to look for very weakly interacting particles that could include dark-matter candidates. Construction is expected to start in 2027 with data taking in 2030. Back on track and taking place each May, CERN’s relay race now includes Nordic walking, and an online app allows CERN Alumni teams in various locations around the globe to take part. The event was cancelled in 2021 and 2022 due to COVID.

150 MeV

Energy reached by protons in a proof-of-principle plasma-acceleration experiment at HZDR, paving the way towards laser-driven ion sources (T Ziegler *et al.* 2024 *Nat. Phys.* doi: 10.1038/s41567-024-02505-0).

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