WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the March/April 2026 issue of *CERN Courier*.

A hadron collider's energy reach is defined by the circumference of its tunnel and the strength of its dipole magnets. Next-generation hadron colliders look set to have tunnels more than three times longer than the LHC. Further expansion of the energy frontier depends on the ability of accelerator physicists to increase the strength of the magnets (p30).

This is one of the hardest problems in applied superconductivity – and exactly the sort of challenge that can inspire spinoff applications, from energy-efficient power transmission in cities to sustainable air travel. This edition's cover illustrates a high-temperature superconducting cable developed by Amalia Ballarino's team at CERN in collaboration with Airbus.

Elsewhere in these pages: meet Fermilab's new director, Norbert Holtkamp (p41); boost into the rest frame of charged particles in a bent crystal (p35); the most important tool you've never heard of (p23); a milestone for the HiLumi LHC (p7); an Eiffel honour for women physicists (p8); all you need to know about little red dots (p10); Michael S Turner on the coming revolutions in high-energy physics and cosmology (p39); and much more.

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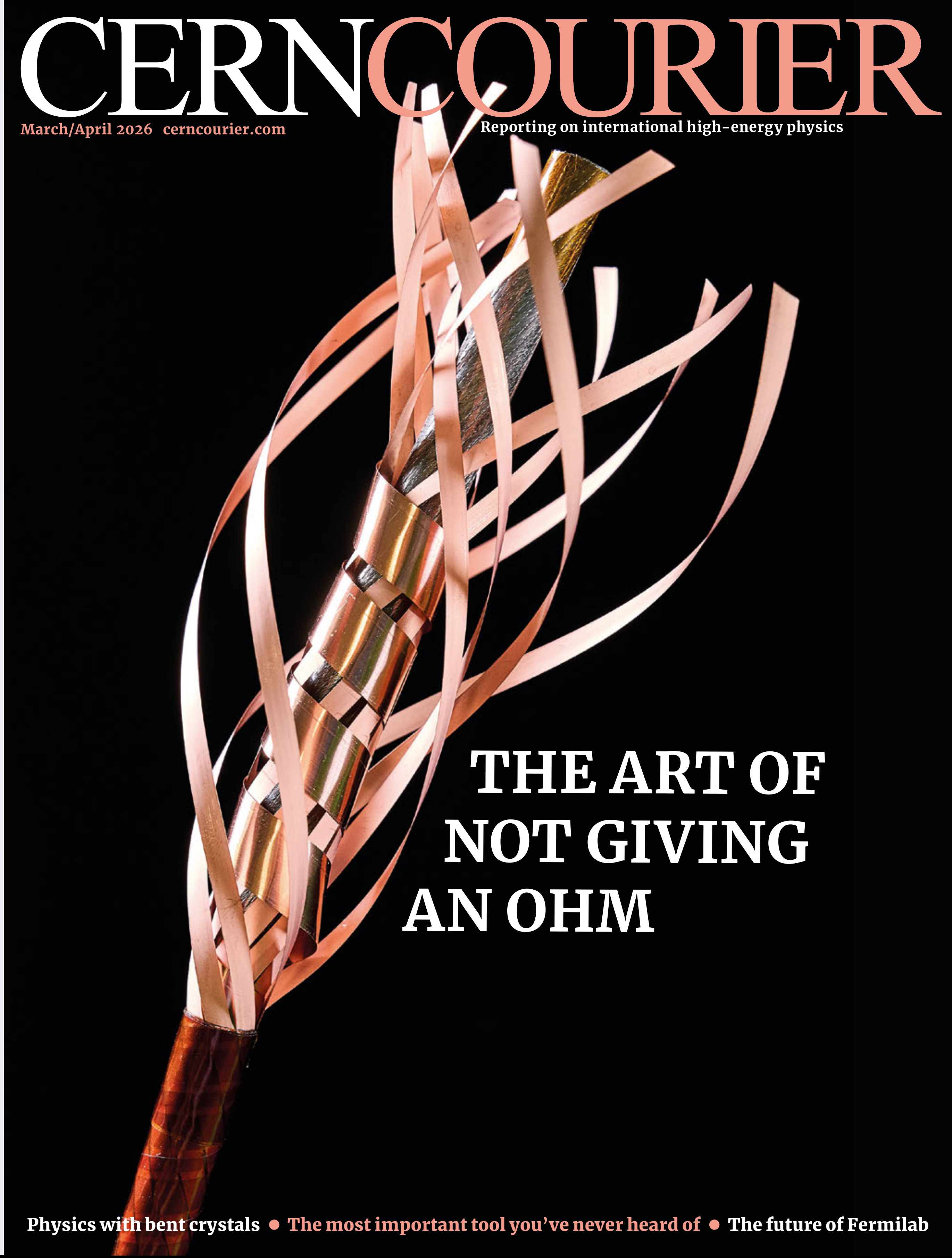
EDITOR: MARK RAYNER



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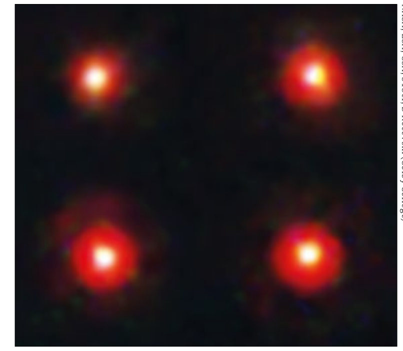

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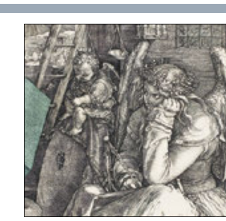

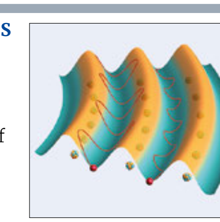

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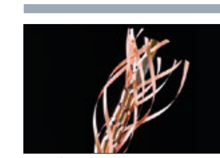

On the cover *REBCO power-transmission cable developed by Amalia Ballarino's team at CERN in partnership with Airbus.* **30**

FROM THE EDITOR

Plastic and vast, one intellectual breeze

Mark Rayner
Editor

The term "magnetic field" was coined by Michael Faraday at his laboratory bench in November 1845. His creativity was awakened, suggests James Hamilton, his biographer, by an intense correspondence with the English mathematician Ada, Lady Lovelace. Lovelace was Lord Byron's daughter, but it was fellow poet Samuel Taylor Coleridge who attended scientific lectures for inspiration, almost anticipating the concept of a field in 1795: "And what if all of animated nature / Be but organic Harps diversely framed, / That tremble into thought, as o'er them sweeps / Plastic and vast, one intellectual breeze."

Today, the ability to generate strong magnetic fields fundamentally limits fundamental exploration. A hadron collider's energy reach is defined by the circumference of its tunnel and the strength of its dipole magnets. Next-generation hadron colliders look set to have tunnels over three times longer than the LHC. Further expansion of the energy frontier depends on the ability of accelerator physicists to increase the strength of the magnets (p30).

This is one of the hardest problems in applied superconductivity – and that's exactly the sort of challenge that may inspire spinoff applications, from energy-efficient power transmission in cities to sustainable air travel. This edition's cover illustrates a high-temperature superconducting cable developed by Amalia Ballarino's team at CERN in collaboration with Airbus.

Oddly, however, high-field magnets don't produce the strongest magnetic fields discussed in this edition of *CERN Courier*. Not by one or two orders of magnitude.

The expansion of the energy frontier depends on the ability of accelerator physicists to increase the strength of the magnets

Accelerator physicists most often use dipole magnets to bend beams, but bent crystals can do better in edge cases. Positively charged particles careen between mechanically deformed crystal planes. No magnetic field is involved in the lab frame, but a Lorentz boost into the rest frame of the particles reveals magnetic fields of hundreds to thousands of tesla, and intriguing experimental possibilities (p35).

Superconducting dipole magnets were first used on a large scale at Fermilab, putting the Tevatron at the energy frontier for a quarter of a century. In this edition's interview, new director Norbert Holtkamp tells the *Courier* about his plans for Fermilab's future (p41). Meanwhile, at CERN, the Tevatron's successor at the energy frontier has passed a significant milestone on the road to its reinvention at high luminosity (p7).

Intellectual spark *Michael Faraday and Ada Lovelace.*

Gravelectricity

Faraday may be said to have attempted the first theory of everything three and a half years later, in March 1849. "Gravity," he wrote. "Surely this force must be capable of an experimental relation to electricity, magnetism and the other forces, so as to bind it up with them in reciprocal action and equivalent effect." He dropped non-magnetic cores through coils from the ceiling of the Royal Institution lecture room and watched for twitches on the galvanometer, never giving up the search for "gravelectricity" – a search that is still ongoing today (p18).

Lovelace would die tragically young just three years later, but she had already articulated some of the first thoughts on symbolic computing. Babbage's Analytical Engine "might act upon other things besides number, were objects found whose mutual fundamental relations could be expressed by those of the abstract science of operations..." Today, symbolic computing is of crucial strategic importance to predictions at future colliders, but the researchers who make the calculations possible are, like Lovelace, all too often underappreciated (p23).

Reporting on international high-energy physics

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NEWS ANALYSIS

ACCELERATORS

HiLumi magnets face full-scale test

CERN has reached a crucial milestone in the advancement of the High-Luminosity Large Hadron Collider (HiLumi LHC) project with the start of the cryogenic cooldown to 1.9 K of its 95-metre-long test stand – a full-scale replica of the innovative equipment that will transform the LHC in the coming years. The test stand is designed to validate the novel magnet system (the inner triplet beam-focusing magnets) and its complex infrastructure, which is a key element in a major upgrade of the LHC that is set to enter operation in 2030.

This summer will mark the start of a four-year-long intensive work period to transform the LHC into the HiLumi LHC – a groundbreaking accelerator that will usher in a new era for high-energy physics. The HiLumi LHC will increase the number of particle collisions by a factor of 10, increasing the volume of physics data available for researchers. This leap forward will allow physicists to explore the behaviour of the Higgs boson and other elementary particles with unprecedented precision and to uncover rare new phenomena that might reveal themselves.

CERN

Cool magnets *CERN has begun the cooldown of a 95 m-long test stand that reproduces the underground configuration of technologies for the Large Hadron Collider's high-luminosity upgrade.*

Exploring the unknown

"I don't think it is possible to overstate the importance and excitement of the High-Luminosity LHC, which is the largest project undertaken by CERN for the past 20 years," explains Mark Thomson, CERN Director-General. "Coupled with advanced new data tools and upgraded detectors, it will allow us to understand, for the first time, how the Higgs boson interacts with itself – a key measurement that will shed light on the first instants and possible fate of the universe. The HiLumi LHC will also explore uncharted territory and could reveal something completely new and unexpected. That's the whole point of exploring the unknown: you don't know what's out there."

Many of the technologies developed for the HiLumi LHC – such as superconducting crab cavities that tilt the particle beams before they collide, crystal collimators designed to remove errant particles and high-temperature superconducting electrical transfer lines to power the HiLumi magnets as efficiently as possible – have never been used in a proton accelerator before. Among these new key technologies, the inner triplet beam-focusing magnets are made of a superconducting compound based on niobium and tin (Nb_3Sn), enabling magnetic fields higher than those achieved with the current LHC niobium-titanium (NbTi) magnets (see p30). These new magnets will be deployed on both sides of the ATLAS and CMS experiments, alongside new cryogenic, powering, protection and alignment systems, and will operate at a temperature of 1.9 K, just like the LHC magnets.

To ensure seamless integration, CERN has built, in an above-ground test hall, a full-scale test stand called the Inner Triplet String (IT String), which mirrors the underground configuration (*CERN Courier* March/April 2025 p8).

"All the systems have already been tested individually. The goal of the IT String is to validate their integration and their collective performance under operational conditions," explains Oliver Brüning, CERN Director for Accelerators and Technology. "The connection and operation of all the equipment in the IT String give us a chance to optimise our procedures before the actual installation in the tunnel, so that we will be prepared and ready for an efficient and smooth installation."

The entire accelerator complex and associated experiments will benefit from the improvements

Harnessing potential

The large LHC experiments ATLAS and CMS will also undergo a major upgrade to enable them to harness the full scientific potential of the HiLumi LHC collisions – work that is being carried out in close coordination with hundreds of institutes worldwide. Additionally, the entire accelerator complex and associated experiments will benefit from improvements, says the lab, solidifying CERN's leadership in high-energy physics.

The cooldown of the HiLumi LHC test string, which is achieved using a liquid-helium refrigeration and distribution system, is expected to take several weeks to complete.

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History and culture

Eiffel honour for women physicists

When the Eiffel Tower opened for the 1889 Exposition Universelle, its girders bore in gold lettering the names of scientists whom Gustave Eiffel said had honoured France since 1789. Every one of them was a man. 137 years later, on 26 January 2026, Anne Hidalgo, the mayor of Paris, accepted the nomination of 72 women scientists to join them.

The list spans nearly 250 years and multiple disciplinary domains. Many made important contributions to nuclear and particle physics, and several had close associations with strong partners to CERN such as the Centre national de la recherche scientifique (CNRS) and the Commissariat à l'énergie atomique et aux énergies alternatives (CEA).

Eiffel honour *The women set to be honoured include (clockwise from top left): Marie Skłodowska Curie, Yvette Cauchois, Toshiko Yuasa, Marie-Antoinette Tonnelat, Cécile DeWitt-Morette, Yvonne Choquet-Bruhat and Lydie Koch.*

Foremost among the women to be honoured is Polish–French physicist Marie Skłodowska Curie (1867–1934), who discovered polonium and radium, helping to establish radioactivity as an intrinsic property of atoms. She carried out systematic measurements of radioactive substances, determined radium's atomic weight and developed methods to isolate radioactive elements from pitchblende. She shared the 1903 Nobel Prize in Physics and later won the 1911 Nobel Prize in Chemistry, becoming the first woman laureate and the only person to receive Nobel prizes in two different scientific fields.

A pioneer in X-ray spectroscopy, Yvette Cauchois (1908–1999) invented the Cauchois spectrometer, a curved-crystal spectrometer widely used for the analysis of X-rays and gamma rays. She introduced X-ray spectroscopy using synchrotron radiation to Europe and later studied the X-ray spectrum of the Sun.

A trailblazer for women physicists in Japan, nuclear physicist Toshiko Yuasa (1909–1980) studied the continuous spectrum of beta radiation emitted by artificial radioactive substances and developed her own double-focusing spectrometer. In 1955 she warned of the dangers of nuclear tests at Bikini Atoll. In the 1960s, promoted to senior research fellow at CNRS, she studied nuclear reactions using a synchrocyclotron.

Marie-Antoinette Tonnelat (1912–1980) worked on early unified theories that sought to connect gravity and electromagnetism. She served as director of research at CNRS.

Henriette Faraggi (1915–1985) introduced new techniques with photographic emulsions and directed the CEA Department of Nuclear Physics from 1972 to 1978. She also served as chair of the Nuclear Physics Commission of IUPAP and became the first woman elected president of the French Physical Society. Convinced early on of the importance of high-energy heavy-ion physics for studying quark-gluon plasma, she played a key role in the decision to build GANIL in Caen.

Cécile DeWitt-Morette (1922–2017) worked in quantum field theory and gravitation, and founded the Les Houches Summer School in 1951, which became a major international centre for theoretical physics training. She later contributed to path-integral methods in quantum theory.

Yvonne Choquet-Bruhat (1923–2025) placed Einstein's field equations of general relativity on a firmer mathematical ground, showing how their behaviour follows from appropriate initial conditions. In 1979 she became the first woman elected a full member of the Académie des Sciences.

A specialist in cosmic radiation, Lydie Koch (1931–2023) led stratospheric-balloon experiments to detect cosmic rays, contributed to the development of innovative germanium and silicon detectors for the HEAO-3 and COS-B satellites, and advanced X-ray and gamma-ray astronomy. She played a central role in the development of astrophysics at the CEA and was head of the Astrophysics Section from 1967 to 1979.

"It is time for this highly symbolic landmark to embrace the cause of equality between women and men, and to restore women to their rightful place on this monument dedicated to the glory of science and scientists," said Hidalgo.

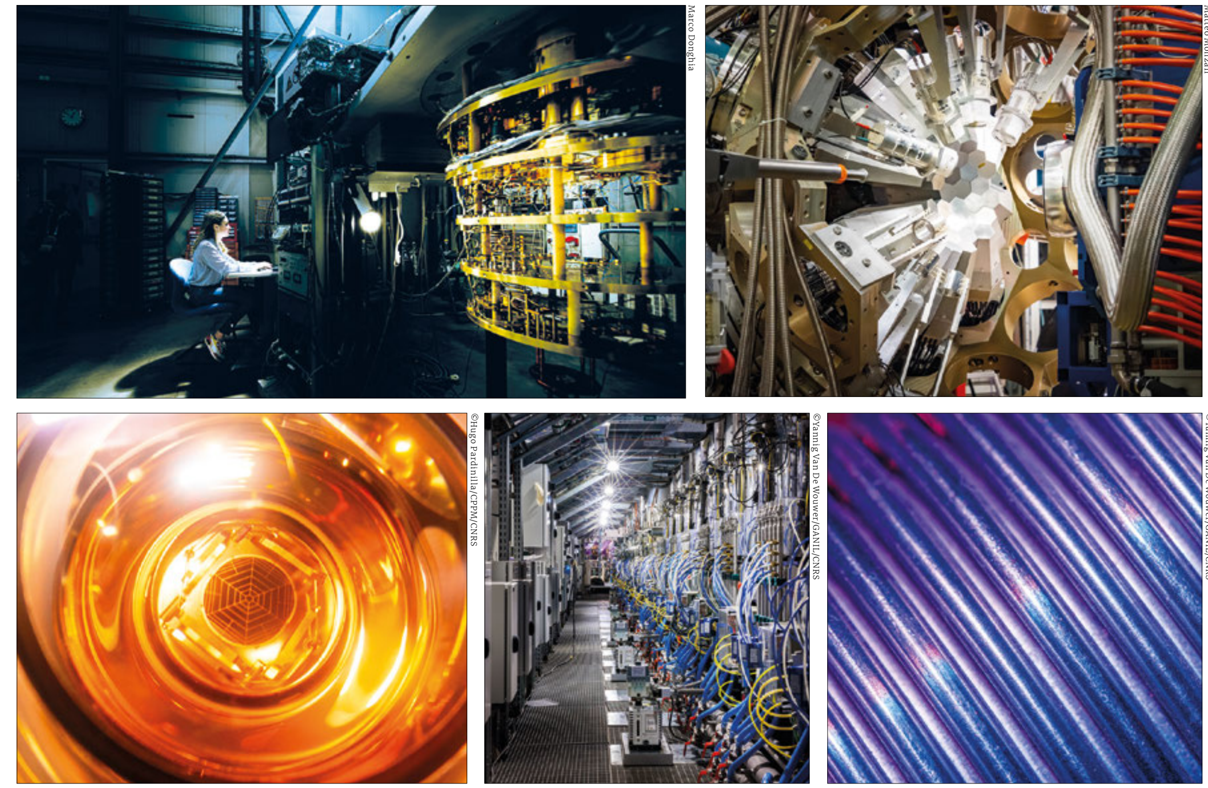
Outreach

Physics labs under the lens

Physics is beautiful in its ideas and in the people who pursue them across borders. What better, then, than for 16 laboratories across Asia, Europe and North America to throw open their doors for a photography competition, allowing the aesthetically inclined to immortalise on film the wonders within. The votes are now in.

Immortalising on film the wonders within

The winning image of the 2025 Global Physics Photowalk, by photographer Marco Donghia, shows INFN National Laboratories of Frascati researcher Raffaella Donghia seated beside an open cryostat during installation of an ultra-cold experiment at COLD, the CryOgenic Laboratory for Detectors (see "First place" image). The apparatus houses an axion haloscope – a cryogenic antenna consisting of a microwave cavity resonating at about 9 GHz, immersed in a powerful 9 tesla magnetic field and connected to an ultra-low-noise amplification system designed to search for ultralight ▷



Award winners *(From top left, left to right)* **First place** *Research at COLD by Marco Donghia.* **Runner up** *The AGATA–PRISMA Setup for Nuclear Physics Experiments by Matteo Monzali.* **Third place** *Eye of a Neutrino Telescope by Hugo Pardinilla.* **Public preference** *The Tunnel by Yannig Van De Wouwer.* **Public runner up** *Vacuum by Yannig Van De Wouwer.*

dark-matter candidates such as axions or dark photons (*CERN Courier* January/February 2026 p21). If ultralight dark matter circulates in a galactic halo, it could excite the resonant cavity at a frequency corresponding to the particle's mass, appearing as a minute increase in electromagnetic power at that frequency. Cooling the system to 10 mK suppresses thermal noise to the point that quantum noise dominates.

"The image stood out for its clear visual storytelling and masterful use of light, which leads the eye through the scene and emphasises the moment of discovery," said judge Tabea Rauscher, then creative lead at the European Molecular Biology Laboratory. "The researcher appears small in relation to the cryostat, highlighting the scale of the technology while keeping the human presence at the centre. The lighting creates a quiet, almost cinematic atmosphere that captures both the intensity and the solitude of scientific work."

The photographs move between abstraction and lived experience

Fellow judge Dmitri Denisov, deputy associate laboratory director for high-energy physics at Brookhaven National Laboratory in the US, noted that while the judges chose Donghia's photograph for its ability to convey the "deep connection between the apparatuses used in particle physics and the human developing them," the second- and third-place photographs were chosen for their "deep looks into the inner workings of experiments and impressive display of colours."

The judges awarded second place to Matteo Monzali for his photograph of a nuclear-physics experiment at INFN National Laboratories of Legnaro in Italy (see "Runner up" image) and third place to Hugo Pardinilla for a close-up image of a photomultiplier from the KM3NeT/ORCA experiment, a neutrino telescope currently being installed in the Mediterranean Sea at a depth of 2500 metres off the coast of Provence, France (see "Third place" image). Members of the public awarded first and second place to Yannig Van De Wouwer's photographs of GANIL, the heavy-ion accelerator in Caen, France, featuring pipes and cables serving the SPIRAL2 linear accelerator and iridescent patterns in a beam pipe (see "Public preference" image). The public's third choice went to Monzali's snap of the AGATA–PRISMA setup in INFN Legnaro.

Deeply human

"Serving as a judge for the 2025 Global Physics Photowalk, I was struck by the range and sensitivity of the submissions," concludes judge Will Warasila, a freelance photographer for the *New York Times*. "The photographs move between abstraction and lived experience – finding form, rhythm and quiet beauty in scientific spaces, while foregrounding the people whose labour and curiosity make this work possible. Across geographies and institutions, these images show how photography can slow us down, make complex systems legible and remind us that science is not only technical, but deeply human."

The Global Physics Photowalk is organised by the Interactions Collaboration (interactions.org), an international network of particle-physics institutions including CERN and over 20 partner laboratories and research infrastructures around the world.

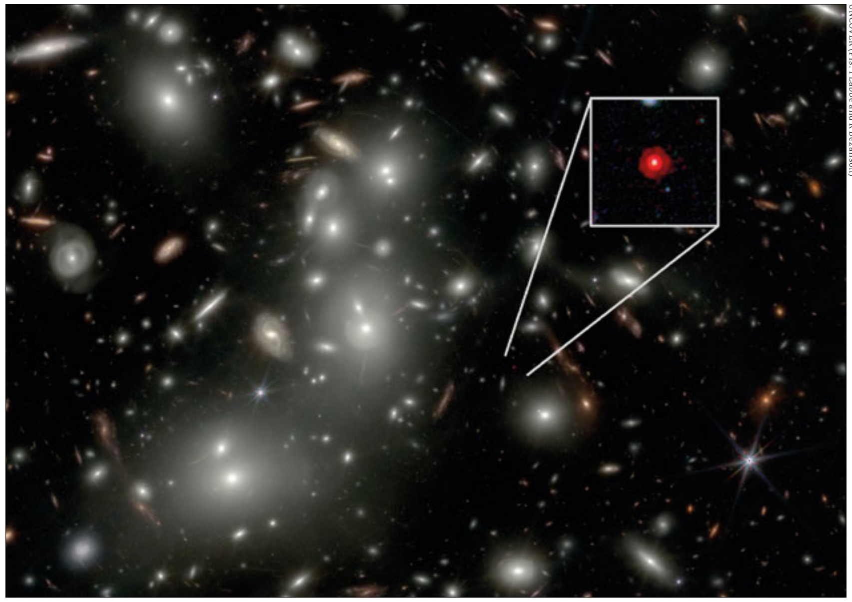
Astrowatch

The mystery of the little red dots

Every new instrument needs its mysteries, and no discovery of the James Webb Space Telescope (JWST) has been more surprising than the "little red dots" it discovered in the early universe. Four years after their discovery, their nature is still an open question, with new papers purporting to solve the mystery on an almost daily basis.

These unexpected objects came into view in JWST's first data release in 2022 thanks to its sharp images and sensitivity in the near infrared. By summer of 2023, a number of discovery papers had been written about them, identifying three traits in common: they were compact in size, had unusual "V-shaped" spectra and they showed emission from high-velocity hydrogen gas. Due to their compact size and red colour in the rest frame, they were dubbed little red dots. A few appeared in every pointing of the JWST imaging camera NIRCam, accounting for a few percent of all known galaxies in the first billion years of cosmic time. The race was on to determine their nature.

Two options initially appeared possible, but both were extraordinary and required a very precise tuning of parameters to fit the observations: too-dense galaxies or too-massive supermassive black holes. In either case, the objects had to be enshrouded in a cocoon of dust.



UNCOVER (PIs: I Labbé and R Bezanson)

Spot the dot *Little red dots appear in every pointing of the JWST imaging camera NIRCam.*

The first paper assumed they were very massive galaxies, with their stars all assembled less than a billion years after the Big Bang

Galaxies or black holes?

The first paper assumed they were very massive galaxies, with their stars all assembled less than a billion years after the Big Bang. In favour of the galactic hypothesis were the V-shaped spectra, which are difficult to model without invoking massive stars. The vertex of the V-shape resembles a "Balmer break", which is produced by the absorption of hydrogen atoms in the n = 2 level. Longward of the break, the optical continuum rises steeply toward the red, which this model attributed to the reddening of these stars by dust, with the UV being produced by starlight that was scattered out of the dust screen. However, the very high masses and early-universe star formation rates required for these models were difficult to reconcile with our understanding of the rate at which galaxies and their dark-matter halos assemble.

The black-hole hypothesis was supported by evidence for very dense gas clouds moving at thousands of kilometres per second in the potential of a massive black hole. In this picture, surrounding dust would preferentially absorb ultraviolet light and re-emit it at longer wavelengths, producing the observed red colour. Though this explanation promised to alleviate the tension arising from the implied galaxy masses, it quickly became clear that these objects were not typical growing black holes. They were not detected in X-rays, nor did they show the characteristic 1000 K dust signature that is ubiquitous in actively accreting black holes. However, the most concerning piece of the black-hole interpretation was the implied black-hole masses. Applying local calibrations to the observed motion of gas in the little red dots implied black-hole masses of ten million to a billion suns, compared with galaxy masses of the same order – a stark contrast with local black holes, which have masses roughly a thousandth of their host galaxies. These overly massive black holes are hard to grow so far in advance of the galaxies, and also overproduce the total amount of black-hole mass created at such an early time.

Explaining their redness

Two major breakthroughs occurred in 2024 that clarified the nature of the little red dots. All the aforementioned models invoked heavy amounts of dust to suppress ultraviolet emission and produce the observed red colours. The conservation of energy implies that all the absorbed radiation should be re-emitted by the dust. However, multiple studies of populations and of luminous individual sources turned up non-detections of dust emission. These stringent limits on the far-infrared energy output were enough to conclusively rule out these entire classes of models, invoking reddening by dust to explain the observed red colours.

At the same time, campaigns to observe the broad population of little red dots discovered a remarkable class of sources with very little ultraviolet emission and extreme Balmer breaks. These breaks could not be produced by anything resembling a stellar population we have seen before, and served as conclusive evidence that normal stars cannot be responsible for producing the optical emission in little red dots; the photoabsorption by hydrogen in the n = 2 energy state must nevertheless be a crucial physical aspect of the little red dots, even if it wasn't happening in the atmospheres of massive stars.

The task is to explain the characteristic red colour of the little red dots without dust obscuration

Plausible scenarios

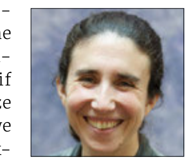
The challenge is therefore to explain the characteristic red colour of the little red dots without dust obscuration. Any successful model would also need a substantial reservoir of hydrogen around to cause the hydrogen absorption that looked like starlight, but wasn't. One plausible scenario that could satisfy these requirements is very dense gas arranged quasi-spherically around the black hole. In this scenario, the black holes powering the little red dots could be significantly less massive than we had originally thought, when we had assumed that dust was obscuring most of the light from the growing black hole.

In this new picture, the little red dots are powered by black holes that are accreting at much higher rates than are typically seen at later times. A higher accretion rate implies greater luminosity for a given black-hole mass, and therefore we infer much lower black-hole masses, perhaps closer to a million suns, and much more aligned with the measured galaxy masses. As a side benefit, lower black-hole masses are much more natural for objects that are so prevalent, because the number of low-mass dark-matter halos and low-mass galaxies is much higher than the number of high-mass systems.

Astronomers are still arguing about how this dense gas is configured and accretes onto the black hole, and everyone has their favourite model. We do not know if the geometry of the system is completely spherical, or if we are seeing a mixed-phase medium where the viewing angle is an important parameter. These details matter, because if we can pin down the characteristic size and density of these gas envelopes, we may be able to infer more robust black-hole masses for the population. There has been some recent speculation that the little red dots may be marking the end stages of black-hole seed growth, in which case they could be a critical missing link in our understanding of the formation of the first black holes. However, without more concrete constraints on black-hole mass, we cannot know for sure. At the same time, we need a much better theoretical understanding of what makes little red dots so distinct from the more typical growing black holes we have studied for decades, and why that mode of growth becomes so much less common as the universe ages.

One thing we do know for sure: the more we learn about the little red dots, the more complex and unexpected they become. We are excited to see what new wrinkles arise as we enter our fifth year of JWST operations.

Guest Astrowatch correspondents



Jenny Greene *Princeton University.*

David Setton *Princeton University.*

Astrowatch

A thousand anomalies hiding in plain sight

The Hubble Space Telescope has been observing the cosmos for more than 35 years, amassing hundreds of thousands of observations. Each image was taken with a specific scientific goal, yet every exposure contains far more than its intended target: background galaxies, foreground objects and unexpected phenomena scattered across the field of view. Systematic human inspection of the millions of source cutouts in the Hubble Legacy Archive is impossible – but artificial intelligence has now uncovered more than a thousand astrophysical anomalies hiding in plain sight.

The challenge of identifying rare signals amid overwhelming backgrounds will resonate with *CERN Courier* readers. At the LHC, experiments increasingly deploy anomaly detection methods to search for new physics beyond the Standard Model without fully specifying the signal in advance. Both fields face a shared problem: isolating rare events from billions of observations with minimal prior assumptions about the target. "Semi-supervised" approaches that marry sparse expert knowledge with vast unlabelled datasets may prove as valuable for collider data as they have for astronomical archives.

The challenge of identifying rare signals amid overwhelming backgrounds will resonate with *CERN Courier* readers

A new semi-supervised machine-learning framework developed at the European Space Agency in December 2025 has identified 1339 unique astrophysical anomalies spanning 19 distinct morphological classes (see "Six out of 1339" figure). Approximately 65% of these – some 811 objects – had no prior reference in the scientific literature, despite residing in data that has been publicly available for years. Some of these newly discovered objects were excellent additions to existing catalogues of which examples are limited. These included collisional ring galaxies, galaxy mergers, jellyfish galaxies and gravitational lenses. Forty-three of the objects completely defied classification and remain unknown objects to this day.

Semi-supervised learning

At the heart of this work lies a fundamental tension in modern astronomy: datasets are growing far faster than our ability to label them. Traditional supervised machine learning requires large, annotated training sets, but expert labelling of millions of images is prohibitively expensive. Semi-supervised learning offers a way forward. In this approach, a model learns simultaneously from a small set of human-labelled examples and a vastly larger pool of unlabelled data, extracting patterns from the abundant unlabelled images to compensate for the scarcity of annotations.

The new code we have developed generates provisional "pseudo-labels" when the model's confidence exceeds a threshold, then enforces consistent predictions with augmented versions of the same ▷

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images. These augmentations take the form of cropping of the images, flipping them, inverting the pixel values, and so forth. This allows the model to leverage the statistical structure of millions of unlabelled cutouts without requiring a human to inspect each one. The algorithm then couples this semi-supervised backbone with human expertise. After each training cycle, the model ranks all images by anomaly score and a domain expert reviews the highest-ranked candidates, correcting misclassifications and confirming genuine anomalies. These newly labelled images feed the next training cycle. This human-in-the-loop design combines the pattern recognition capabilities of deep learning with the domain knowledge of an astronomer, achieving an efficiency that neither could match alone.

In our study, the entire process began with 128 standard astrophysical phenomena and three labelled anomalies where finding further examples would be valuable. The chosen examples were edge-on protoplanetary disks – young stellar objects with a proto-planetary disk around a host star that exhibits strong emission with a direct high-energy jet and secondary emission in a striking butterfly shape. Through successive iterations, the training set grew to 1400 images, at which point the model could flag anomaly types it had never been shown.

ESA/Hubble & NASA, D O'Ryan, P Gómez (European Space Agency), M Zamani (ESA/Hubble)

Six out of 1339 *Six anomalous images of galaxies identified by artificial intelligence, including: a galactic merger (top right); a "collisional ring" galaxy that has been smashed by a secondary galaxy in a perfectly aligned interaction (top left); a galaxy resembling the Starship Enterprise that defies classification (bottom left); and three gravitational lenses with arcs distorted by gravity (top middle, bottom middle and bottom right).*

Community access

A search of this scale was made possible by ESA Datalabs, a collaborative science platform that provides researchers with direct access to ESA's mission archives alongside computational resources – including GPU acceleration – through a browser-based environment. Rather than downloading terabytes of Hubble data, we brought our analysis code to where the data already resides. The full inference run across 99.6 million images completed in just 2.5 days on a single GPU, demonstrating that large-scale anomaly detection does not require vast computational resources, a consideration that matters as the community increasingly weighs the sustainability of data-intensive research.

The most abundant anomalies were galaxy mergers: 629 systems hosting tidal tails, bridges and other signatures of gravitational interactions that exist at the very limit of our detection power. We also found 140 candidate gravitational lenses and 39 gravitational arcs, where the warping of space-time distorts background sources into characteristic rings. Mergers give us snapshots of hierarchical structure formation, while spacetime distortions provide direct tests of general relativity and enable dark-matter mapping on cosmological scales.

Even decades-old data can yield hundreds of new discoveries when the right tools are brought to bear

The model also independently recovered five previously catalogued quadruply lensed quasars in the Einstein cross configuration – a fourfold splitting of a distant quasar's light by a foreground galaxy. That the model identified these without any lensed quasars in its training set validates its ability to generalise beyond the anomaly types it was explicitly taught. Fewer than 50 such systems are known, and each enables an independent "late universe" measurement of the Hubble constant; such measurements are invaluable given the persistent tension between values derived from the cosmic microwave background and the local distance ladder (*CERN Courier* March/April 2025 p28).

Among the genuinely new discoveries were two collisional ring galaxies – extreme systems that have undergone such an extreme galaxy interaction that a shockwave is moving through the galaxy, causing a burst of star formation through the galaxy. Thirty-five jellyfish galaxies shaped by ram pressure stripping in the intracluster medium also provide an excellent laboratory to understand the relationship between the galactic environment and the internal gas of the galaxy. Finally, 43 sources had morphologies that defied classification entirely – curved, distorted objects that fit none of the established categories and have been released to the community for further investigation.

With the Euclid space telescope now operational, and the Vera C. Rubin Observatory and Square Kilometre Array soon to follow, data volumes will dwarf Hubble's archive by orders of magnitude. Our work shows that even decades-old data can yield hundreds of new discoveries when the right tools are brought to bear – and that AI-assisted discovery, guided by human expertise, is only just getting started.

Further reading

D O'Ryan and P Gómez 2025 *Astronomy & Astrophysics* **704** A227.

Guest Astrowatch correspondents

David O'Ryan *European Space Agency.*

Pablo Gómez *European Space Agency.*

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

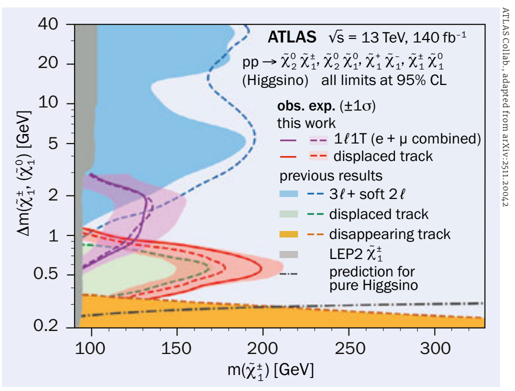
ATLAS

The most elusive higgsinos

Supersymmetry has so far eluded discovery at the LHC, yet it retains strong theoretical appeal as an extension of the Standard Model (SM), and potential hiding places remain. In two recent analyses, the ATLAS collaboration sets new bounds on compressed higgsino models, where the proposed particles lie very close in mass. The collaboration used machine-learning techniques to target some of the most elusive signatures at the LHC: low-momentum decay products.

Without extreme fine tuning, quantum corrections would drive the Higgs-boson mass far above the electroweak scale. Supersymmetry prevents this by introducing fermion partners for the SM bosons (and vice versa) so that their quantum contributions naturally cancel. The result is a partner for every SM particle – including higgsinos, the fermionic counterparts of the Higgs field. Higgsinos mix with the partners of the electroweak gauge bosons to form electrically neutral and charged states known as neutralinos ($\tilde{\chi}^0$) and charginos ($\tilde{\chi}^{\pm}$). The lightest neutralino ($\tilde{\chi}^0_1$) is stable in a wide class of models and may naturally account for the observed dark-matter abundance.

In compressed scenarios, the tiny mass-splitting between these new particles poses a distinct experimental challenge. When a heavier state decays to $\tilde{\chi}^0_1$, the small mass difference leaves little energy for the accompanying SM particles. The visible decay products therefore carry very low momentum and may fall below reconstruction and identification thresholds. The new analyses focus precisely on this regime using the full Run 2 dataset collected at $\sqrt{s} = 13$ TeV, with two complementary strategies optimised for different values of the mass splitting.



ATLAS Collab., adapted from arXiv:2511.20042

Fig. 1. *Observed and expected limits at 95% CL for 1ℓ1T (purple) and displaced track (red) searches are shown in the chargino–neutralino mass difference versus chargino mass plane, along with previous limits from the LEP2 (grey) and ATLAS (blue, light green and orange) experiments.*

Firstly, a "displaced track" search targets scenarios with a mass difference between the lightest chargino $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_1$ of 0.3 to 1 GeV, in which the $\tilde{\chi}^{\pm}_1$ has a non-negligible lifetime and can travel a few millimetres before decaying into an invisible $\tilde{\chi}^0_1$ and a low-momentum charged pion. The resulting event signature is a pion track with a large transverse impact parameter and high missing transverse momentum from the neutralinos. Significant improvement in signal sensitivity is achieved by the use of two dedicated neural networks (NNs), where one exploits the global event kinematics and the other focuses on the displaced track characteristics.

A "one-lepton-one-track (1ℓ1T)" search instead targets scenarios with a larger mass splitting of 1 to 3 GeV, in which the heavier neutralino $\tilde{\chi}^0_2$ promptly decays into the $\tilde{\chi}^0_1$ and two low-momentum leptons. Since these could elude the existing ATLAS identification techniques, dedicated low-momentum electron and muon identification algorithms have been developed using NNs that exploit track and calorimeter information. The new algorithms are applied to leptons with momentum as low as 0.5 GeV for electrons and 1 GeV for muons, below the standard reconstruction thresholds, resulting in a signature consisting of one lepton and one lepton-like track. An additional NN enhances sensitivity for event classification, exploiting kinematic features that depend strongly on the mass splitting.

The observed data are consistent with the SM predictions, with no signs of new physics emerging in the targeted phase-space. Based on this result, lower limits on the higgsino masses are set at 95% confidence level (CL) (see figure 1). The 1ℓ1T search excludes a mass-splitting region between 0.8 and 2.0 GeV, extending previous limits from the LEP experiments up to a maximum $\tilde{\chi}^{\pm}_1$ mass of 132 GeV for a 1.8 GeV mass splitting. The displaced track search extends the exclusion limits previously set by the ATLAS experiment by about 30 GeV, reaching a $\tilde{\chi}^{\pm}_1$ mass of 199 GeV for a 0.6 GeV mass splitting. Together, the two searches exclude $\tilde{\chi}^{\pm}_1$ masses below 126 GeV at 95% CL over the targeted mass splitting range. Limits set by the ATLAS collaboration now supersede those from the LEP experiments in all mass-splitting ranges.

With this result, ATLAS is now able to set limits over the full range of higgsino mass splittings that are interesting for naturalness, marking a significant milestone in the search for supersymmetry. The new Run 3 dataset, along with advanced analysis techniques, will push these searches even further – perhaps towards the discovery of physics beyond the SM.

Further reading

ATLAS Collab. 2025 arXiv:2511.20042.

CMS

Suppression grows with system size

When atomic nuclei collide at the LHC, they produce tiny droplets of quark-gluon plasma (QGP) and energetic partons plough through it, slowing down in the process. In a new analysis, the CMS collaboration compared high transverse momentum (p_T) particle yields in oxygen–oxygen, neon–neon, xenon–xenon and lead–lead collisions, with the nucleon numbers of the colliding particles increasing in the sequence 16 < 20 < 129 < 208. The results suggest a steady growth of parton energy loss with the size of the colliding system.

The results should help inform the choice of ion species

High-p_T particles come from the fragmentation of quarks and gluons produced in the earliest hard scatterings of a collision. As these partons cross the QGP, ▷

they interact with the medium and radiate, losing energy in the process. This is one of the clearest signatures of QGP formation. How much energy partons lose depends on how far they travel inside the medium, which in turn grows with the size of the colliding nuclei. Although firmly established in xenon–xenon and lead–lead collisions, the precise way this quenching depends on the path length is not yet fully understood.

Light-ion collisions provide a controlled way to vary the system size and isolate this path-length dependence. In July 2025, the LHC delivered its first ever oxygen–oxygen and neon–neon collisions (*CERN Courier* November/December 2025 p8). The CMS collaboration analysed the data from this dedicated one-week run to perform a systematic study of high-p_T charged-particle suppression across multiple collision systems.

The analysis combines existing measurements in oxygen–oxygen, xenon–xenon and lead–lead collisions with the first measurement of the charged-particle nuclear modification factor, R_{AA}, in neon–neon collisions at a centre-of-mass energy of 5.36 TeV per nucleon pair. The observable R_{AA} quantifies how particle yields deviate from expectations based on proton–proton collisions. The four systems were analysed using identical p_T-intervals, enabling a consistent comparison across systems.

For smaller nuclei, such as oxygen and neon, many experimental uncertainties shared with the proton–proton reference largely cancel, for example, those related to tracking. This leads to particularly precise measurements of R_{AA} across a wide p_T range, which is difficult to achieve in larger systems. Combined with the wide span of nuclear sizes, this precision enables a more direct assessment of how parton energy loss depends on in-medium path length.

For a fixed transverse momentum interval, the suppression increases smoothly with system size, from light to heavy ion collisions (see figure 1). Conversely, for a given nuclear system, the suppression is stronger at lower transverse momenta and progressively weakens as it increases. Expressed in terms of the cube root of the nucleon number, which is proportional to the nuclear radius, the results follow a simple ordering with the size of the system, offering a natural framework to test the evolution of energy loss with system size.

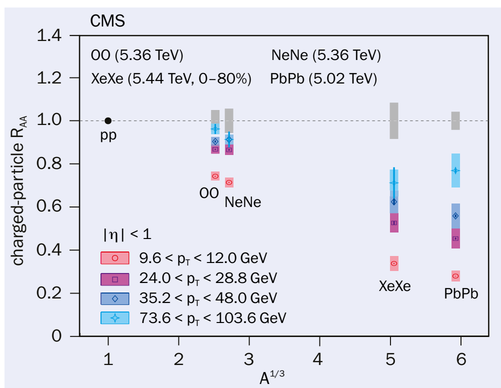


Fig. 1. *Charged-particle nuclear modification factor R_{AA} in oxygen–oxygen, neon–neon, xenon–xenon and lead–lead collisions at the LHC. R_{AA} is shown as a function of the cube root of the nucleon number A, which is proportional to the nuclear radius.*

The data indicate that nuclear suppression develops gradually as the nuclear system grows, consistent with a picture in which partons interact with QGP droplets whose extent and density evolve smoothly across collision systems. Calculations that omit energy loss show little variation with system size and do not describe the observed suppression, whereas models that include it qualitatively reproduce the observed trend within uncertainties. The data, presented this way, offer a guide for further improvements on their A-dependence.

This study places new quantitative constraints on parton-energy-loss mechanisms and on the emergence of QGP-like behaviour in small nuclear systems. The results should help guide future theoretical developments and inform the choice of ion species in upcoming heavy-ion studies at the LHC.

Further reading

CMS Collab. 2026 arXiv:2602.21325.

LHCb

Charm and beauty alike in fragmentation

Proton–proton collisions at the LHC fling quarks and gluons out at massive energies. As they radiate and split into ever more partons, the strong force confines them into sprays of hadrons called jets. The total momentum of a jet, split among its components, approximates that of the initial quark or gluon, which cannot be accessed directly. By tracking how much of a jet's momentum each hadron carries, the LHCb collaboration has now compared how charm, beauty and light quarks hadronise.

While the production and radiation of individual quarks and gluons can be treated perturbatively, their conversion into hadrons occurs in the non-perturbative regime and cannot be calculated from first principles. Instead, the transition is described using phenomenological probability distributions, called fragmentation functions, which encode how a quark of a given flavour produces specific hadrons. Measuring the content and structure of jets, as well as their kinematic properties,

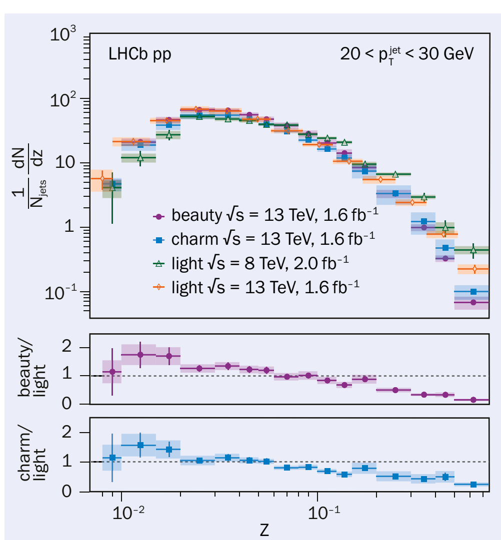


Fig. 1. *Distribution of the longitudinal momentum fraction z of charged hadrons in light- (green/orange), charm- (blue) and beauty-quark-initiated (purple) jets. The lower panels show the ratios of beauty to light (purple) and charm to light (blue). Heavy-quark jets appear suppressed at high z.*

can help constrain these functions.

Previously, the LHCb collaboration measured observables sensitive to fragmentation functions in samples dominated by light-quark-initiated jets. The same measurements were recently carried out for charm- and beauty-quark-initiated jets, allowing a direct comparison of hadronisation across three different jet flavour categories at a single experiment. The light-quark sample was obtained by selecting jets produced nearly back-to-back with a Z boson. In such events, the single parton initiating the jet is typically a gluon or a light quark. In the forward kinematic region accessible to the LHCb detector, where one incoming parton often carries a large fraction of the proton momentum, the proportion of light-quark jets gets further enhanced. Samples of predominantly charm- and beauty-quark-initiated jets were instead obtained using a dedicated flavour-tagging algorithm, which makes use of LHCb's excellent performance at heavy flavour identification and reconstruction.

A key observable for constraining fragmentation functions is the longitudinal momentum fraction z, defined as the share of jet momentum carried by a hadron along its axis. With respect to their light-quark analogues, heavy-quark-initiated jets appear suppressed at high z, consistent with the leading heavy-flavour hadron carrying most of the jet momentum (see figure 1).

Previous measurements of the hadronisation of a heavy quark into a single heavy-flavour hadron showed that this hadron carries most of the parent quark's momentum. The new LHCb analysis extends this picture to the full multi-hadron structure of heavy-quark-initiated jets and is consistent with single-hadron measurements: relatively few charged hadrons possess a large fraction of the jet momentum – a result compatible with the heavy-flavour hadron carrying most of it. This result

The new measurements allow a direct comparison of hadronisation across three different jet flavour categories

demonstrates the complementarity of single- and multi-hadron measurements, which are both necessary to fully understand high-energy hadronisation.

The analysis also measured the transverse momentum of the hadron with respect to the jet axis, which is sensitive to transverse-momentum-dependent fragmentation functions. Experimental constraints on these functions remain limited, yet they are crucial in reconstructing a three-dimensional description of hadronisation.

Further reading

LHCb Collab. 2025 arXiv:2511.10216.

ALICE

The flavour dependence of jet structures

Partons produced in heavy-ion collisions at the LHC must push their way through a hot, dense quark–gluon plasma (QGP). In doing so, they experience medium-induced energy loss that depends on the parton's mass. In a recent analysis, the ALICE collaboration compared the yields of charged particles associated with electrons from heavy-flavour hadron decays with those of the light hadrons. Both show a suppression of high-momentum particles emitted opposite to the tagged particle, with no significant difference between the two.

After a hard scattering, high-energy partons fragment into collimated sprays of hadrons known as jets. These are well described in proton–proton (pp) collisions, where their substructures provide stringent tests of perturbative QCD. In heavy-ion collisions, instead, they propagate through the QGP and emerge modified – a phenomenon known as jet quenching. Previous measurements (*CERN Courier* March/April 2025 p13) suggest that jets initiated by charm and beauty quarks lose less energy than those from light quarks and gluons, owing to their larger mass. This difference is commonly attributed to the dead-cone effect, which suppresses gluon emission by heavy quarks at small angles. Jet-quenching effects can be further characterised by measuring the transverse-momentum distribution of particles within jets, providing insight into the redistribution of the quenched energy.

To study this, the ALICE collaboration employs azimuthal-correlation measurements. This technique measures the angular correlation between a heavy-flavour hadron or its decay daughter ("trigger" particle) and other associated charged particles in the same event. The resulting distribution features

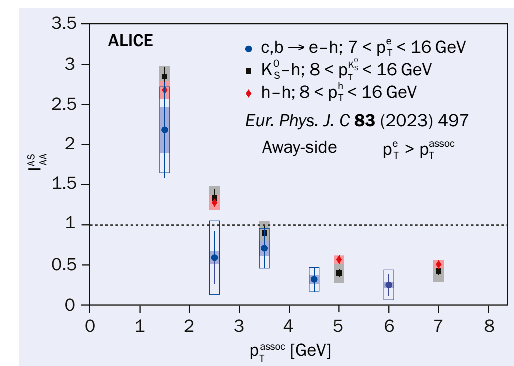


Fig. 1. *Away-side per-trigger nuclear modification factor I_{AA} as a function of the associated-particle transverse momentum. Blue circles show jets tagged by electrons from heavy-flavour hadron decays; black squares and red diamonds show light-flavour reference measurements.*

two correlation peaks: a near-side peak from particles produced alongside the trigger and an away-side one from the recoiling jet, particularly sensitive to jet–medium interactions. Jet quenching is then quantified by the per-trigger nuclear modification factor I_{AA}, which is the ratio of away-side charged-particle yield in heavy-ion collisions to pp collisions. Values of I_{AA} deviating from unity indicate QGP-induced modifications of the jet.

The ALICE collaboration now reports the measurements of jet-like structures in the heavy-flavour sector of lead–lead collisions at a centre-of-mass energy of 5.02 TeV per nucleon pair. The analysis, based on LHC Run 2 data, uses electrons from semi-leptonic decays of charm and beauty hadrons as trigger particles. Electron identification relies on a combination of energy-loss measurements in the time-projection chamber, energy-momentum matching in the calorimeter and selection of shower shapes. Invariant-mass tagging techniques allowed for the subtraction of the large backgrounds from photon conversions and light-meson decays to electron–positron pairs.

The measurement is challenging due to the high multiplicity of lead–lead collisions and the need to extract jet-like correlations from large combinatorial and collective-motion backgrounds. A corresponding analysis of pp collisions at the same energy provides the reference needed to compare jet evolution in the presence of the QGP.

The away-side shows a suppression for associated particles with transverse momenta between 4 and 7 GeV/c (see figure 1), indicating relevant jet quenching with a 2.5σ significance. Conversely, a hint of an enhancement is observed below 2 GeV/c, possibly signalling the redistribution of lost energy into the medium and the subsequent formation of additional low-momentum particles.

These results are consistent with corresponding measurements using light-flavour triggers across all measured intervals. While this suggests that the QGP modifies jets consistently regardless of the initiating parton's mass, important caveats remain. Variations in parton-to-hadron momentum scaling, as well as the fact that the heavy flavour is tagged via decay electrons, could introduce kinematic differences that complicate a direct comparison. Whether QCD predicts a deviation remains an open question for future modelling of mass-dependent parton–medium interactions.

LHC Run 3 will provide an order of magnitude more heavy-ion events. This increased luminosity will enable higher-precision analyses, offering a deeper understanding of how QGP modifies heavy- and light-flavour jets.

Further reading

ALICE Collab. 2025 arXiv:2507.13197.

FIELD NOTES

Reports from events, conferences and meetings

INTERDISCIPLINARY ANTIMATTER WORKSHOP

All that antimatters in the universe

Applying the Standard Model (SM) to early cosmological times leads to an uninhabitable universe, with tiny and equal amounts of matter and antimatter. Yet the universe is habitable and the local universe strongly matter-dominated. Observations of the diffuse gamma-ray background and cosmic microwave background show no evidence for the presence of antimatter on large scales and rule out a matter–antimatter symmetric universe.

From 19 to 22 January, 80 particle physicists, astronomers and cosmologists gathered at CERN for the first "All that Antimatters in the Universe" workshop to explore the frontier between the laboratory and astrophysical perspectives on the matter–antimatter asymmetry of the universe.

CERN

Intersections *The interdisciplinary antimatter workshop explored laboratory, astrophysical and cosmological probes of antimatter.*

Broad panorama

Julia Harz (Mainz University) reviewed a broad panorama of baryogenesis models in which physics beyond the SM produces a homogeneous matter excess within the first seconds after the Big Bang, before light elements are synthesised. She highlighted their features and potential tests and constraints, including searches at colliders like the LHC and indirectly with experiments such as those looking for neutrinoless double-beta decays.

Questioning our assumptions about antimatter was a central thread of the workshop, with several presentations highlighting non-standard baryogenesis models that allow domains of antimatter to survive the Big Bang, as well as others in which antimatter is hidden in compact nuggets that could also constitute dark matter. A lively discussion explored how to hunt for these scenarios using astrophysical and cosmological observables. For example, spectral distortions of the cosmic microwave background could indicate energy injections from matter–antimatter annihilation in the early universe. Observations at 21 cm-wavelengths offer another probe: these signals trace neutral hydrogen during the cosmic-dawn epoch, when the first stars and galaxies formed, and could reveal anomalous heating or ionisation patterns characteristic of antimatter annihilation.

Questioning assumptions about antimatter was a central thread of the workshop

The discrete symmetries of charge conjugation (C), parity (P) and time reversal (T) have been central to particle physics since the discovery that nature violates them individually, yet their combined action (CPT) appears to be preserved in all standard interactions. In a particularly sharp presentation, Gabriela Barenboim (University of Valencia) stressed that while much attention is devoted to the search for differences in the interactions between particles and antiparticles through CP-symmetry violation, the more fundamental possibility of CPT violation remains largely unexplored. Unlike CP violation, which can occur within the Standard Model, any breakdown of CPT symmetry would signal new physics and could manifest as differences in the intrinsic properties of particles and antiparticles, including their masses and lifetimes.

Leading stress-tests of CPT symmetry are now carried out at CERN's Antimatter Factory (AF), whose experiments presented an array of impressive results at the workshop. Eric Hunter (CERN) highlighted the potential of boosting the yield of antihydrogen formation at the AF experiments, showing how this could improve our knowledge of antimatter physics enormously. Improved yields of antimatter replicas of naturally occurring matter-based atoms would enable higher precision tests of key electromagnetic transitions and gravitational interactions of antimatter.

Much attention went to antimatter in cosmic rays. Primary cosmic rays are particles accelerated at astrophysical sources such as supernova remnants and injected into the galaxy, whereas secondary cosmic rays are produced when those primaries collide with gas and dust in the interstellar medium. In standard galactic cosmic-ray models, antimatter is purely a secondary product of the interactions of primary cosmic rays with the interstellar medium. However, the AMS-02 experiment operating on the International Space Station has firmly established a positron excess requiring a primary source, possibly pulsars. AMS-02 antiproton data also show some anomalies, but uncertainties in the propagation models and interaction cross-sections remain large.

Mind the GAPS

Complementary searches for cosmic-ray antimatter are also carried out by balloon-borne experiments. Principal investigator Chuck Hailey (Columbia University) described how the GAPS balloon experiment, uniquely suited to probe low-energy antiprotons, antideuterons and antihelium, reported its first data from a 25-day flight completed in early 2026. The specificity of GAPS is the exploitation of the characteristic X-ray emission produced by short-lived bound states between antimatter nuclei and ordinary atoms, which results in excellent particle-identification and background-rejection capabilities.

The atmosphere at the workshop was excellent, with participants curious to learn from other communities and expand their horizons everywhere that antimatter matters in the universe, from the cosmos to the lab, via astrophysical systems. While antimatter still holds many mysteries, All that Antimatters in the Universe brought us one step closer to answering them.

Miguel Escudero Abenza *CERN* *and* **Luigi Tibaldo** *IRAP, Université de Toulouse.*

IBERIAN STRINGS 2026

String pilgrimage to Santiago

IGFAE

One hundred researchers gathered in Santiago de Compostela from 21 to 23 January for Iberian Strings, the annual meeting of the vibrant Spanish and Portuguese string theory community. From the idea that black holes may test quantum gravity to the new, string-inspired ways of organising quantum field theories using symmetries and defects, the programme offered a broad overview of where string theory and holography currently sit. What stood out was the extent to which very different problems are now being tackled with a shared set of theoretical tools.

Black holes remain a clean laboratory for probing ideas about quantum gravity. Decades of work have shown they behave much like ordinary thermodynamic systems, with quantities such as temperature and entropy. A central question is how this simple large-scale behaviour arises from an underlying quantum description. Vijay Balasubramanian (University of Pennsylvania) emphasised that the challenge is not only reproducing the familiar area law – which links entropy to the area of the event horizon – but also understanding what different semiclassical calculations are really describing.

Calculations under control

One way to address this problem is to count the quantum states that give rise to a black hole's entropy. To make progress, researchers often focus on settings where calculations are under better control. Gabriel Cardoso (IST Lisbon) discussed BPS black holes, highly symmetric solutions that allow precise calculations using holography. Stefano Trezzi (University of Barcelona) showed that near-extremal black holes, systems close to a zero-temperature limit, exhibit a universal near-horizon behaviour that provides a clean setting to study how quantum effects modify the semiclassical picture.

So much for static black holes; what about their evolution in time? Marija Tomašević (CERN) suggested that quantum effects can form a horizon where classical gravity would predict a naked singularity. Pablo A Cano (University of Murcia) and Marina David (KU Leuven) explored instead how black holes react when they are perturbed, emitting gravitational waves as they settle back to equilibrium through a process known as ringdown. Across these contributions, the focus was on separating what can be understood within controlled semi-classical calculations from what requires genuinely microscopic, quantum-gravitational input.

Modern methods *Researchers are converging on a common set of tools for string theory, holography and quantum gravity.*

Some particle theories may have been gravity all along. And vice versa. These seemingly disparate worlds, with particle beams and colour confinement in one (particle physics) and curved spacetime in the other (gravity), may simply be two languages for the same physics. To translate between them, the particle side must live in one fewer dimension. Just as a hologram stores a 3D image on a 2D plate, a gravitational theory in D dimensions may be exactly equivalent to a non-gravitational quantum field theory in D–1 dimensions. This holographic correspondence is central to modern approaches to quantum gravity. The focus at the workshop was on its more applied uses, as a controlled way to learn about dynamics at strong coupling.

Elias Kiritsis (University of Crete) provided a concrete example. Using familiar spacetime physics, he studied how strongly interacting quantum systems respond to gentle deformations at low temperature, a standard probe of transport. In this setting, quantum effects can modify quantities such as the ratio of viscosity to entropy density beyond the semiclassical value.

To round the picture, Francesco Nitti (APC Paris), explored holographic models in which varying the curvature of spacetime can affect confinement, while Shota Komatsu (CERN) presented an overview of matrix-model methods in holography, emphasising how they can provide tractable descriptions of strong-coupling dynamics in specific regimes, such as large-N limits. Following 't Hooft, theorists often treat the number of colours in an SU(N) gauge theory as a tunable parameter, providing a controlled simplification of strongly coupled dynamics.

Black holes remain a clean laboratory for probing ideas about quantum gravity

Working in simplified settings can be an effective way to make progress. In holography, a quantum field theory in two dimensions can map to a three-dimensional spacetime with a negative cosmological constant. Symmetries then constrain the gravity side, allowing us to pose – and sometimes answer – questions that would be far harder to tackle in higher dimensions or less symmetric settings. In this spirit, Stéphane Detournay (Université Libre de Bruxelles) showed how near-extremal black holes themselves can behave like two-dimensional systems, where effects due to thermodynamics, symmetry and quantum corrections can often be disentangled cleanly.

Rapid progress in understanding generalised symmetries and defects was a hot topic. Guillermo Arias-Tamargo (Imperial College London) described how recent work on non-invertible symmetries in non-linear sigma models pushes beyond the traditional picture of symmetries as simple group actions on local fields. In this modern framework, symmetries are realised through extended objects, such as defects or interfaces. Tracking how observables transform across these structures provides concrete constraints on the dynamics and phases of the theory.

A particularly sharp application came from José Calderón Infante (Caltech), who used defect-based arguments to rule out global shift symmetries in quantum gravity. Interfaces also featured prominently as physically meaningful probes, naturally connecting abstract symmetry ideas to concrete quantities such as boundary degrees of freedom and entropy-like measures – as discussed by Carlos Hoyos (Universidad de Oviedo).

The meeting covered a wide range of active topics, but controlled semiclassical arguments, low-dimensional holographic models and defect-based symmetry arguments resurfaced throughout the programme. In that sense, Iberian Strings provided an overview not only of open questions but also of modern methods.

Saskia Demulder *CUNEF Universidad.*

QUARKONIUM WORKING GROUP

Quarkonium experts regroup at CERN

N Brambilla

Internal structure *The 17th Quarkonium Working Group attracted more than 200 researchers to CERN.*

Quarkonium physics dates back to the November Revolution of 1974 and the discovery of the J/ψ, a bound state of a charm quark and its antiquark; this was soon followed by the excited ψ(2S) state and its bottom–antibottom analogue ϒ(1S) (*CERN Courier* September/October 2025 p35). These non-relativistic systems hold a unique place in QCD, encompassing a precise hierarchy of characteristic energy scales. Some, such as heavy-quark masses, are amenable to perturbative treatment, while others, such as the confinement scale, are inherently non-perturbative. To capture this interplay systematically, effective field theories such as non-relativistic quantum chromodynamics (NRQCD) were developed from the 1990s onwards.

The quest to interpret quarkonium phenomena within this unified framework, combined with an explosion of experimental results from B factories and hadron colliders, sparked the creation of the Quarkonium Working Group (QWG) Workshop in 2002. Now organised roughly every 18 months at research institutions around the world, the workshop has become a regular meeting point for the quarkonium community. The 17th QWG brought together more than 200 researchers at CERN from 17 to 21 November.

Renaissance

The first part of the workshop naturally reflected this historical and conceptual foundation, focusing on spectroscopy and decays. In recent years, quarkonium spectroscopy has become a driver of new discoveries in QCD. A prime example is the so-called charmonium renaissance, marked by the observation of several exotic states – including the $\chi_{c1}(3872)$, $T_{cc+}(3875)$ and charged Z_c states. These "XYZ" states can't be interpreted as conventional charmonia and their internal structure remains under active investigation both at the experimental and theoretical levels (*CERN Courier* November/December 2024 p33).

Experimental talks in the opening sessions reported on searches for exotic hadrons and their decay channels. Dmytro Meleshko (Giessen University) from the Belle II collaboration reported on excited bottomonium states, placing particular emphasis on the ongoing analysis of the ϒ(10753) resonance, and the experimental signatures that can distinguish between a tetraquark, a hybrid and a S–D mixed bottomonium state. Ilya Segal (Bochum University) presented recent results by the LHCb collaboration on the radiative decay $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$. Yue Xu (University of Washington) illustrated an analysis for fully-charmed tetraquarks in the J/ψ–ψ(2S) channel by the ATLAS collaboration, confirming the X(6900) resonance with high significance.

On the theory side, Abhishek Mohapatra (TUM) described ongoing efforts to extend effective-field-theory methods originally developed for quarkonium to more complex exotic systems using the Born–Oppenheimer (BOEFT) approach, which takes lattice QCD inputs to address the QCD non-perturbative dynamics without assuming a specific internal structure for the exotic states.

The third day turned to production. Some NRQCD calculations predict negative production rates for J/ψ and χ_c mesons at high transverse momentum, a clearly unphysical result. Hee Sok Chung (Gangneung-Wonju National University) highlighted how this problem can be addressed by improving the formal treatment of emissions near the production threshold. New production measurements for J/ψ and ψ(2S) from the CMS and ALICE collaborations were presented, alongside new calculations for the production of the $\chi_{c1}(3872)$ and of the pentaquarks $P_{c\bar{c}}(4312)$ and $P_{c\bar{c}}(4457)$.

The programme then broadened to Standard Model applications, where quarkonium observables can constrain fundamental QCD parameters such as the strong coupling constant and gluelump masses – the gluonic mass contribution in quarkonium hybrid states, as obtained from lattice QCD. Laurids Jeppe (DESY) from the CMS collaboration discussed the enhancement observed around the top–antitop threshold in the invariant mass spectrum, first measured by CMS and later confirmed by ATLAS (*CERN Courier* September/October 2025 p9). In a round-table discussion, participants debated the signal's interpretation in terms of a quasi-bound top–antitop meson or a possible new-physics origin, with both scenarios allowed by the current level of experimental precision, and with the main uncertainties coming from the background modelling. The workshop closed with sessions on quarkonium in media, featuring recent progress in calculating quarkonium transport coefficients from both lattice QCD and perturbation theory.

The field's rapid evolution makes the time ripe for a third, comprehensive QWG document

Progress and puzzles

The discussions across previous QWG workshops crystallised into two foundational documents named "Heavy quarkonium physics" and "Heavy quarkonium: progress, puzzles, and opportunities", that have since trained generations of young physicists and stand as key references for the community. The field's rapid evolution makes the time ripe for a third, comprehensive QWG document to capture the wide range of new and enduring topics that currently define it, including the BOEFT framework as a tool to achieve a unified description of all XYZ exotic states, studies of non-equilibrium quarkonium evolution in the QCD medium, informed by new data from the CBM experiment, and the recent development of new automated event generators for quarkonium production.

The next workshop will take place in spring 2027.

Tommaso Scirpa *Technical University Munich.*

PD2025

Photon detectors light up Bologna

The 7th international workshop on new Photon-Detectors (PD2025) took place from 3 to 5 December 2025 at Bologna's Palazzo d'Accursio, attracting more than 150 researchers working on the development and application of photon-detection technologies. The medieval city-hall library, with its transparent floor above archaeological remains spanning more than two millennia, provided a striking setting for three days of discussion on state-of-the-art detector technologies.

Compelling contrast *At Bologna's medieval city hall, 150 researchers discussed cutting-edge detector technologies above ancient archaeological remains.*

Photon detectors lie at the heart of modern experimental physics. Their ability to measure extremely faint light signals, down to the single photons, makes them indispensable in areas ranging from high-energy and nuclear physics to astroparticle physics, astronomy, medical imaging and emerging quantum technologies. In recent years, rapid progress in devices such as silicon photomultipliers (SiPMs), avalanche photodiodes (APDs) and microchannel-plate (MCP-PMT) detectors has delivered improvements in timing resolution, radiation tolerance and large-scale integration. PD2025 provided a timely snapshot of this evolving field, combining technology-driven discussions with reports from experiments already exploiting these advances.

A significant fraction of the invited talks focused on the latest developments in SiPM technology, which has become the workhorse photodetector for many contemporary experiments. Alberto Gola (FBK) and Edoardo Charbon (EPFL) highlighted progress in custom SiPM and digital SPAD devices, respectively, stressing their improvements in photon-detection efficiency and sub-100 ps timing performance, as well as ongoing efforts to mitigate correlated noise and radiation-induced degradation. These technological developments were complemented by reports from large-scale experiments – such as ALICE3, CMS, DARKSIDE, DUNE, ePIC and JUNO-TAO – in high-energy and astroparticle physics, outlining the status of ongoing developments and the anticipated role of SiPM-based systems in large-area calorimetry, precision timing and Cherenkov imaging in future detectors.

Equally prominent were contributions on vacuum photodetectors and on enabling technologies. Albert Lehmann (University of Erlangen-Nürnberg) reviewed the status and future prospects of microchannel-plate photomultiplier tubes (MCP-PMT), while Angelo Rivetti (INFN Torino) addressed the challenges of fast, low-power front-end electronics capable of handling the ever-increasing channel counts of modern detectors. Modelling of photon-detection devices was discussed by Werner Riegler (CERN), who introduced an analytic description of timing and efficiency in SPADs and SiPMs, clarifying their performance limits for single-photon and charged-particle detection.

Several contributions underlined the increasingly close relationship between academia and industry in photon-detector development, touching on technology transfer, production scalability and long-term reliability, issues that are becoming central as detectors transition from small-scale prototypes to systems comprising hundreds of thousands, or even millions, of channels, such as in the case of the use of digital SiPMs for physics experiments.

The next edition of the conference will take place in May 2027 in Beijing.

Roberto Preghenella *INFN Bologna.*

International Conference on Accelerators and Beam Utilizations

ICABU fishes for accelerator innovations in Pohang

The 27th International Conference on Accelerators and Beam Utilizations (ICABU2025) attracted 300 experts to Pohang, South Korea, from 12 to 14 November 2025. Once a small fishing village, Pohang has developed into a major research hub and now hosts more than 22 R&D institutions. These include Pohang University of Science and Technology (POSTECH), the Pohang Accelerator Laboratory – home to the 3 GeV PLS-II synchrotron radiation source and PAL-XFEL hard X-ray free-electron laser – and the Asia-Pacific Center for Theoretical Physics. ICABU itself began in 1997 as the International Proton Accelerator Workshop, hosted by the Korea Atomic Energy Research Institute. Since 2009, it has grown into an international conference. ▷

Korean innovation *ICABU focuses on accelerator technologies and applications.*

Particle beams are becoming increasingly important to materials engineering. Yunseok Kim (Sungkyunkwan University) discussed how helium-ion irradiation can be used to manipulate hafnium oxide, a material widely employed as an insulating layer in modern microelectronics. In very thin films, hafnium oxide can sustain a switchable electric polarisation that allows information to be stored, known as ferroelectricity. Yet, this state is normally fragile. Kim showed that controlled irradiation with low-energy helium ions can introduce and rearrange atomic-scale defects in the crystal lattice, stabilising the polarised state.

The meeting also addressed applications in nuclear medicine. A team from the Institute for Rare Isotope Science (IRIS) reported progress towards a domestic production route for the therapeutic alpha-emitter actinium-225, based on irradiation of thorium-232 targets with 50–70 MeV protons. Actinium-225 is both expensive and scarce, with current clinical use relying heavily on imports. Even an initial domestic supply would improve clinical availability and support the wider adoption of targeted alpha therapies.

Alongside applications, contributions also focused on progress in accelerator hardware itself. Garam Hahn (PAL) and collaborators reported on a compact 5 T magnet system based on high-temperature superconductors (see p30). Operating without liquid cryogens, it is designed to shift the wavelength of synchrotron radiation, since stronger magnetic fields force tighter beam curvature and raise the characteristic photon energy. The system drew substantial attention from the accelerator-technology community, as it has the potential to increase high-energy photon brilliance by many orders of magnitude.

Alongside applications, there was also a focus on progress in accelerator hardware itself

Beyond technical developments, ICABU2025 also addressed the evolving policy landscape for large-scale research infrastructure. In South Korea, the Korea Large Accelerator Act was recently established to manage, support and govern large accelerator facilities. Dongsoo Jang, deputy director of the Ministry of Science and ICT (MSIT), outlined strategies aimed at improving coordination, access and long-term planning across the country's accelerator infrastructure.

Next year, the event will be hosted by the Korea Multi-purpose Accelerator Complex (KOMAC) and held in Gyeongju. Often described as a "museum without walls," Gyeongju is one of Korea's most historic cities and a symbol of cultural diplomacy, aligning well with the spirit of ICABU.

Moses Chung, **Jaeyu Lee** *and* **Jaehun Park** *POSTECH.*

TOP 2025

The top turns thirty

The 18th International Workshop on Top Quark Physics (TOP2025) brought the top-quark community to Seoul, South Korea, from 21 to 26 September 2025. Hosted at Hanyang University, the event offered 135 experimentalists and theorists a chance to exchange results, discuss open questions and explore the future of top-quark physics.

Heavy celebration *Delegates marked three decades of top physics.*

2025 marked the 30th anniversary of the top quark's discovery by the DØ and CDF experiments at Fermilab. Three decades on, and despite ever-increasing experimental precision, the top quark's properties remain only partially understood. While its mass is now known at the sub-GeV level and its production cross sections agree well with Standard Model predictions, questions persist about its electroweak couplings, its interactions with the Higgs boson, and the detailed structure of top–antitop production at high energies. Because of its large mass and correspondingly strong coupling to the electroweak sector, many in the community continue to view the top quark as a sensitive probe of physics beyond the Standard Model.

The conference opened with an inspiring keynote address by Juan Antonio Aguilar Saavedra (IFT Madrid), who explored the connections between top-quark physics and quantum science and technology. A notable example is the recent observation of quantum entanglement in top-quark pair production by the ATLAS and CMS experiments, which has opened a promising new line of research linking collider physics with concepts more familiar to quantum information researchers. Entanglement can be measured in the top–antitop system because top quarks decay before hadronisation takes place, allowing direct access to their spin correlations.

Top physics is currently enjoying a golden era. Last year, the CMS collaboration reported an excess near the top–antitop threshold (*CERN Courier* May/June 2025 p7), later confirmed by ATLAS with a significance of 7.7σ above the background predicted by perturbative quantum chromodynamics (*CERN Courier* September/October 2025 p9). This excess is consistent with expectations from non-relativistic quantum chromodynamics, an effective theory that describes the dynamics of heavy quark pairs near threshold and with simplified models involving a pseudoscalar "quasi-bound-state", called toponium.

During a mini-workshop dedicated to toponium, Benjamin Fuks (LPTHE) presented an intriguing scenario in which the excess could be explained by two contributions: one from a top–antitop bound state and another from a beyond-the-Standard-Model signature, although the data are also compatible with Standard-Model-only components.

The next edition of the TOP conference will take place in Antalya, Turkey, from 5 to 9 October 2026.

Tae Jeong Kim *Hanyang University,* **Roberto Tenchini** *INFN Pisa and* **Malgorzata Worek** *RWTH Aachen University.*

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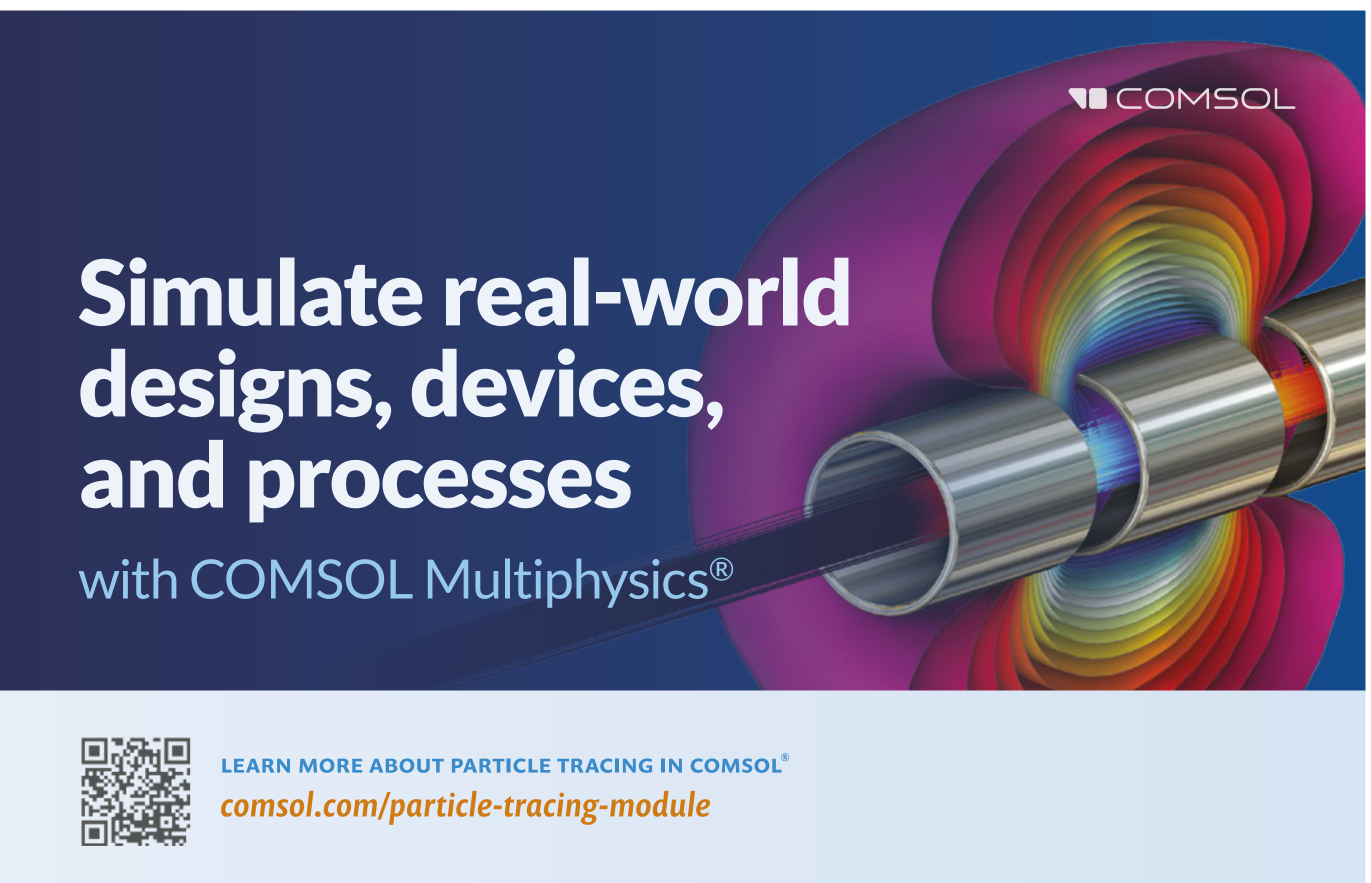


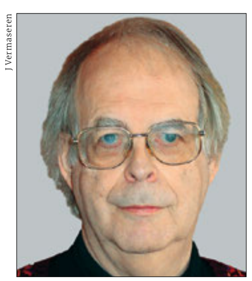
THE MOST IMPORTANT TOOL YOU'VE NEVER HEARD OF

Commercial software can't keep pace with experimental precision when it comes to large-scale computer-algebra calculations in quantum field theory. Maintained by a single theorist for decades, FORM is often the only option, underpinning a remarkable fraction of papers in high-energy physics. The *Courier* interviewed key figures from its past, present and future.

A Dürer, Melencolia I, 1514. Public domain. Image adapted by the editors

FORM before meaning Melencolia I *(1514) by Albrecht Dürer is often read as an allegory of mathematical thought confronting its limits: the tools of calculation.*

Jos, FORM has been at the heart of precision calculations for decades. But the story starts earlier, with Martinus Veltman (see "The pioneer" image). What was he trying to do?



J Vermaseren

The inventor *Jos Vermaseren, Nikhef.*

Jos Vermaseren In 1963, Veltman was interested in the renormalisation of Yang–Mills theories. He wanted to check whether certain models produced unphysical infinities that could not be removed. These calculations are a lot of work: you don't do that by hand. So he built himself a program, which he called Schoonschip, to do that calculation.

What was computing like in those days?

Vermaseren Very primitive by current standards. When Veltman started at CERN, they had a CDC 6600, which was for a while the biggest computer in the world. But you had to share it with maybe a few thousand people, so you had to wait for your program to come out (see "The first supercomputer" image). At Nijmegen University in the early 1970s, we had an IBM computer where you had to hand in your computer cards, then wait a few hours for output. If your program was big, it would only run during the night. Make a typo, and you'd find out the next day that nothing had happened. That kind of primitive computing was left behind when personal computers came in the 1980s. I bought an Atari ST in late 1985, and the fun part was that at Nikhef, the Dutch National Institute for Subatomic Physics, we had a CDC 173, but my Atari had more memory! That was quite amazing. Every decade, the computers became more powerful, and with that the calculations became larger. I've been involved in calculations where the intermediate formulas were terabytes big. That is kind of hard to imagine. But if you put in enough effort and enough checking, you still get

THE AUTHOR

Interview by **Davide De Biasio** *CERN.*

FORM enabled calculations that would never have been possible with any other tool

the correct answer. There is simply no way you could ever do that by hand. No way. That's why we absolutely need these algebra programs.

Where did Schoonschip – I apologise for my pronunciation – fit in the landscape of early computer algebra?

Vermaseren Ah, Veltman did that intentionally to tease all the foreigners. [chuckles] There were already ideas about algebraic software in the 1960s – Feynman was suggesting something in the 1950s – but nothing really usable for physics calculations when Veltman started. Around the same time, Tony Hearn started with the REDUCE program, which was formally more elegant but less powerful. Those were the main players for a while, but they all had limitations. REDUCE wasn't nearly as fast as Schoonschip and couldn't handle very big expressions. Schoonschip's limitation was that Veltman had written it in assembly, so you could only use it if you had the correct computer.

How did you enter this story?

Vermaseren I was very much used to Schoonschip and was quite a good programmer with it, but CDC computers were expensive and being phased out. So there I was, faced with the idea that I wouldn't have Schoonschip any longer. I also wanted to make a giant system for doing automated calculations that would need computer algebra in a more flexible way than Schoonschip provided. If I needed new features, I'd have to go to Veltman and wait probably a year. Veltman had built in what he needed and was so nice to provide other people with his program. But if you get a free program, you shouldn't come up with too many demands. The conclusion was that if I really wanted to make what I needed, I would need my own program.

Schoonschip had a couple of weak points. One was the sorting mechanism, which meant that with very large expressions, the program became outrageously slow. The handling of functions and function arguments was not flexible at all. And then there was the whole business of computer availability. I asked Nikhef management if they would allow me to take some time out to work on it, and they thought it was a good idea, so my back was covered.

This may resonate with early-career researchers who want to build long-lived tools today. What would you tell them?

Vermaseren You have to put in an enormous amount of time, and if you want to get a job in physics, you can only get credit for that if at the same time you use what you make for good calculations that draw attention. You need physics publications. If you go in as a postdoc to just write useful software, you have a problem, unless somebody has already promised you a decent job.

People like to count citations, and organisations usually look at citations in the first two years. But when you have a paper about a calculation, the opposite usually occurs. In the beginning you don't get very many citations because people aren't using it yet. I have a lot of papers that started with hardly anything, and then after a few years they pick up and keep growing. But for a postdoc, that is a disaster.

University of Zurich

The calculator *Thomas Gehrmann, University of Zurich.*

Thomas Gehrmann I'd add to this that recognition for contributions to scientific software is usually underrated when evaluating a researcher's performance. It's not recognised at the same level as publications or plenary talks. We should really try to communicate to senior people making funding decisions the importance of the whole body of scientific output. Scientific software development is very useful to the community but much less easily quantifiable than citations.

Vermaseren Although, for universities it is very nice to eventually have somebody there who is generating a lot of citations and educating people to do big calculations, they just don't recognise it. The world of theory software development needs more institutional support.

Thomas, can you describe FORM's impact on particle physics?

Gehrmann FORM enabled calculations that would never have been possible with any other tool. At each given moment in time, ever since the inception of FORM version one in the late 1980s, early 1990s, the cutting-edge calculations were usually done with FORM. Many of these calculations were redone a few years later with other tools, but what had changed was that computers became more powerful, had more memory, more storage space and were faster, so you could also do similar calculations in Mathematica or Maple. However, FORM was always at the avant-garde of the calculations.

In groups that are performing multi-loop calculations, the first-week's task for a new student is usually: learn FORM on a simple example, compute the scattering matrix elements in FORM to get you used to its environment. For students working on cutting-edge projects – the next loop on a scattering amplitude, the next order on a benchmark cross-section – it's made clear from the very onset that FORM is the tool to be used, because it's only with this tool that there's a realistic chance to get through the project in a finite amount of time.

Can you give an example of a particularly important calculation?

Gehrmann The LHC is a proton–proton collider, but the hard scattering processes underlying the collisions are not proton–proton but collisions of quarks and gluons. To make precise predictions for anything you observe at the LHC, you need to know how quarks and gluons are distributed inside the proton. These parton distribution functions are extracted from combined fits to huge sets of data from different experiments at vastly different energy scales. I mean, from a 35 GeV electron beam at SLAC up to multi-TeV collisions at the LHC. That's almost three orders of magnitude.

Parton distributions evolve with energy scales via the Altarelli–Parisi evolution equations: knowing the Altarelli–Parisi splitting functions to sufficient theoretical precision is one of the cornerstones enabling these fits. The calculation that enabled the current level of precision was done in the early 2000s by Jos and his collaborators Sven Moch and Andreas Vogt. It went alongside the development of FORM version three, and was a crucial result for the entire LHC physics programme.

Looking ahead to the High-Luminosity LHC and a potential FCC, how important is FORM's continued development?

Gehrmann Both are extremely high-statistics, high-luminosity machines. They'll give us measurements at a statistical precision never achieved before in a collider experiment. Researchers need to be empowered with proper tools to make the most of the physics, with a whole new generation of precision calculations. FORM has grown with the field, due to both the ingenious design choices Jos made at inception, when a lot was already conceived in a scalable fashion, and through continuous development addressing bottlenecks. It's very hard to predict what will be the bottlenecks for High-Luminosity LHC calculations, and it's even harder for the FCC. But they will require adaptations to how we do computer algebra. And, of course, committed developers.

Josh, you've been working on FORM 5. Why is a major release necessary now?

University of Liverpool

The developer *Joshua Davies, University of Liverpool.*

Joshua Davies Being able to release new versions helps convey to the community that there's progress. Most users stick to a released version rather than rebuilding from GitHub. Being able to say "this is a new version with well-tested new features" is important for users to trust it for their work.

What are the major new features?

Davies The first is a Feynman graph generator built into FORM, from a collaborator of Jos, Toshiaki Kaneko. FORM now has an interface to this generator that lets you produce graphs from within the code without relying on external tools. It's written in a more flexible way, which lets you add features or modify it much more easily than other tools. I also put in an interface that improved polynomial arithmetic performance. This is increasingly necessary now that people study processes with higher multiplicities or more mass scales. You end up with computations depending on many more variables than in the past.

Vermaseren The third main feature is the ability to have floating-point coefficients as opposed to rational numbers. Modern algorithms still can't determine everything through normal calculations. You're restricted to doing certain parts in arbitrary-precision floating point. But these capabilities have other good features. If you want to do a calculation for the LHC, in the end these run in Monte Carlo integration programs: you take a very big formula and sample it billions of times. But how numerically stable is that formula? If I have floating-point capability, I can figure out the numerical stability before I evaluate it billions of times in another program. I can determine whether I'll run into disasters.

The first supercomputer *The remote input/output station to CERN's CDC 6600 in 1972. The card reader on the left and the line printer on the right were operated by programmers on a self-service basis.*

What does the future hold for FORM's development?

Davies It seems unlikely that anyone is suddenly going to fund a permanent job where the main role is looking after FORM. But if we can foster an environment where postdocs or PhD students feel they can contribute and be recognised for it, and it helps them apply for their next position, this needs to be the way packages like FORM are developed. I'm a postdoc trying to apply for longer-term positions, but the future of FORM isn't secure. I've put in a lot of effort, alongside Coenraad Marinissen and Takahiro Ueda, to get FORM to version five, but it's not guaranteed people working on FORM will be able to continue.

Do we need a different institutional framework to support this kind of development?

Davies We need more recognition from the people who decide where funding goes for contributions to software work. On the experimental side, there are people whose job is the LHC software that goes into the analysis chain. We don't really have this equivalent on the theory side. People work on software alongside their physics projects, and you always have to have physics results coming out if you want to continue to get jobs. No one can truly focus one hundred percent on the tools. What would really help is if contributing to a project like FORM was

Recognition for contributions to scientific software is usually underrated when evaluating a researcher's performance

The pioneer *Martinus Veltman (1931–2021) was a Dutch theoretical physicist who, together with Gerard 't Hooft, elucidated the quantum structure of electroweak interactions and showed how to renormalise the underlying gauge theory, enabling precision calculations that helped make the emerging Standard Model predictive. For this work, they shared the 1999 Nobel Prize in Physics. Beyond the core theory, Veltman was a pioneer of computer-assisted quantum field theory.*

clearly recognised as a valuable scientific output in its own right, alongside physics papers. If young researchers felt that contributing to core tools genuinely strengthened their career prospects rather than putting them at risk, it would completely change how sustainable projects like this are.

Gehrmann This is exactly right. Over the years, it was crucial to have Jos as a developer in the background regularly talking to the community, getting feedback: "This is the current bottleneck we're up against." But that only worked because Jos could actually focus on it. We've been trying to improve community involvement over the past five years with dedicated workshops, bringing together developers with users pushing FORM to their limits and students coming into the field. This format has started to take off successfully. At these workshops, in the mornings the senior developers explain the internal structure of the code. And then in the afternoons people work on concrete exercises like bug fixes or small features, almost like a hackathon. But this is a bottom-up initiative. It needs a top-down approach to make the project sustainable and create career perspectives for FORM developers like Josh. I can only hail the visionary decisions Nikhef management made 40 years ago when they decided to leave Jos alone for a few years to develop version one. Without institutional recognition that creates actual career paths for theory software developers, we risk losing the very people who can secure FORM's future – and with it, our ability to make the most of the next generation of colliders. ●

Frontier superconductors *A closeup of a Nb_3Sn wire and a 4 mm-wide REBCO tape. Both conductors can carry 500 A, but REBCO, a high-temperature superconductor, can withstand fields well in excess of 20 tesla at temperatures above 10 K. Credit: M Struik*

SUPERCONDUCTORS FOR THE ENERGY FRONTIER

Ezio Todesco charts the future of high-field dipole magnets – a technology set to advance the boundaries of high-energy physics and the societal applications of superconductivity.

Fill hundreds of copper tubes with a powder of niobium and tin, and then stack them in the form of a cylinder. Draw this out into a composite wire hundreds of kilometres long and barely a millimetre in diameter. Braid it into a rectangular cable and insulate it in fibreglass. Wind it into coils, bake for a week at precisely 650 °C and impregnate with resin. Assemble them with sub-millimetre precision under a compressive stress of one tonne per square centimetre, cool the magnet to a few kelvin and power it with tens of thousands of amps. This is not alchemy. This is a possible recipe for a Nb_3Sn magnet.

Whether made of Nb_3Sn or higher-performance superconductors, such devices promise to substantially improve the discovery potential of hadron colliders. Since their energy reach scales as the dipole field times the size of the tunnel, each additional tesla directly expands the energy frontier.

What makes these magnets unique is their compactness. Superconducting coils can carry a current density of order 500 A/mm^2, a factor 100 higher than what can be tolerated by copper with active cooling. A magnet based on superconductivity can therefore have coils that are narrower and lighter.

No application of superconductivity pushes this limit harder than an accelerator magnet. Larger coils mean larger magnets and an unaffordably large tunnel to accommodate them. Accelerator magnets must therefore be highly optimised in space and cost – the capsule hotels of superconductivity – and this extreme optimisation creates opportunities for spinoff applications, from lightweight motors for electric aircraft to power transmission beneath the pavement of a crowded metropolis. Superconducting accelerator devices have already paved the way for societal applications in medical imaging and advanced accelerators

THE AUTHOR
Ezio Todesco
CERN.

for cancer therapy, and the field continues to benefit from strong research synergies with fusion tokamaks, though their toroidal coils don't need to push the limits of current densities in the same way.

Superconductors also save energy. At the LHC, more than a thousand niobium–titanium alloy (Nb–Ti) superconducting dipoles are powered by only 40 MW. This is much less than what is consumed by the LHC's injectors.

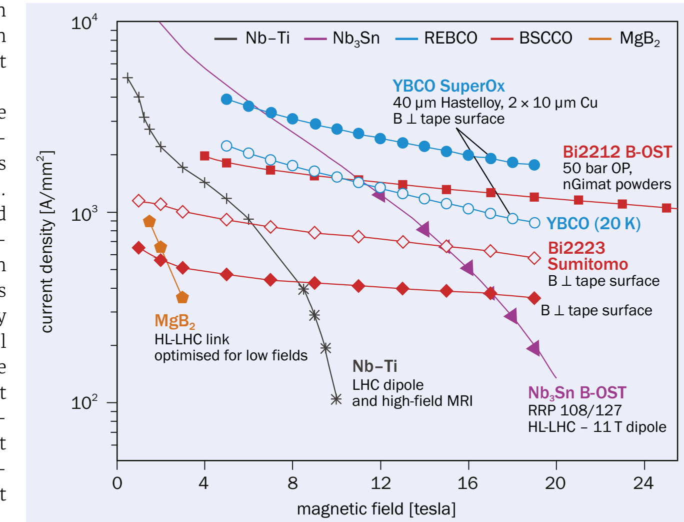
As dipoles based on Nb–Ti superconductors are limited to a maximum achievable field of nearly 10 tesla, corresponding to an operational field of about 8 tesla with acceptable margins, accelerator physicists and engineers are exploring the use of better superconductors to roughly double their field. The options include Nb_3Sn, which will soon be used in an accelerator for the first time at the HL-LHC, and "high temperature" superconductors that promise much higher performance and a simplified accelerator infrastructure. But dipoles are much more difficult to design than solenoids. Though 30 tesla solenoid magnets are already available on the market, no one has yet succeeded in building a 20 tesla dipole magnet.

Shear complexity

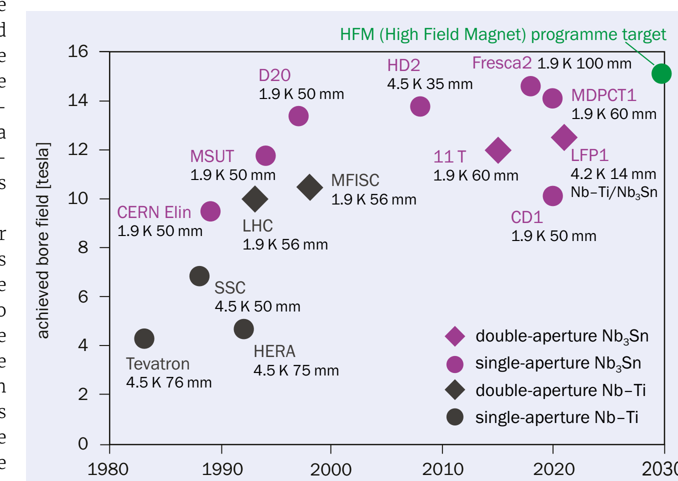
An accelerator dipole poses several challenges compared to a solenoid. While a solenoid's current loops generate an axial magnetic field, a dipole must use vertically separated coils to generate a vertical magnetic field; for the same total coil thickness and current density, a solenoid can provide twice the field strength of a dipole; and the field distribution and the forces exerted on the coils are much more difficult to control. In a solenoid, electromagnetic forces are perpendicular to the conductor, but in a dipole they push the coil towards the midplane and outwards, with a two-dimensional distribution that includes shear stresses.

The engineering challenge is increased by the need for dipoles to operate precisely during the ramp, when particles gain energy with every turn after being injected into the collider, requiring increasingly strong magnetic fields to bend them. To ensure that accelerator physicists can make tightly focused beams collide with high luminosity inside the experiments, the field must be uniform to better than one part in 10^4 across two thirds of a dipole's aperture as the field increases up to a factor 15. These challenges are not present in either medical-imaging magnets or the toroidal coils used for fusion, which must operate at a constant current, though the toroidal coils used for fusion are subject to rapidly varying external magnetic fields.

In the context of the 2026 update to the European Strategy for Particle Physics (ESPP), advanced high-field dipole magnets would be needed by the hadron-collider phase of the Future Circular Collider (FCC-hh) and the proposed muon collider. Due to its exceptionally large and unstable beams, a muon collider would also require a kilometre-long channel of superconducting solenoids with alternating gradient, and a final superconducting cooling solenoid with a strength of roughly 40 tesla before the collider ring. These challenges are complementary to what is required by the FCC-hh, and the community is devoting significant research and development in this direction.



Superconductors for high-field accelerator magnets *Constant temperature (4.2 K unless specified) slices of the "critical surface" of several superconductors. Superconductivity is lost for higher values of current density and surface magnetic field, and a balance must be struck between compactness (high current density) and field strength.*



Niobium dipoles *The evolution of the achieved field in Nb–Ti and Nb_3Sn dipoles.*

The targets initially set for the FCC-hh in 2014 were based on round numbers: a 100 km tunnel and a centre-of-mass energy of 100 TeV. This required 16 tesla dipoles, one or two tesla above what can be done with adequate margins and costs with present technology. After a decade of studies, the tunnel size was reduced to 91 km to fit geological constraints, and the field was brought down to 14 tesla, allowing a centre-of-mass energy of 85 TeV after some optimisation of the lattice. This 15% reduction in the energy in the centre-of-mass frame has had a major effect on the energy consumption of the collider, as synchrotron radiation reduced by 50%. A similar tuning occurred for the

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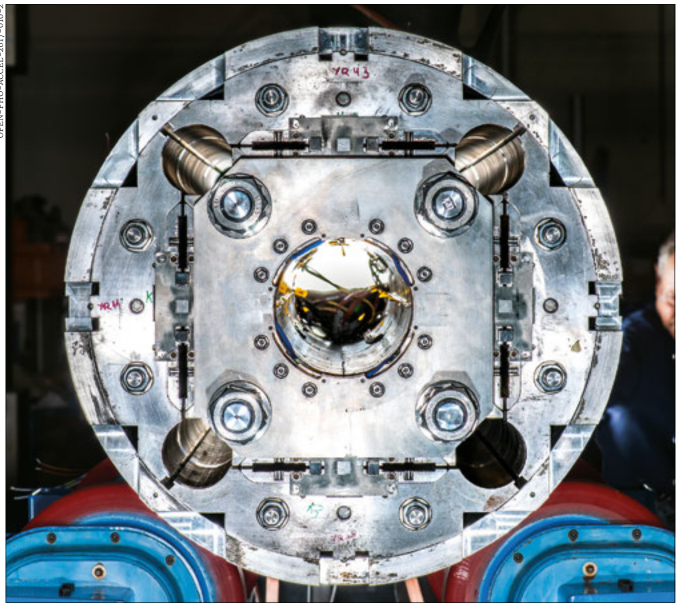
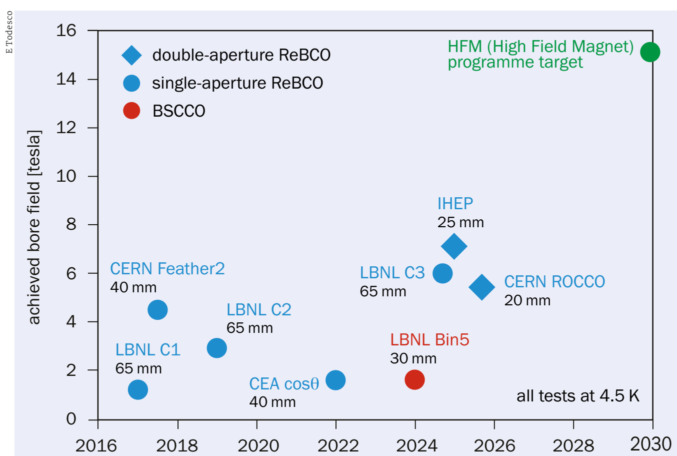


Nb_3Sn quadrupoles *The cross section of one of the new final-focus quadrupoles for the High-Luminosity LHC. Operating at peak fields of up to 11.5 tesla, the quadrupoles will provide significantly stronger focusing and larger apertures than the Nb-Ti magnets used in the LHC, enabling tighter beam squeezing and higher collision rates. When the upgraded collider comes online in 2030, these quadrupoles will become the first Nb_3Sn magnets to be used in a working accelerator.*



HTS dipoles *The evolution of the achieved field in HTS dipoles.*

LHC, which was initially imagined at 16 TeV with 10 tesla magnets rather than today's 13.6 TeV and 8.1 tesla.

The baseline design for the FCC-hh dipole magnets is Nb_3Sn technology operated at 1.9 K, though the ESPP documents also note three other possibilities: hybrid magnets that use substitute Nb-Ti for Nb_3Sn in the lower field regions; operation at 4.5 K; and a high-temperature-superconductor option operating between 4.5 and 20 K with magnetic fields in the range 14 to 20 tesla.

The Nb_3Sn path

Nb_3Sn was discovered a few years before Nb-Ti and has the advantage of providing current densities in excess of 500 A/mm^2 up to 16 T (see "Superconductors for high-field accelerator magnets" figure). After 35 years of research, fields have now reached 14.5 tesla, close to the 15–16 tesla target needed to have magnets operating at 14 tesla in the FCC-hh with adequate margins (see "Niobium dipoles" figure). The main goal today is to produce a double-aperture short-model Nb_3Sn magnet with all features specified in the FCC-hh design. This should be achieved by 2030 and then scaled up in length.

A key challenge is to reduce the quantity of Nb_3Sn, thereby lowering both the cost and hysteresis losses during field ramping. As the magnetic field changes, currents are induced within the superconducting filaments, leading to energy dissipation that must be carefully controlled. Minimising these losses is one reason for the complex, multi-filamentary architecture of superconducting wires. The smaller filaments of Nb-Ti can significantly reduce the losses, and Nb-Ti costs five to 10 times less than Nb_3Sn.

A second engineering challenge is to achieve a mechanical structure capable of keeping the coil in compression during powering but not overstressing it. The stress limits of Nb_3Sn are of the order of 200 MPa, and the required precompression for a 14 tesla dipole is about 150 MPa.

Another challenge of the low-temperature path would be logistical: the production of roughly 5000 tonnes of Nb_3Sn. This corresponds to a 1 kA cable from the Earth to the Moon at a cost of several billions of dollars. These numbers are an order of magnitude larger than what was needed for the Nb-Ti coils of the LHC.

Despite these challenges, Nb_3Sn technology is now well established for small series, and will soon play a key role at the High-Luminosity LHC – the technology's first use in a working accelerator, though for focusing beams rather than bending them (see "Nb_3Sn quadrupoles" figure). But newer superconductors may well prove competitive.

The high-temperature path

In 1986, Johannes Georg Bednorz and Karl Alexander Müller announced the discovery of superconductivity above 35 K, something not foreseen by theory, and well above the boiling point of liquid helium. "High-temperature" superconductors (HTS) not only remain superconducting at high temperatures, in many cases above the boiling point of liquid nitrogen (though at 77 K HTS performance is not yet adequate for our needs), but also at high fields. HTS solenoids have been constructed with fields up to 40 tesla, and though the problem of degradation is not yet totally solved, progress has been outstanding.

Three families of superconducting conductors are currently available or emerging on the market: rare-earth barium copper oxides (REBCO), bismuth strontium calcium copper oxides (BSCCO) and iron-based superconductors (IBS).

REBCO is of strong interest in the world of fusion. Billions of dollars of investment have reduced the cost by more than an order of magnitude in the past decades. REBCO comes in tapes (see "Frontier superconductors" figure). A 12 mm-wide tape has thickness of 0.1 mm and can carry 1500 A at 4.5 K, or about half that at 20 K. 20 tesla peak field coils have been built and tested for fusion applications, and private investors plan to build reactors that are much more compact than ITER, which is based on Nb_3Sn technology.

Manufacturing REBCO coils is greatly simplified compared to Nb_3Sn as the tape needs no temperature treatment; but the technology used to wind the tapes is not easy to adapt for accelerator dipole magnets, which are radically different from the toroidal coils designed for tokamaks. The challenge here is not to develop a conductor for accelerator magnets, but to adapt our magnet designs to this amazing tape. There is a long way to the 15–16 tesla target, but the potential is huge, with progress being made in Europe, the US and China (see "HTS dipoles" figure).

And what of the other HTS superconductors? BSCCO has the great advantage of round wires, but must be treated at 800 °C and it does not profit from synergies with fusion. At present, this path is only being pursued in the US, with achieved fields of just 1.8 T. IBS is being actively developed in China and Europe, but its current density has not yet matched the performance of REBCO, and the best results were obtained for tapes rather than wires.

HTS would allow operation at 20 K, with a simplification of the cooling scheme and a possible reduction in the energy consumption of the collider, though at 85 TeV half of the heat loads are due to synchrotron radiation, which does not depend on the operational temperature of the magnets. Moreover, REBCO tape has a single filament, as wide as the tape, and therefore the saving from the higher operational temperature could be compensated by larger heat losses. Estimating the energy balance is far from trivial: do not draw easy conclusions!

REBCO is of strong interest in the world of fusion

Optimal solution

Addressing these challenges is the work of the High Field Magnet (HFM) programme, an international collaboration with 15 institutes steered by CERN that was founded in 2021. HFM is exploring multiple different designs to find the optimal solution, from the most classical to the more exotic, and novel ideas should be explored in parallel to the most conservative paths. Though there are major challenges ahead, solving them promises societal benefits via a number of diverse spinoff applications.

High-field magnets remain one of the hardest problems in applied superconductivity. The next decade will be decisive for understanding the feasibility and cost of the FCC-hh. ●

Further reading

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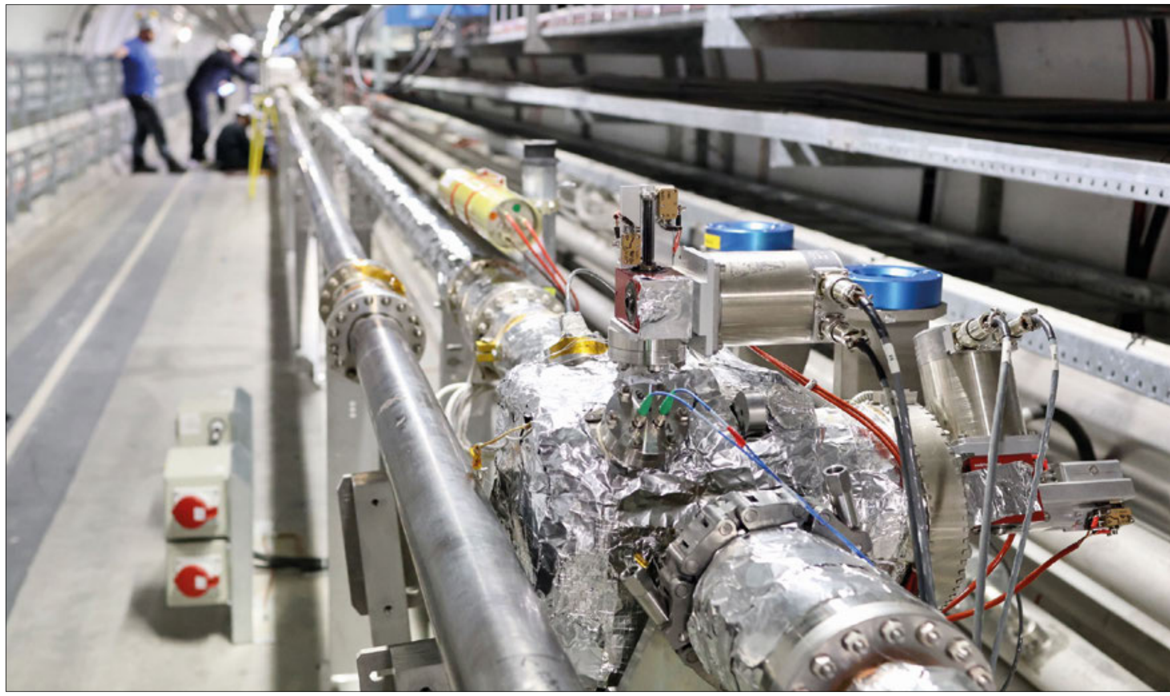
NEW DIRECTIONS FOR BENT CRYSTALS

Long-established in accelerator physics, bent crystals are now being explored as tools to measure the fundamental properties of short-lived charm baryons.



S Redaelli/CERN-PHOTO-202503-098-2

Halo extraction *The first bent crystal of the TWOCRYST experiment extracts protons from the halo of the circulating LHC beam and directs them onto a second bent crystal 120 metres downstream, leading to the first demonstration of double channelling of TeV particles last year.*

Soviet accelerator physicists were the first to bend particle beams using bent crystals. Under controlled conditions, the technique can produce beam deflections equivalent to those generated by magnetic fields of hundreds of tesla, far exceeding the limits of superconducting magnets.

Even more strikingly, genuinely enormous magnetic fields also arise in a more subtle way. At LHC energies, the electric fields between crystal planes are Lorentz-boosted into effective magnetic fields of hundreds to thousands of tesla in the rest frame of passing particles. This opens up some unique possibilities for particle physics: probes of new physics once limited to long-lived particles in conventional, orders-of-magnitude weaker magnets may now come within reach for short-lived baryons.

A bobsleigh on a track

Energy loss and multiple scattering are the fate of most charged particles in matter. If carefully aligned to particle trajectories, crystals can be an exception: as positively charged particles fly past nuclei in the planes of the crystal lattice, they experience an averaged electrostatic potential that channels them between the crystal planes. Provided they don't have enough transverse energy to cross the potential barrier to a neighbouring crystal plane, the particles oscillate between the atomic planes like a bobsleigh on a track (see "Guided paths" figure). If the crystal is mechanically bent, the entire track curves, steering the particles along with it.

Crystal channelling was predicted in simulations by Robinson and Oen in 1963, experimentally confirmed the same year by Piercy, and given its theoretical founda-

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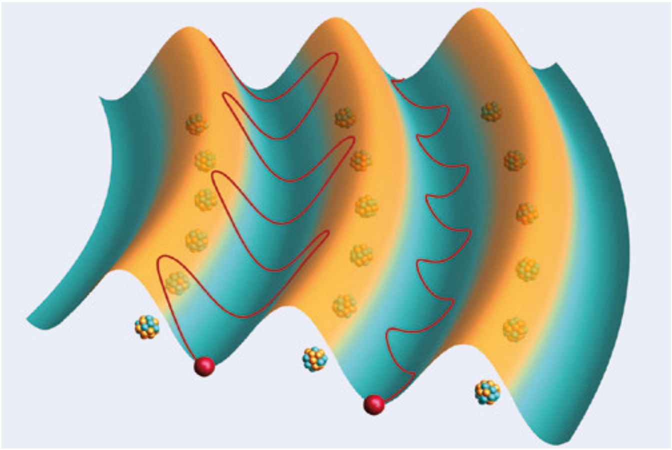


Guided paths *Positively charged particles (red) can be "channelled" along the trough of the electrostatic potential (shaded surface) between planes of nuclei in a bent crystal, achieving a far stronger curvature than conventional magnets. In this artist's impression, length scales have been adjusted for clarity.*

tion by Lindhard in 1965. The idea of using bent crystals for beam control was first proposed in 1976 by Tsyganov. Proof-of-principle experiments at JINR Dubna in 1979 demonstrated the channelling of 8.4 GeV protons, achieving deflections equivalent to an 81-tesla magnetic field, and practical applications followed soon after.

A key modern application of bent crystals is the selective extraction of particles from the beam halo rather than the beam core, to produce a secondary beam. Crystal-based beam extraction was demonstrated up to 8.4 GeV at JINR in Dubna in 1984, then with higher energy protons at IHEP Protvino in 1989, and at CERN's Super Proton Synchrotron (SPS) in 1993. Later in that decade, Fermilab's Tevatron extracted beam particles using crystals at a record energy of 900 GeV.

Bent crystals are also used in modern accelerators' collimation systems to deflect stray particles in the beam halo into shielding blocks that safely absorb them. The exploration of bent crystals for beam collimation began in the 1990s at Brookhaven National Laboratory and Fermilab, but the field underwent a step change in 2006 with the experimental observation of volume reflection at Petersburg Nuclear Physics Institute. This advance was enabled by new manufacturing techniques for high-quality bent silicon crystals. Predicted in the mid-1980s by Taratin and Vorobiev, volume reflection occurs when a particle is coherently deflected by the collective field of bent crystal planes without becoming trapped in a channel, effectively rebounding from the planar potential barrier.

Bent crystals could open new frontiers in particle physics at the LHC

Crystal clear

These breakthroughs motivated the UA9 Collaboration and experts in beam collimation to undertake a systematic programme of crystal-based beam manipulation at the SPS. This effort culminated in 2023, when crystal collimation became an operational reality at the LHC (see "Heavy-ion collimation" figure).

This technique addressed a critical limitation of heavy-ion operation: conventional amorphous collimators fragment heavy nuclei into lighter ions, some of which escape the collimation system and can quench downstream superconducting magnets. Bent crystals, by contrast, coherently and deterministically steer beam halo particles onto dedicated absorbers. As a result, crystal collimation was demonstrated to reduce heavy-ion beam losses at LHC magnets by factors of 5 to 13 compared with standard collimation.

New frontiers

The success of TeV-scale beam collimation at the LHC laid the groundwork for another ambitious goal: using bent crystals in the LHC not just to steer beams, but also to probe the spin of short-lived particles. In the intense internal fields between crystal atomic planes, a particle's spin behaves much like a spinning top in a gravitational field. Rather than simply tipping over, the top's angular momentum rotates slowly – precesses – under the action of a torque. In close analogy, the magnetic moment of a relativistic particle traversing a bent crystal precesses under the torque generated by the effective magnetic field experienced in its rest frame.

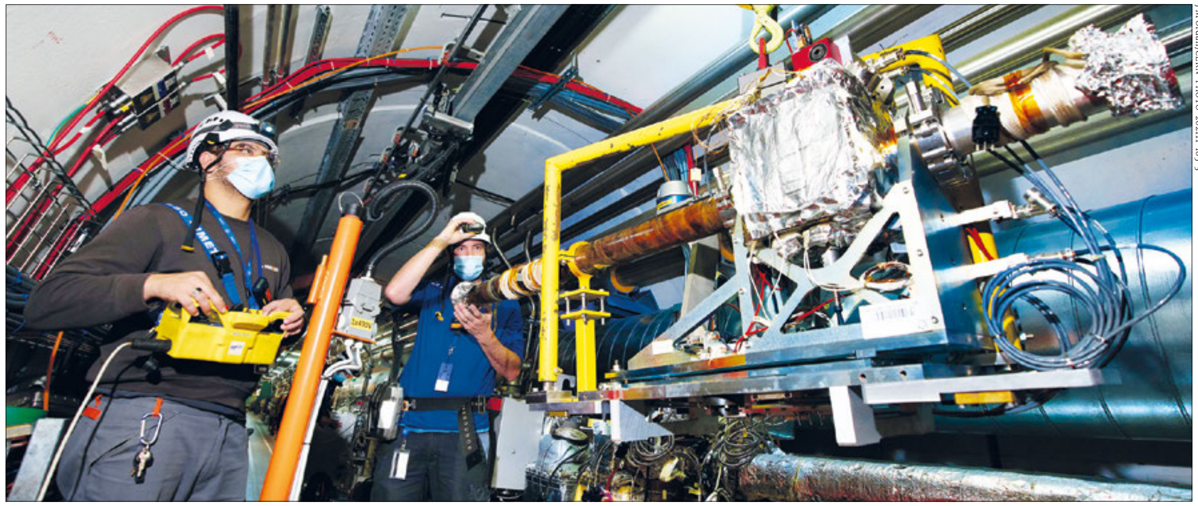
In 1992, the E761 collaboration used the fixed-target proton beam from the Tevatron to perform the first experimental demonstration of the effect by measuring the magnetic moment of the Σ^+ hyperon (uus). This pioneering work used two 4.5 cm-long bent silicon crystals to induce spin precession, proving that the technique could effectively substitute for massive conventional magnets.

Bent crystals could open new frontiers in particle physics at the LHC. The TWOCRYST collaboration is exploring whether the technique can be extended to study the spin of short-lived charm baryons. The idea dates back to 1996, when Samsonov extended the E761 findings to charm baryons and demonstrated that despite their extremely short lifetimes, the intense effective fields of bent crystals could induce measurable spin precession. In 2016, Scandale and Stocchi proposed to use this technique to measure the magnetic dipole moments of charm baryons at the LHC.

The lightest charm baryon, the Λ_c^+ (udc), has an extremely short lifetime of roughly 200 femtoseconds. Even at 1 TeV, it only travels a few centimetres before decaying. The magnetic fields needed to study its spin precession cannot be provided by conventional magnets, but are well within reach if bent crystals are used. If produced at a fixed target, a clean sample of its decays to a proton, a kaon and a pion can be obtained via tracking and invariant-mass reconstruction, with decay angles yielding spin information.

Such measurements promise a unique opportunity to explore QCD at the interface between heavy and light quarks. Measurements of its spin precession would also provide exceptional sensitivity to a possible electric dipole moment – a potential signature of physics beyond the Standard Model. The ALADDIN (An LHC Apparatus for Direct Dipole moments INvestigation) experimental proposal aims to measure the electromagnetic dipole moments of charm baryons, the Λ_c^+ and the Ξ_c^+ (usc), using a double-crystal scheme in the LHC. In this concept, a first bent crystal extracts a small fraction of the LHC beam halo and guides 7 TeV protons onto a fixed target located inside the LHC vacuum pipe, producing, amongst other particles, the charm

J M Ordan/CERN-PHOTO-202111-185-3



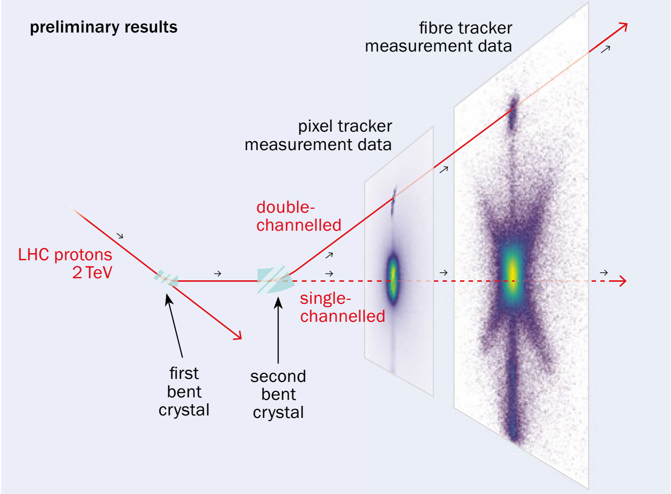
Heavy-ion collimation *A crystal collimator is installed at the LHC, where it is used to deflect halo particles onto an absorber located roughly 90 metres downstream.*

baryons of interest. The particles would then impinge on a second bent crystal, whose intense inter-planar fields would induce a measurable spin precession.

Such an experiment must deal with challenging demands on the crystal alignment. Channelling only occurs if particles enter a crystal within a narrow angular range, known as the Lindhard angle, which decreases with increasing beam energy. At TeV energies in the LHC, this angle is only a few microradians, meaning that misalignments far smaller than the width of a human hair over a metre are sufficient to suppress channelling entirely. This alignment will be particularly challenging for ALADDIN, which will rely on protons that have scattered off the primary collimators.

TWOCRYST was installed at Insertion Region 3 (IR3) in early 2025 (see "Halo extraction" figure). The experiment marks a significant leap in complexity compared to previous LHC crystal tests. Last year, the experiment successfully channelled LHC protons through two crystals (see "Double channelling" figure). These measurements marked the first controlled deployment of a double-crystal setup in the LHC, demonstrating the technique at 450 GeV, 1 and 2 TeV – a new world record, surpassing the 270 GeV achieved by the UA9 collaboration at the SPS and corresponding to an equivalent magnetic field of 600 tesla. Preliminary analyses of the recorded data indicate that more than 20% of protons were channelled successfully at 1 TeV.

TWOCRYST/J V Dos Santos



Double channelling *In TWOCRYST, a 4 mm splitting crystal deflects protons by about 50 microradians, followed 120 metres downstream by a 5 mm fixed tungsten target and a 7 cm-long precession crystal with a bending angle of 7 milliradians. Downstream of the crystals, movable vacuum-sealed "Roman pots" house a silicon pixel detector based on the LHCb VELO and a fibre tracker provided by the ATLAS–ALFA collaboration.*

Bent crystals have come a long way since the pioneering experiments at JINR Dubna in 1979. TWOCRYST's demonstration of double-channelling at a record energy of 2 TeV represents an important step toward using the technique for precision particle-physics measurements with bent crystals at the LHC.

Measurements of spin precession have long played a central role in particle physics, providing deep insights into fundamental interactions and symmetries. The anomalous magnetic moments of the proton and neutron – measured in the 1930s and 1940s – remained unexplained for decades until the emergence of the quark model in the 1960s. While conventional magnet-based techniques remain highly effective for relatively long-lived particles such as the muon (*CERN Courier* March/April 2025 p21), particles as short-lived as charm baryons have so far remained experimentally inaccessible. The results from TWOCRYST suggest that bent crystals may allow the first direct experimental probe of electromagnetic dipole moments in charm baryons, opening a new window on QCD dynamics and offering a sensitive test for physics beyond the Standard Model. ●

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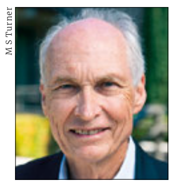
OPINION VIEWPOINT

The revolution ahead

Michael S Turner argues that the next breakthrough in particle physics and cosmology may be just around the corner.



M S Turner

Michael S Turner *is an adjunct professor of physics and astronomy at UCLA and an emeritus professor at the University of Chicago. He recently co-chaired the US National Academies' study of the future of US particle physics,* Elementary Particle Physics: The Higgs and Beyond.

Particle physics is the modern manifestation of the two-thousand-year quest to understand nature at the most fundamental level possible. That journey has not only deepened our understanding of the physical world but has also reaped enormous benefits for humanity, and is continuing to do so.

I have experienced two revolutions in this quest – the 1974 revolution in particle physics and the 1998 ΛCDM revolution that cemented the relationship between particle physics and cosmology. I am now anxiously awaiting a third. This one will deepen the connections between the quantum world of elementary particles and Einstein's expanding universe by answering big questions about the origin of space, time and the universe as well as the unity of the particles and forces.

Powerful ideas, big surprises

In the early 1970s I was a graduate student at SLAC; it was an exciting and confusing time. Deep-inelastic scattering experiments at SLAC revealed free partons inside neutrons and protons, but they could not be knocked out. The SU(3) quark model successfully classified the elementary particles and predicted mass relations, but without any dynamics. There were powerful theoretical ideas – quantum field theory, the bootstrap, Regge trajectories, the eightfold way and scattering amplitudes – but no unifying picture.

In November 1974, the discovery of the J/ψ particle was announced. It seemed like overnight the Standard Model of particle physics, with its SU(3) of colour (not flavour) and the SU(2) × U(1) electroweak unification, was in place. All the pieces had been on the table earlier – Weinberg's broken symmetry model of the weak and electromagnetic interactions, Gross–Wilczek–Politzer's asymptotic freedom, the GIM mechanism, and evidence for quarks, but it was the discovery of the J/ψ that was needed to make it gel.

The 1980s and 1990s were exciting as new connections between the inner space of elementary particles and the outer space of cosmology were identified – some involving my own research. Inflation and particle dark matter in the form of slowly-moving particles – cold dark matter – led to an expansive theory about the early evolution of the universe along with strong predictions, including a flat, critical density universe, formation of structure from the bottom up, and scale-invariant density perturbations that arose from quantum fluctuations.

But, measurements of the matter density were coming up far short of the critical density, predictions for the large-scale distribution of matter didn't fit the observations, and the age of the universe and Hubble constant measurements conflicted with a flat universe and possibly each other. Amidst all the confusion, some thought the bubble of enthusiasm would burst.

Then, in early 1998, two supernovae teams announced that the expansion of the universe is speeding up, not slowing down, and the missing piece of the puzzle had been found. ΛCDM quickly fell into place: a flat universe with cold dark matter accounting for a third of the critical density and the other two thirds in dark energy – something like a cosmological constant.

A bittersweet memory reminds me how fast things changed. My close friend and mentor, cosmologist David Schramm, was slated to debate whether the universe was flat with Jim Peebles in April 1998. David, who had the seemingly indefensible "flat" side of the debate, died tragically in a plane crash just weeks before the discovery of cosmic acceleration. When the debate took place and I subbed for David, the title had been changed to, "Cosmology solved?"

Here we are today. Two highly successful standard models which also raise profound questions about the fundamental nature of matter, energy, space and time. There are an abundance of powerful theoretical ideas not yet fully exploited or even completely understood.

There are plenty of clues. The 125 GeV Higgs – who ordered that? The dark-matter particle, dark energy and neutrino mass are not part of the Standard Model and hint at deeper connections between inner and outer space. Recent results from DESI indicate that dark energy may be evolving and is not a cosmological constant. And there is the Hubble tension, which could be telling us something is missing, both in cosmology and particle physics.

On the hunt

But sensitive searches for the dark-matter particle, at the LHC and other colliders, in deep underground experiments and space observatories, have come up short. The Higgs has yet to reveal its secrets. And there has yet to be experimental evidence for the predictions of the powerful theoretical ideas of supersymmetry, grand unification and string theory, which must play a role in moving forward.

We are ready for another revolution that transforms our view of matter, energy, space and time, but when? Take it from a cosmologist: predicting the past is hard and predicting the future is even harder. Nonetheless, just to illustrate, I mention two possibilities, based upon two speculative papers I have written.

The first, is the detection of gravitational waves from an unexpected cosmological phase transition at a temperature of 100 TeV or so by LIGO, and the second is the discovery that the observed CMB dipole is misaligned with that expected from large-scale structure and arises instead as a revealing relic of cosmic inflation. Either would shake things up, and lead to additions, discoveries and connections. Moreover, I am confident that the real triggering event will be even more impactful and exciting.

The discovery frontier today is very broad, from table-top experiments to colliders to telescopes on the ground and in space, and big ideas abound. The world is waiting and watching. Now is the time to double down and to believe that the next result will be the one that ushers in the coming revolution in our understanding of matter, energy, space and time.

We are ready for another revolution that transforms our view of matter, energy, space and time, but when?

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OPINION
INTERVIEW

Execution mode

After a moment of turbulence, Norbert Holtkamp returns to Fermilab with a clear mandate: deliver DUNE, honour the laboratory's legacy of bold leadership and reaffirm big science's responsibility to society.

Going all the way back to Robert Wilson in the 1960s, some formidable figures precede you as Fermilab director...

Coming back to Fermilab is, for me, a little like coming home. My family and I moved to the United States in 1998, and Fermilab was the first place I worked in the Department of Energy (DOE) system. It was also a place where people really took me in. Fermilab, like many national laboratories, is built on the shoulders of giants – and Robert Wilson was one of them.

He got this huge site, more than 6000 acres, with a real vision for expansion and growth in science. He was also a genuine fan of architecture, truly inspired by it. Our Wilson Hall is a tribute to that. It echoes what people call the folding hands of Beauvais Cathedral in France. Having that building stand out from the prairie was a statement.

That's Robert Wilson's legacy at Fermilab: a science of statements and the ability to do things fast, effectively, things that people thought could not be done. So, honestly, sitting in that chair feels good.

Wilson's 1969 Congressional testimony is one of the most celebrated defences of fundamental science. What do you make of his case today?

He told Congress that high-energy physics had to do with dignity and all the things that we really venerate and honour in our country. That is still true. Despite the strain on science funding and all the questions about whether we are spending money effectively, the government is still willing to invest more than five billion dollars at Fermilab over the next five to ten years. This feels almost contrarian to what you hear in the press. Yes, science is under pressure.

Project person *Norbert Holtkamp was appointed Fermilab's new director in December 2025. He previously served as director of the Accelerator Systems Division for the Spallation Neutron Source at Oak Ridge National Laboratory, principal deputy director-general of the international nuclear fusion experiment in France (ITER) and deputy laboratory director at SLAC's Linac Coherent Light Source II (LCLS-II).*

But the commitment is there, for the very same reason Bob Wilson stated back then.

That said, I believe we carry a genuine responsibility to deliver to society. That has been the basis of the social contract since Vannevar Bush wrote *Science, the Endless Frontier* in 1945; the document that helped create the national laboratory system and agencies such as DOE, the National Science Foundation and NASA. I don't expect every citizen to understand exactly what a neutrino does or why it matters. But the outcomes of science, and the technology we develop on the way, whether that's AI, quantum information tools, electronics, those are things we have to deliver. It's part of the social contract.

Then, under Leon Lederman, and driven forwards by figures like Helen Edwards, Fermilab expanded the world's energy frontier with the Tevatron...

Helen Edwards is actually directly responsible for the fact that I'm in this country. It's her fault, really. When I was a group leader at DESY in 1998, 37 years old, with two small kids and having just built a house in Germany, Helen walked into my office. She asked, "Norbert, what do you want to do with your future?" She was very direct and wouldn't take no for an answer. I hesitated, and she said, "You need to think about this. You should go to the United States." Six months later, I was at Fermilab.

She was undeterrable. If she had a mission, a North Star, there was no lab director, no government official, no one who could deflect her from it. She and Alvin Tollestrup, a name that doesn't get talked about enough, developed the superconducting magnet technology under Leon Lederman's leadership that made the Tevatron what it was. That technology later allowed DESY to build HERA and ultimately landed in the LHC at CERN.

Alvin could explain superconductor physics on first principles and very quickly come to how you wind a magnet and what fundamentally limits its performance. A physicist and a technologist at the same time. They were both giants. There's no question about it.

You mentioned moving from Europe to the United States. How different were the two scientific cultures, in the late 1990s?
You sure you want to write about this? [chuckles] Before I left DESY, I went to the director, Björn Wiik. He was himself a visionary leader, the person behind the TESLA concept for superconducting RF. When he asked where I saw myself in five or ten years, I answered, "I want your job. I want to be a director." He was very direct too. "You are only 35 years old," he said. "To become a director in Europe, you have to look like me. You have to have grey hair and a beard." I found that frustrating. But I think it was largely true at the time.

In the United States, age didn't matter. Nationality didn't matter. What mattered was: could I do it? A 39-year-old German, alongside a Canadian, Thom Mason, and the son of Croatian immigrants, Anthony Chargin, suddenly found themselves in charge of building one of the biggest science projects in the United States: the Spallation Neutron Source, inspired by a former South Korean accelerator physicist, Yanglai Cho. That's a story you can't make up. That is where my career really started.

The transition from Lederman to John Peoples coincided with the golden age of the Tevatron and the era of the Superconducting Super Collider (SSC). What do those two directors, and that moment, tell us about leadership in big science?
I knew Leon well because I actually lived in his house. He had a place off-site, and when my family first arrived we had very little money, so he said: "You need a house. I have one." And we moved in. He came by regularly, stored his Porsche in the garage, and we talked a great deal. I learned a lot from him.

He was the kind of person you simply liked. Everybody at Fermilab loved Leon. He was funny, extraordinarily smart and he had a vision for the laboratory. I asked him once why he stepped down after nine years as director. He told me, "If you are a lab director, you have to make important decisions, and with every decision you make, you lose 10 percent of your friends. After 10 decisions, they are all gone. That is when you step down." That was a true Leon answer. But it reflected his deep understanding of what leadership really costs.

I deeply believe high-energy physics can again be a launchpad for open international collaboration

John Peoples was very different. He was hands-on, deeply involved in building the complex and the Antiproton Source. Where Leon was the beloved visionary, John was the builder who wanted to be involved. And he had two extraordinarily difficult jobs at the same time: managing the closure of the SSC in Texas, which you could see drain him, and running a programme that ultimately delivered the discovery of the top quark.

These were very different people, very different characters. I think every character has its time. That is as true at Fermilab as it is at CERN. You can tell the same story through CERN's directors. We just lost one, Herwig Schopper, who was a phenomenal leader. He spoke openly about the sacrifices he and the laboratory had to make to get CERN going. And when you look at CERN 50 years later, that is still a defining legacy, with the 27-kilometre tunnel and the science that continues to come out of it.

What lessons does the abandonment of the SSC hold for the large-scale projects being discussed today?
The real lesson of the SSC isn't the failure itself. It is about implementation. The days when you could go to a government and say your project costs this much, then come back the next year and ask for 20 percent more, and the year after that another 20 percent – those days are gone. That is not the world we live in, and at the scale of projects we are talking about today, it would not be responsible.

John understood that deeply. I have tried to carry it through my own career. On my watch, I will always be direct with our funding agencies about what I see as risks and what things actually cost. That is non-negotiable for me.

Fermilab then repositioned itself at the intensity frontier. How do you keep the laboratory aligned behind the Long-Baseline Neutrino Facility (LBNF) and the DUNE experiment?
You form a team, you focus the team and you execute. That sounds pretty mundane and simple. It is not. It is really hard. CERN went through something very similar under Robert Aymar with the LHC: the necessity to focus every resource and every engineering capability on one thing to make it happen.

I am a scientist, but also a project guy. I wake up every morning thinking about those five billion dollars. That is roughly eight hundred million a year. Three million dollars a day. My job is to organise a team that can responsibly and effectively deploy that every single day to build LBNF/DUNE.

When I spoke at my first all-hands meeting here, I laid out three bullet points, because nobody remembers more than three. First: beam at the DUNE far detector by 2031. Second: science at the High-Luminosity LHC and delivering on our commitments there. Third: develop science, technology and innovation for the benefit of society. Those are the three and everything flows from them.

I use the story of JFK visiting NASA and asking the janitor why he is there. The janitor says: "To put a man on the Moon." That is the answer I want from everyone here. So I go around and ask people why they are here. And if I don't get the answer I want, I ask again.

Neutrino physics is also receiving major investments in China and Japan, with JUNO already closing in on the neutrino mass hierarchy and Hyper-Kamiokande equipped to measure leptonic CP violation when it comes online. How does DUNE fit in that landscape?
We live in a world that is not the world of 20 or 30 years ago. We have to recognise that. But I deeply believe high-energy physics can again be a launchpad for open international collaboration.

The neutrino story is phenomenal for the US with the DOE's support of the DUNE project. It is also great for CERN. The most significant large-scale investment CERN has made in an external experiment is in DUNE. And it goes both ways: Fermilab contributes significantly to the HL-LHC programme. That is one of the healthiest collaborations in the field, both at the personal level and at the level of laboratories and programmes.

As for competition among neutrino facilities, it's healthy. It is all about what I call the three C's: collaboration, cooperation, competition. Every scientific relationship works better when you are clear about which is which. There is competition with other neutrino experiments, of course, in the sense that whoever reaches an answer first gets the golden nugget. But there is also technology exchange, open science and the free sharing of knowledge. Both things are true.

When you look at the DUNE detector and the beam we are building, it will be, hopefully sooner than later, the most effective research instrument for this kind of science. It is nice to be number one. You never stay number one forever, but it is nice. CERN is number one in collider physics right now – a pretty good feeling. But you also have to deliver results.

In my world, it is better to make the wrong decision and correct it than to make no decision at all

How would you describe Fermilab's culture right now?
Scientists are driven by curiosity. That hasn't changed and it won't. But when a large institution commits to building a major instrument, there is real tension between the broad research culture that develops over time and the laser focus that construction demands. Is there stress in the system? Yes, honestly, there is. The best thing you can do is recognise that, talk about it openly and make sure people can see the light at the end of the tunnel.

The people who love construction have a clear finish line. The researchers have an extraordinary instrument coming, and the conceptual and technical work they do now is their investment in what comes after. The two groups are not perpendicular to each other. A good instrument requires constant feedback from the science side on what it actually needs to deliver, but you also can't have an infinite conversation about what to build while you are trying to finish building it. Finding that line is delicate, and I spent my life basically walking it. At the SNS, at LCLS-II, at ITER. You pick.

There is a saying I keep coming back to: culture eats strategy for breakfast. Getting the culture right will take time and requires healthy tension. But it also requires the willingness to make decisions. I am not afraid to make a decision. Sometimes the wrong one, and that's fine, it needs to be corrected. But in my world, it is better to make the wrong decision and correct it than to make no decision at all.

Where should Fermilab position itself in the next chapter of global high-energy physics?
I wanna stretch my hand to Europe, and to CERN in particular. I am very proud of the connection between our two institutions, at the programmatic level and at the personal level. I think we need to continue discussing how to keep the world open for those that want to share our values and share our way of doing science. People like me should be able to come to the United States. People from here should be able to go to CERN. That's the foundation of everything we do.

Interview by **Davide De Biasio** *associate editor.*

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When accelerators turn into sweaters

In the Spaces Between: Transmission, Experience & Dialogues
Edited by Mónica Bello
dpr-barcelona

What happens when an artist enters a particle-physics laboratory, not to explain its discoveries or visualise its equations, but simply to remain, observe and respond? *In the Spaces Between*, a sustained reflection on the long-running Arts at CERN programme, argues that what emerges is not illustration or explanation, but a shared space of inquiry – one that works with uncertainty rather than resolving it, echoing the statistical, instrument-mediated nature of contemporary physics.

Both art and particle physics push at the edges of what can be known, imagined and expressed. Through its programmes, Arts at CERN hosts artists for extended residencies at the laboratory, where they meet physicists and engineers, attend seminars, visit experimental sites and engage directly with ongoing research. The artists are not tasked with illustrating experiments or communicating results. Instead, they develop independent works – installations, performances, films, sculptures – shaped by sustained dialogue with the scientific community.


J Urbonas

Accelerator materiality *Knitted from copper wire, the piece* When Accelerators Turn into Sweaters, *by artist Julijonas Urbonas, reduces accelerator infrastructure to garment scale.*

Creating coalitions

Edited by Mónica Bello, former head of Arts at CERN (*CERN Courier* March/April 2025 p41), the book brings together essays, images and reflective texts by artists, scientists and collaborators involved in the artist residency programme. Rather than presenting a catalogue of finished works, it focuses on the conditions that make exchange possible: how artists encounter scientific infrastructures, and how meaning begins to form in spaces where neither discipline fully sets the rules.

The book is organised around four broad themes: "quantum", cosmology, experimentation and the unknown. These function less as explanatory frameworks than as loose points of orientation, allowing contributions to remain fragmentary and open-ended. The structure mirrors the reality of interdisciplinary work, which rarely unfolds in clean, linear ways, but instead through moments of partial understanding, misalignment and return.

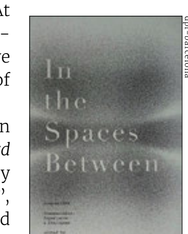
For readers trained in physics, this approach may feel unexpectedly familiar. Scientific knowledge rarely emerges fully formed; it develops through iteration, uncertainty and interpretation. In a similar spirit, the contributions resist tidy conclusions and treat concepts not as definitions to be settled, but as materials for creative reworking. What matters is less resolution than the act of thinking itself, an openness that mirrors the exploratory character of research. At times this displacement can feel destabilising, yet it is precisely this imaginative expansion that gives the book much of its intellectual force.

This sensibility is vividly captured in Rohini Devasher's *Beyond the Standard Model*. Spread across a dark, planetary surface, words such as "uncertainty", "duality", "observer", "wonder" and "serendipity" – form a dense, drifting constellation. Some terms carry clear scientific weight; others belong to the emotional and imaginative registers that accompany research but rarely appear in formal papers. For Devasher, the interest lies precisely in language. By placing these words on the same visual plane, the piece loosens disciplinary hierarchies and allows concepts to float, cluster and collide. As the artist notes, the words are intended to be read as a web. Rather than explaining physics, it evokes the conceptual environment in which physics thinking takes place.

Places and perspectives

On another page, language again becomes material in Cecilia Vicuña's *Ceque*. The work draws on the ceq'e system of the Inca civilisation: a network of conceptual and ceremonial lines radiating outward from the city of Cusco, that are used to organise ritual practice, social relations and cosmological understanding. Rather than functioning as fixed geometrical paths, ceq'es describe relationships between places, perspectives and moments in time.

The page opens with the line "The ceq'e is not a line, it is an instant, a gaze." Around it, words tilt, scatter and spiral – "a thought, radiating", "another meridian", "seen from above or from below". Reading becomes a spatial act rather than a linear one. Meaning is not extracted or fixed; it unfolds uneasily alongside the order, diagrammatic structures through which Western science typically organises knowledge. The book offers little explicit explanation of the concept, allowing the work instead to function as an alternative way of organising knowledge: relational, situated and resistant to a single point of view.



dpr-barcelona

Visual thinking also surfaces in drawings from Suzanne Treister's project *The Holographic Universe Theory of Art History (THUTOAH)*, including Alessandra Gnecchi's *Holographic Universe Principle*. The work resembles a hand-drawn cosmology sketched in coloured pencil: strings, branes and horizons coexist with handwritten annotations and looping arrows. The emphasis is not on polished representation, but on the labour of ▷

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thinking – the scribbles, approximations and half-formed connections that precede formalisation. Theory appears not as a final statement, but as something constantly under construction.

One of the more quietly striking works in the book is Julijonas Urbonas's *When Accelerators Turn into Sweaters*: a translucent garment constructed from fine copper-stabilised superconducting fibres (see "Accelerator materiality" image). The title collapses the scale of accelerator infrastructure into a wearable object, shifting attention from machines as abstract systems to the materials from which they are built. As Urbonas puts it, the work aims to "bring a monumental, sealed infrastructure into the scale of the body, not just visually, but physically and imaginatively... a translation from the remote language of high-energy physics into something you can almost inhabit."

In doing so, it foregrounds the material reality of high-energy physics – copper as thread and cable at once. Though made of copper, the sweater evokes the magnetic levitation of the Meissner effect, a reference to the cryogenic superconductivity of the LHC. As Urbonas observes, "the accelerator needs extreme cold to do its job, while a sweater's whole purpose is warmth." By keeping that gap open, the piece operates less as demonstration than as speculation: a domestic object positioned against an environment colder than outer space, inviting viewers to rethink how scientific infrastructure is imagined. Urbonas leaves the reader with a provocation: "What if physicists talked in the knitwork of the world instead?"

The contributions make clear that Arts at CERN is not a peripheral outreach activity, but a mature programme of sustained exchange

For accelerator physicists, this change of scale may register not simply as metaphor, but as a reminder that even the largest facilities depend on materials physically assembled, connected and maintained by hand. By reframing accelerator infrastructure at human scale, the piece foregrounds construction and material composition rather than the monumental image of the machine, aligning with the book's broader emphasis on process over spectacle.

In the Spaces Between does not romanticise interdisciplinarity as a seamless merging of perspectives or a frictionless dialogue between equals. Several contributors openly acknowledge the asymmetries between artistic and scientific practice within a large research institution, where scientific priorities and infrastructures inevitably set the operating conditions. Rather than glossing over these tensions, the book treats them as productive constraints that actively shape how collaboration unfolds.

Taken together, the contributions make clear that Arts at CERN is a mature programme of sustained exchange. Its longevity has not led to conceptual closure; instead, the dialogue has deepened while remaining exploratory, evolving rather than resolving.

With its emphasis on process rather than outcomes, the book offers a rare window into how artistic inquiry operates inside a laboratory environment. It does not try to merge art and science, nor to reduce one to the language of the other. Instead, it traces the intellectual and imaginative terrain that lies between them, a space defined not by synthesis, but by ongoing negotiation.

Ultimately, *In the Spaces Between* suggests that experimentation runs deeply through both artistic and scientific practice, not only as a set of methods for testing ideas, but as a shared commitment to iteration, risk and revision. The sustained dialogue documented here does not aim at synthesis or resolution; rather, it creates conditions in which new forms of knowledge can emerge, forms that remain open-ended. The book will be of particular interest to those working at the intersections of art, science and research institutions, and to readers interested in what happens when disciplines meet without being forced into premature coherence.

Caroline Clavien *CERN*.

Space Radiobiology: Synergies Between Astroparticle and Medical Physics

By Alessandro Bartoloni and Lidia Strigari

World Scientific

Astronauts are exposed to elevated levels of cosmic radiation during spaceflight. As missions become longer and venture farther from Earth, understanding how this radiation affects the human body has become a pressing scientific challenge. This emerging field of space radiobiology has strong and perhaps unexpected links to the far better established discipline of radiobiology in medical physics, where physicists work closely with clinicians to design and optimise cancer treatments using ionising radiation. In both contexts, the central question is the same: how does radiation interact with living cells, and how can its harmful effects be predicted, mitigated and controlled?

Space Radiobiology is authored by Alessandro Bartoloni (INFN Bologna) and Lidia Strigari (University Hospital of Bologna), whose combined expertise spans astroparticle physics, radiation transport and clinical radiobiology. The book explores a meeting point between two fields that have long followed separate paths but are now clearly converging around shared questions in radiation science.


NASA

Safer space *The Alpha Magnetic Spectrometer (AMS) on the International Space Station measures cosmic rays with high precision, generating data that also inform space radiobiology and radiation-risk for human spaceflight.*

At its core, the book argues for a closer integration of astroparticle physics and medical physics, demonstrating how both fields benefit from a common radiobiology perspective and a shared concern for radiation protection. At the heart of the volume is a thorough and well balanced discussion of space radiation and its implications for human spaceflight. The authors guide the reader through the complexity of the space-radiation environment – galactic cosmic rays, solar-particle events and their interactions – without losing clarity. These elements are consistently linked to real concerns for astronaut health, both for short missions and for the long-duration journeys that are becoming increasingly realistic. By connecting radiation sources, transport mechanisms and biological effects, the book builds a clear picture of where the risks lie and how they might be managed, making it especially relevant at a time when deep-space missions are moving from concept to planning.

What makes the book particularly engaging is that it never treats space research as an isolated niche. Instead, it repeatedly shows how ideas and tools developed for space can feed back into medical physics. From dosimetry and radiation monitoring to risk assessment, the authors highlight how methods refined for astroparticle experiments ▷

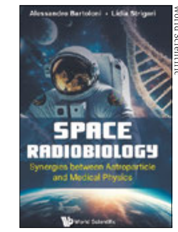
can be applied in clinical and research settings on Earth. Advances in detectors, modelling and data analysis developed for space missions are presented not as abstract achievements, but as practical contributions that can improve radiation therapy and diagnostic imaging.

From space to the hospital

This interdisciplinary spirit comes through especially well in the case study of the Alpha Magnetic Spectrometer group at INFN Roma Sapienza. Operating aboard the International Space Station, AMS was designed to study cosmic rays and search for signs of dark matter and antimatter. The book shows, however, that its high-precision measurements of charged-particle spectra, particle composition and energy deposition in low-Earth orbit have direct relevance for space radiobiology and radiation-protection research. In particular, AMS data helped characterise the flux, charge and energy distribution of galactic cosmic rays and solar energetic particles, key parameters for modelling dose, dose-rate and track-structure effects in biological tissue. These measurements inform risk assessments for astronaut exposure, improve shielding models, and support more realistic simulations of DNA damage and long-term health effects associated with chronic low-dose, high-energy radiation in space. Rather than serving as a standalone example, this case study acts as a concrete illustration of how cross-disciplinary collaboration actually works in practice: how shared technologies, experimental approaches and theoretical frameworks can produce insights that matter across fields.

The sections on radiobiology strike a careful balance between accessibility and depth. Topics such as DNA damage, cellular responses and long-term health effects are explained clearly, without oversimplifying issues that are inherently complex (*CERN Courier* November/December 2025 p27). One of the book's strongest messages is that space radiobiology, with its extreme and unconventional exposure conditions, offers a unique lens for understanding radiation effects that are also relevant to clinical and occupational environments on Earth.

By focusing on shared biological endpoints and common dosimetric challenges, the book shows how progress in one area can meaningfully inform the other. The discussion on developing common platforms for radiation measurement and monitoring reinforces this point, arguing that integrated approaches



World Scientific

are not only efficient but scientifically necessary in increasingly complex radiation environments.

Space Radiobiology succeeds in bringing together different scientific communities around a common language and set of challenges. It will resonate with researchers in physics, space science, radiobiology and medical physics, as well as with graduate students looking for a broader, more connected view of radiation science. At a moment when deep-space exploration is becoming a tangible goal rather than a distant idea, the book offers a thoughtful and convincing picture of how lessons learned beyond Earth can shape safer and more effective uses of radiation here at home.

Angelica Facoetti *CNAO*.

PEOPLE CAREERS

Policymaking with data

James Robinson reflects on a journey from the ATLAS collaboration to the Environment and Sustainability programme at the Alan Turing Institute.

Alan Turing Institute

James Robinson *is the software engineering research lead at the Alan Turing Institute's Environment and Sustainability programme.*

In physics, as in life, it's important to persevere in the face of setbacks. When James Robinson joined the ATLAS experiment at CERN in 2008, the Large Hadron Collider had just sputtered into life. "I remember the excitement of the initial startup and the disappointment when data taking was delayed for a year," recalls Robinson." Over the next decade, Robinson built a career in experimental particle physics, analysing jets and soft-QCD events, convening subgroups, tuning Monte Carlo generators and helping measure luminosity.

By 2018, Robinson was beginning to ponder his professional priorities. "I didn't really want to spend another three years writing grants and not having much time to do physics," he says. Constant relocation was another strain. "It was really nice having the freedom to travel, but in your mid-thirties you start thinking maybe it's time to settle in one location."

Real-world research

That's when he spotted an opening at the Alan Turing Institute, the UK's national centre for data science and AI. The Institute is a research-led organisation who hire experts and academics to find solutions to real-world challenges and to advise UK public policy. The role Robinson initially applied for focused on advanced computing and AI strategy, one that would apply his academic skills, and help develop his practical ones. "The Institute has a lot in common with CERN," he says. "But I applied because of its larger focus on applications of research, rather than pure blue-sky work."

Today, Robinson is the software engineering research lead in the Turing's Environment and Sustainability programme, where teams of researchers, data scientists and engineers tackle urgent global challenges. "Right now we're working with the Met Office on using AI to get faster and better weather predictions in the UK," he explains. "For other projects, we also partner with African countries to improve forecasts in the global South, and model changes in Arctic and Antarctic sea ice, which is useful for everything from animal migrations to navigation."

One of Robinson's first projects was to model London's air quality to inform the mayor's office on pollution hot spots. "Traffic turned out to be the most important factor," he says. "We could point to areas where we thought air quality was bad but under-measured, and the mayor's office deployed mobile sensors to check. During COVID we even repurposed the project to monitor how busy London was coming out of lockdown. It felt really nice to see a project pivot quickly and directly feed into policy."

Although the Turing Institute engages with government and public-sector partners, it isn't a commercial consultancy. Each team decides which areas they would like to work in, and the problems they focus on improving. Once they identify a problem, the next stage is to find the best partner who will allow their models to make the most impact. "We're not here to build a slightly better algorithm for its own sake," says Robinson. "We want to apply AI to make change in the real world."

The Institute's mission echoes the one that first drew Robinson to physics. "One of the big similarities with CERN is the sense that what you're doing is worthwhile and good for the world," he says. "It's still research, but more applied. Improving the weather forecast that everyone sees on their phone – that's easy to explain to your grandparents."

Robinson, who had previously been part of decades-long, large-scale research projects at ATLAS, felt it extremely satisfying to see the direct impact of his work. "At CERN you contribute a tiny part to a huge experiment," he says. "Here I get to see a project from start to finish, and sometimes adapted straight into real-world decision making."

Transferable skills

But was high-energy physics a good preparation for Robinson's current career?

The answer is a resounding yes. Having done a PhD and two post docs, he was used to flexible and adaptable timelines. "I was often handed a problem without a clear solution," he recalls. "Sometimes we have to pivot quickly away from one idea or plan and dive straight into another. That ability to rethink and improve has transferred directly to Turing."

A lack of formal technical qualifications also need not be a problem. "Many of us were self-taught programmers at CERN," he says. "The fact you've done research, adapted and developed those skills is what matters."

Collaboration is another common thread. "Like CERN, Turing is a meeting place for people from many different institutions," he says. "No one can just order work to happen. You negotiate, you build consensus."

But Robinson notes that applying for non-academic roles requires a shift in mindset. While academic CVs and cover letters are often long and detailed, applications for industry, consultancy or somewhere in between like the Institute, may look different.

"Don't go into the specifics of your ATLAS analysis because it won't be directly relevant in industry," says Robinson. "Show your research experience, but focus on the skills: problem-solving, collaboration, adaptability."

But most importantly, make sure the values of the company you're applying to align with your own. For Robinson, the Turning Institute was an obvious choice.

"I'm taking the same mindset I had at CERN and using it to make a difference you can see," says Robinson. "That's the rewarding part: turning data into something that genuinely helps people."

Interview by Alex Epshtein *CERN.*

Appointments and awards

University of Chicago

Holtkamp takes the helm

On 12 January, Norbert Holtkamp became director of Fermi National Accelerator Laboratory. A veteran manager of large scientific facilities, he previously served as deputy director of SLAC National Accelerator Laboratory, where he oversaw construction of the Linac Coherent Light Source upgrade, the world's most powerful X-ray laser. He was also principal deputy director general of ITER, the multinational fusion-energy project. Currently a senior fellow at the Hoover Institution, Holtkamp has emphasised the importance of international scientific collaboration. "Fermilab has done so much to advance our collective understanding of the fundamentals of our universe," he says. "I am committed to ensuring the laboratory remains the leader of neutrino research in America." He succeeds Young-Kee Kim, who served as interim director from January 2025 (see p41).

DESI wins Berkeley Prize

The American Astronomical Society (AAS) has announced its selection of the DESI collaboration as the recipient of the 2026 Lancelot M. Berkeley–New York Community Trust Prize. Established in 2011, the prize is awarded annually for highly meritorious work advancing astronomy in the previous year. The 2026 prize recognises the DESI collaboration for two papers published last year. The first, published in February, presents baryon acoustic oscillation results from the first year of DESI data, while the second, published in October, reports BAO results from observations of 14 million galaxies and quasars, obtained in the first three years of DESI operations. The observations constitute the largest 3D map of the universe ever made, providing strong hints that dark energy evolves over time (*CERN Courier* May/June 2025 p11).

IFAE appoints Núñez Freixa

Jordi Núñez Freixa has been appointed general manager of IFAE, Spain's Institute for High Energy Physics. An industrial engineer from BarcelonaTech, Núñez Freixa has developed his career in public administration and strategic management. Until now, he has served as general manager of the City Council of Rubí, where he has led projects related to urban and sustainable transformation, the promotion of energy self-consumption, and the development of the local industrial and business ecosystem.

Lilienfeld Prize for Murayama

The American Physical Society has awarded the 2026 Julius Edgar Lilienfeld Prize to Hitoshi Murayama (University of California, Berkeley) for outstanding contributions to theoretical and experimental particle physics, as well as

UC Berkeley

inspirational public outreach and effective science advocacy. Murayama founded the Kavli Institute for the Physics and Mathematics of the Universe at the University of Tokyo in 2007, and chaired the decadal P5 report on particle physics in 2023.

Shapley wins Heineman Prize

Alice Shapley (University of California, Los Angeles) has received the 2026 Dannie Heineman Prize for Astrophysics for landmark observational campaigns and creative techniques that advanced the study of galaxy formation and evolution. Shapley is recognised for advancing rest-frame ultraviolet and optical spectroscopic studies of high-redshift galaxies, including large surveys with the Keck Observatory and early observations with the James

UCLA College

Webb Telescope that revealed the physical and chemical properties of galaxies in the early universe.

APS Medal for Francis Halzen

Francis Halzen (University of Wisconsin–Madison) will be awarded the 2026 American Physical Society Medal for Exceptional Achievement in Research for his contributions to neutrino astrophysics, particularly his leadership of the IceCube Neutrino Observatory and the discovery of high-energy astrophysical neutrinos. He has been the principal investigator of IceCube since its early predecessor experiment AMANDA in the late 1980s, which laid the groundwork for the giant cubic-kilometre detector. Alongside Alan D Martin, he authored the beloved and ubiquitous particle-physics textbook *Quarks and Leptons: An Introductory Course in Modern Particle Physics*.

Rossi Prize goes to Krawczynski

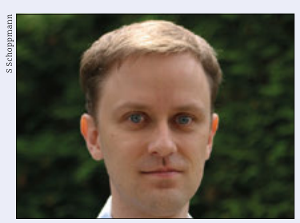
Henric Krawczynski (Washington University, St. Louis) has received the Bruno Rossi Prize of the AAS High-Energy Astrophysics Division, which recognises major contributions to high-energy astrophysics, for his work on the theory, instrumentation and scientific interpretation of X-ray polarimetry. His work helped establish X-ray polarisation as a powerful probe of black holes and neutron stars, including the first hard X-ray polarisation measurements with the balloon-borne XL-Calibur experiment and contributions to discoveries with NASA's Imaging X-ray Polarimetry Explorer.

Honorary doctorate to Sterman

George Sterman (Stony Brook University) has been awarded an honorary doctorate by ETH Zürich in recognition of his groundbreaking theoretical research in particle physics. Sterman is recognised for foundational contributions to quantum field theory, including infrared safety, factorisation and resummation, and for longstanding leadership of the C.N. Yang Institute of Theoretical Physics.

ICFA Instrumentation Awards

On 5 February, at the TIPP Conference in Mumbai, India, the International Committee for Future Accelerators (ICFA) presented its 2026 ICFA Instrumentation Award to Nicolò Cartiglia (INFN Torino), Hartmut Sadrozinski (University of California, Santa Cruz) and Abraham Seiden (University of California, Santa Cruz). The trio are recognised for the groundbreaking development of ultra-fast silicon detectors for precision timing, now widely used in the particle-physics community, and enabling 4D tracking detectors. The 2026 ICFA Instrumentation Early Career



S Schoppmann

Award was presented to Stefan Schoppmann (University of Mainz; pictured), for pioneering hybrid and opaque scintillator technologies, advancing neutrino and dark-matter detectors through innovative materials, patented developments, and leadership in next-generation low-background experimental instrumentation.

PEOPLE OBITUARIES

ANTONINO ZICHICHI 1929–2026

Extraordinary energy and vision

Antonino Zichichi, one of the most influential figures in high-energy physics and a towering presence in Italian scientific culture, passed away in Rome on 9 February 2026, at the age of 96.

Born in Trapani, Sicily, in 1929, into an ancient family from Erice, Zichichi graduated from the University of Palermo in the early 1950s. In 1955 he joined CERN, at the dawn of its experimental programme, and in 1965 he led the experiment at the Proton Synchrotron that culminated in the discovery of the antideuteron – an antinucleus composed of an antiproton and an antineutron that provided decisive confirmation of the existence of nuclear antimatter.

A professor of physics at the University of Bologna since 1960, he led the Bologna–CERN–Frascati collaboration, which carried out the first search for the tau lepton and established the experimental method through which its discovery would later be achieved at SLAC National Accelerator Laboratory. Beyond these early milestones, his results and discoveries were numerous and fundamental, including significant limits on free quark production in strong and weak interactions, the discovery of the effective energy in QCD and evidence for the first beauty baryon.

A master of invention

Equally important were his early inventions, among them the electronic circuit for time-of-flight measurements, the preshower for calorimetry and a new technology for high-precision polynomial magnetic fields. Later, by securing Italian funding for the LAA project at CERN, he launched an extensive R&D programme on innovative detection technologies. This notably allowed the development of microelectronics, which together with the design of silicon strip and pixel detectors, would become crucial for the LHC experiments and the development of the Multi-gap Resistive Plate Chamber (MRPC), a detector with record time resolution. The first large-scale implementation of MRPC technology was the ALICE experiment's Time-of-Flight (TOF) system that Zichichi led for over two decades.

His scientific legacy cannot be separated from his profound and lasting contribution to the Italian National Institute for Nuclear Physics (INFN). Serving as its president from 1977 to 1982, he played a decisive role in strengthening the institute at a crucial stage of its development, consolidating its international standing and reinforcing Italy's participation in the great global enterprises of particle physics. Under

Esercito Italiano

All who met him were struck by Antonino Zichichi's unfailing enthusiasm and deep passion for science.

his leadership, INFN expanded its experimental commitments at CERN and in the US, while investing strategically in detector development and advanced technologies.

Zichichi was instrumental in establishing major research facilities and many large projects are tied to his name: from the LEP and LHC projects at CERN to the HERA project at DESY, and the Gran Sasso National Laboratories at INFN, that he conceived and strategically designed with its experimental halls pointing towards CERN. Today recognised as the world's foremost underground laboratories for astroparticle physics, attracting thousands of scientists from leading institutions across the globe, the Gran Sasso National Laboratories stand as a monumental testament to Zichichi's foresight. The idea that an international research centre such as the Gran Sasso Laboratories can serve as a crossroads for scientists from different backgrounds, cultures and institutions, collaborating in fundamental research, reflects the vision that Zichichi consistently pursued. A vision that sees science as a means of diplomacy, enabling dialogue among nations around a common goal.

Strongly convinced that scientific cooperation could be a concrete tool for diplomacy and peacebuilding, Zichichi founded the Ettore Majorana Foundation and Center for Scientific Culture in Erice, Sicily, in 1963, which became a hub for international scientific collaboration and a forum for discussion among researchers from around the world. From there, in 1982, he promoted the Erice Statement for Peace, an urgent appeal to the international scientific community to place its work in the service of peace rather than war, at a time of heightened risk of global nuclear conflict.

That same conviction informed his engagement in European and international scientific governance. Zichichi was among the founders of the European Physical Society (where he served as its president from 1978 to 1980), chaired the NATO Committee on Disarmament Technologies and represented the European Economic Community on the scientific committee of the International Science and Technology Center in Moscow. From 1986 onwards, as president of the World Lab and the World Federation of Scientists, he supported scientific development in emerging countries and focused attention on planetary emergencies.

He did not limit himself to building bridges between scientists, but also between science, culture and society. A highly skilled communicator and educator, he published widely read books and essays aimed at the broader public, and appeared frequently in the Italian media, inspiring young people across Italy and conveying to them his passion for, and belief in, the importance of scientific research. He helped shape scientific culture in Italy in the latter half of the 20th century, insisting that fundamental research is not merely a technical endeavour but a cornerstone of human progress.

Multiple honours

Over the course of his long career, Zichichi received more than 60 awards and honours in Italy and abroad, including the Knight Grand Cross of the Order of Merit of the Italian Republic and the Enrico Fermi Prize of the Italian Physical Society. He was also president of the Enrico Fermi Historical Museum and Research Centre, further testifying to his dedication to preserving and promoting Italy's scientific heritage.

With his death, the global scientific community loses a visionary researcher, a formidable architect of international scientific collaborations, and a tireless advocate for science as a vehicle of dialogue and peace. What always struck those who shared with him the demanding and inspiring journey of research was his unfailing enthusiasm and deep passion for science, which he cultivated tirelessly until his final days. That same passion lives on not only in his discoveries and in the institutions he helped to create, but also in the generations of scientists who continue to build bridges across borders in the name of knowledge.

Antonio Zoccoli *INFN and University of Bologna.*

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Erich Lohrmann 1931–2026

A scientist of great foresight

Erich Lohrmann, an experimental physicist who shaped the research programme at DESY, passed away on 10 January 2026 at the age of 94.

Lohrmann was born on 25 May 1931 in Esslingen am Neckar near Stuttgart. From 1950 to 1955 he studied at the Technische Hochschule Stuttgart (TH Stuttgart), where in his doctoral dissertation, completed in 1956, he investigated particle production by cosmic rays in nuclear emulsions and together with Martin Teucher observed the creation and annihilation of an antiproton shortly after its discovery at Berkeley. For this discovery, Owen Chamberlain and Emilio Segrè were awarded the Nobel Prize in Physics in 1959. From 1956 to 1961, Lohrmann continued his work on cosmic rays at TH Stuttgart and at the universities of Bern, Frankfurt and Chicago. In Chicago he also met Masatoshi Koshiba, with whom he shared a lifelong friendship.

M Mayer/DESY

Erich Lohrmann was held in high esteem for his patience in listening and his enlightening comments.

Lohrmann joined DESY in 1961. He convinced the director, then Willibald Jentschke, that a liquid-hydrogen bubble chamber exposed to the photon beam from the 6 GeV electron synchrotron would be ideally suited to investigate hadronic reactions. Five million bubble-chamber photographs were analysed by a large collaboration, resulting in a rich scientific harvest that received great international recognition. To facilitate the measurement and analysis of millions of photographs, Erich worked on automated measurement methods and data analysis, and founded DESY's IT group. In 1969, together with Peter Stähelin, he established the Institute of Informatics at Hamburg University, where he and members of the DESY IT group gave lectures on informatics and data analysis.

As research director from 1968 to 1972 and from 1979 to 1981, he played a key role in strategic decisions at DESY. He was one of the few scientists who encouraged Jentschke to build the electron–positron storage ring DORIS. In the years from 1966 to 1968, it was a risky decision to base DESY's future on this technique, since the prevailing opinion among particle physicists was that it would only allow tests of the validity of QED. The discovery of the "new particles" in the November Revolution of 1974 (*CERN Courier* November/December 2024 p41) showed that this was the right decision, and it has shaped research at DESY until today.

Lohrmann was the driving force behind the conception and realisation of the PLUTO detector at the DORIS storage ring. Against considerable opposition, he insisted on a superconducting coil, which laid the foundation for DESY's expertise in superconducting technology. This was subsequently a crucial prerequisite for the construction of HERA. The experimental programme at DORIS, in which Koshiba's group was also heavily involved, proved to be extremely successful. The strong Japanese–German collaboration was continued at the large electron–positron storage ring PETRA and later at HERA. The PETRA experiments produced a wealth of new results, the most important of which was the discovery of gluons. After his term as research director ended, Erich then played an influential role in the TASSO experiment.

In the HERA project, he strongly supported Björn Wiik's forward-looking proposal to build an electron–proton collider with a superconducting proton storage ring 6 km in circumference. In the ZEUS experiment, Lohrmann played a central role in setting up the collaboration, designing the interaction region and in data analysis, to name just a few examples. His important contributions to the critical analysis of publications continued until very recently.

Erich also promoted research with synchrotron radiation through the conversion of DORIS into a high-brilliance radiation source. Later, PETRA was also converted into a synchrotron radiation source. Today, DESY is a world leader in photon science.

From 1976 to 1978, Lohrmann served as CERN director responsible for research. Until his retirement in 1996, he was a professor at the University of Hamburg. With his lectures on physics, statistics and methods of data analysis, he inspired numerous students and provided them with a solid education. Based on his teaching experience, he also authored three books, one of them, *Statistical and Numerical Methods of Data Analysis*, with his colleague Volker Blobel. Together with Paul Söding, he described the history of DESY in detail up to 2008 in the book *Von schnellen Teilchen und hellem Licht*. Even after his retirement, Lohrmann was frequently at DESY and remained active in research. One example is the GRAVI experiment, which investigates Newton's law of gravitation in weak fields.

Despite his great scientific achievements, Erich remained modest. Thanks to his sober yet humorous Swabian manner, his expertise and his commitment to scientists, he enjoyed great trust and esteem.

With the passing of Erich Lohrmann, physics loses a scientist of great foresight and an inspiring teacher. His contributions to physics and his scientific legacy will continue to inspire us in the future.

Manfred Fleischer, **Robert Klanner**, **Peter Schmüser**, **Paul Heinrich Söding** and **Albrecht Wagner** *DESY and University of Hamburg.*

Matts Roos 1931–2025

Order in the particle zoo

Matts Roos, who promoted the international standardisation of high-energy-physics data and developed the popular statistical minimisation system, passed away on 25 November 2025 in his hometown of Helsinki at the age of 94.

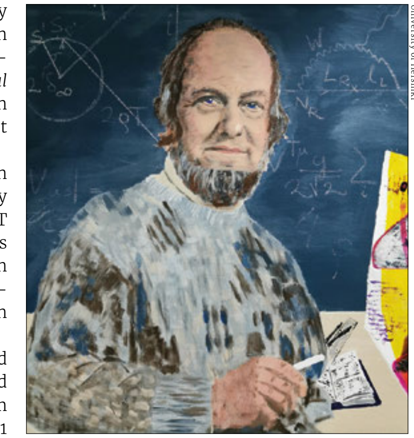
Roos was born on 28 October 1931. He completed an MSc degree in technical physics at the Helsinki University of Technology in 1956 and began his career in Stockholm at AB Atomenergi, where he investigated materials for radiation safety. However, he had basic science in his genes, or at least on his mind. Encouraged by his uncle, Ragnar Granit, who in 1967 was awarded the Nobel Prize in Physiology or Medicine, Roos became a research assistant in theoretical physics at the University of Stockholm, from where, a few years later, he continued to the Nordic Institute for Theoretical Physics and the Niels Bohr Institute in Copenhagen. In 1967, he defended his doctoral thesis on CP non-invariance in neutral-kaon decays.

Together with Arthur H Rosenfeld from Berkeley, Roos laid the foundations of the Particle Data Group (PDG). Rosenfeld published the first tables of particle data in 1957 and in 1963 Roos published his own particle tables. In 1964 these two tables were merged into what is now known as the *Review of Particle Physics*. Sixty years later, this highly cited opus has swollen to 1400 pages.

A particularly significant phase in Roos' career were the five years he spent at CERN in Geneva, although Finland was not yet a member of CERN in 1965. Victor Weisskopf, the Director-General of CERN, invited Roos, on the basis of his work with the PDG, to apply for a temporary position in the Theory Division, then lead by Léon Van Hove. Motivated by the work on the validation of properties of by then discovered elementary particles, CERN then invited Roos to lecture on statistical methods. This course eventually crystallised into *Statistical Methods in Experimental Physics*, published in 1971 in collaboration with Fred James, Daniel Drijard, Bernard Sadoulet and William Eadie.

Roos' international reputation is also based on another CERN-period achievement that greatly benefited the scientific community: the MINUIT software developed together with James. This is a versatile statistical tool that has been used in particle-physics research throughout the decades, with reference to the original publication still increasing today.

The years abroad brought the sociable and multilingual Roos a wide circle of friends and acquaintances among researchers and made him cosmopolitan. Roos returned to Finland in 1971 after the University of Helsinki appointed him as an associate professor in the field of elementary particle physics. From 1977 until his retirement, he served as a personal professor of particle physics. Later, Roos turned to cosmology in addition to elementary particles. He devoted himself to the field by writing a textbook, *Introduction to Cosmology*, which went through four editions between 1994 and 2015. Roos also served



University of Helsinki

A self portrait of Matts Roos.

as a member of the International Neutrino Commission for decades. In 1996 he organised the 17th International Conference on Neutrino Physics and Astrophysics in Helsinki.

In his spare time, Roos began to pursue visual arts in the 1980s, developing over the years from an enthusiastic amateur to a professional painter. He stated that art provides a counterbalance to research work, because "science progresses logically and art illogically". His interest in art must have been rooted in the family, as his father and brother were well-known photographers and filmmakers, and his sister was an architect.

Roos took an active part in the debates in society, supported colleagues behind the iron curtain with forbidden scientific literature or Solzhenitsyn, and established a think tank on the civil use of nuclear power. He also helped introduce Transcendental Meditation into Finland, after having experienced it himself during a congress in California in the early 1960s.

After returning to Finland, Matts Roos settled in Helsinki with his Swiss-born wife Jacqueline, whom he met while participating in a choral music society, and with the family's three children. In the summers, the family enjoyed their cottage in the Sipoo archipelago, where many colleagues also were invited.

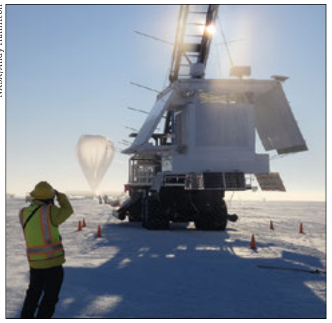
We shall keep the memory of the Dear alive.

Moshe M Chaichian and **Christophe Roos** *University of Helsinki*, and **Jukka Maalampi** *University of Jyväskylä.*

BACKGROUND

Notes and observations from the high-energy physics community

Dark-matter balloon



NASA/Andy Hamilton

In December 2025, the balloon-borne General Antiparticle Spectrometer (GAPS) flew at about 35 km above Antarctica. The mission targets low-energy cosmic-ray antinuclei, especially antideuterons, that some dark-matter models predict to arise from the galactic halo. Antideuterons could be produced in the annihilation of dark matter or its decay.

3.1 million

Detector channels in each endcap of CMS's new high-granularity calorimeter for the High-Luminosity LHC, an order of magnitude more than the calorimeter it will replace

Media corner

"The collider's gone, but RHIC will live on through the data."

Linda Horton, acting associate director of the US Department of Energy's Office of Nuclear Physics, reflects on the closure of Brookhaven's Relativistic Heavy Ion Collider after 25 years of operation (6 February, *Scientific American*).

"It is a 3D imaging of the proton, really in full glory."

Brookhaven physicist **Elke-Caroline Aschenauer** looks forward to the Electron–Ion Collider that will build on RHIC's discoveries, occupying the same tunnel and reusing much of the collider's equipment and infrastructure (6 February, *Science News*).

"Before we confirm one, what I want to do is rule out every other possible scenario that could cause a star to 'disappear.'"

Emma Beasor of Liverpool John Moores University urges caution in interpreting a vanishing star in the Andromeda galaxy as a newly formed black hole (12 February, *Scientific American*).

"AI is making people worse at physics. What we need is humans to read textbooks and sit down and think of new solutions to the hierarchy problem."

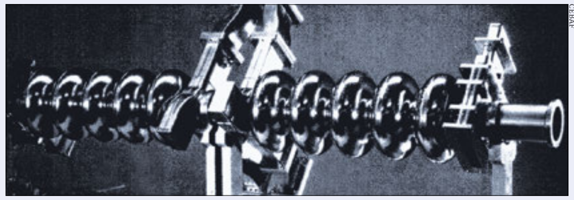
Cari Cesarotti, theory postdoctoral fellow at CERN, on how increasing reliance on AI tools may affect problem-solving and conceptual understanding in physics education (26 January, *Quanta Magazine*).

"If you cool something down to a temperature it's never been at before, it might do something interesting."

Richard Haley, professor of low-temperature physics at Lancaster University, speaking to BBC Future about ultra-cold experiments in particle physics and quantum technologies (13 January, *BBC*).

From the archive: March/April 1986

US nuclear physics: some like it cold



CEBAF

Two linked superconducting accelerating cavities, each of five cells, developed in a Cornell/CEBAF collaboration.

A new US nuclear physics research tool will soon make its appearance. It is the Continuous Electron Beam Accelerator Facility, CEBAF, proposed for construction at Newport News in Virginia. The latest plans aim for a superconducting linear accelerator which could be the first machine to use superconducting radiofrequency accelerating cavities on a large scale.

The advantages of superconducting cavities over conventional copper cavities have been evident for a long time. However, realizing these advantages has not been easy. European achievements have considerably boosted world confidence in the technology, leading to decisions to incorporate cryogenic cavities in projects at Darmstadt, DESY, KEK, and CERN. The CEBAF decision to go superconducting was also influenced by the progress in Europe.

The design has been revamped to incorporate a superconducting linear accelerator. The linac will be in two sections, each capable of giving 0.5 GeV to the electrons. To achieve the design energy of 4 GeV, the beam has to be recirculated four times through the linac and recirculating arcs are therefore needed at each end of the linac sections. In the two sections there will be a total of 50 cryostats containing 400 superconducting cavities, each 0.5 m long, operating at 1500 MHz. The cavity design has been developed at Cornell where prototypes have all exceeded the design specification of an accelerating gradient of 5 MeV per metre with a quality factor Q of 3×10^9.

● Text adapted from *CERN Courier* April 1986, pp 17–18.

Compiler's note

Further impetus for using superconducting radiofrequency (SRF) cavities at CEBAF came with plans for LEP at CERN, where energies much beyond 50 GeV per beam would require SRF technology. The aim for CEBAF to be the first machine to use SRF cavities was fulfilled with the first beam in 1994. At the dedication ceremony in 1996, the lab was renamed the Thomas Jefferson National Accelerator Facility, now better known as Jefferson Lab. CEBAF's energy was later pushed from 4 GeV to 6 GeV and, following an upgrade, since 2017 it has run at 12 GeV.

Until LEP II started up in 1995, CEBAF was the world's largest implementation of SRF cavities. Another innovation was its use of multipass beam recirculation. In 2003, CEBAF demonstrated energy recovery at just over 1 GeV, with one acceleration pass and one recovery pass – still the record for the highest energy recirculated for energy recovery.