WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the May/June 2026 issue of *CERN Courier*.

Most of the universe is void. Of the rest, most is invisible. Yet it weaves a sprawling cosmic web, lit at its nodes by clusters of galaxies. Stack many cluster pairs and a faint radio glow appears between, brighter than diffuse intergalactic gas alone can account for. Theorist Elena Pinetti explains how the excess may set new constraints on dark-matter models (p35).

A more earthly web threads Europe, carrying vital radiopharmaceuticals for modern cancer therapy. Produced in accelerators, reactors and mass separators, the isotopes must reach their destination before they decay. The supply chain that now sustains clinics began as an instrument of fundamental science (p30).

This edition of *CERN Courier* also explores neutrino tagging, a technique for taming the systematics that limit next-generation oscillation experiments. Conceived by Bruno Pontecorvo in 1979, it has come within reach of modern fast-timing technology, and a dedicated CERN facility has been proposed to do it at scale (p23).

In December, the European Strategy Group recommended the FCC-ee as CERN's next flagship collider. Alain Blondel, one of the earliest advocates of a circular Higgs factory, traces the case back half a century (p41).

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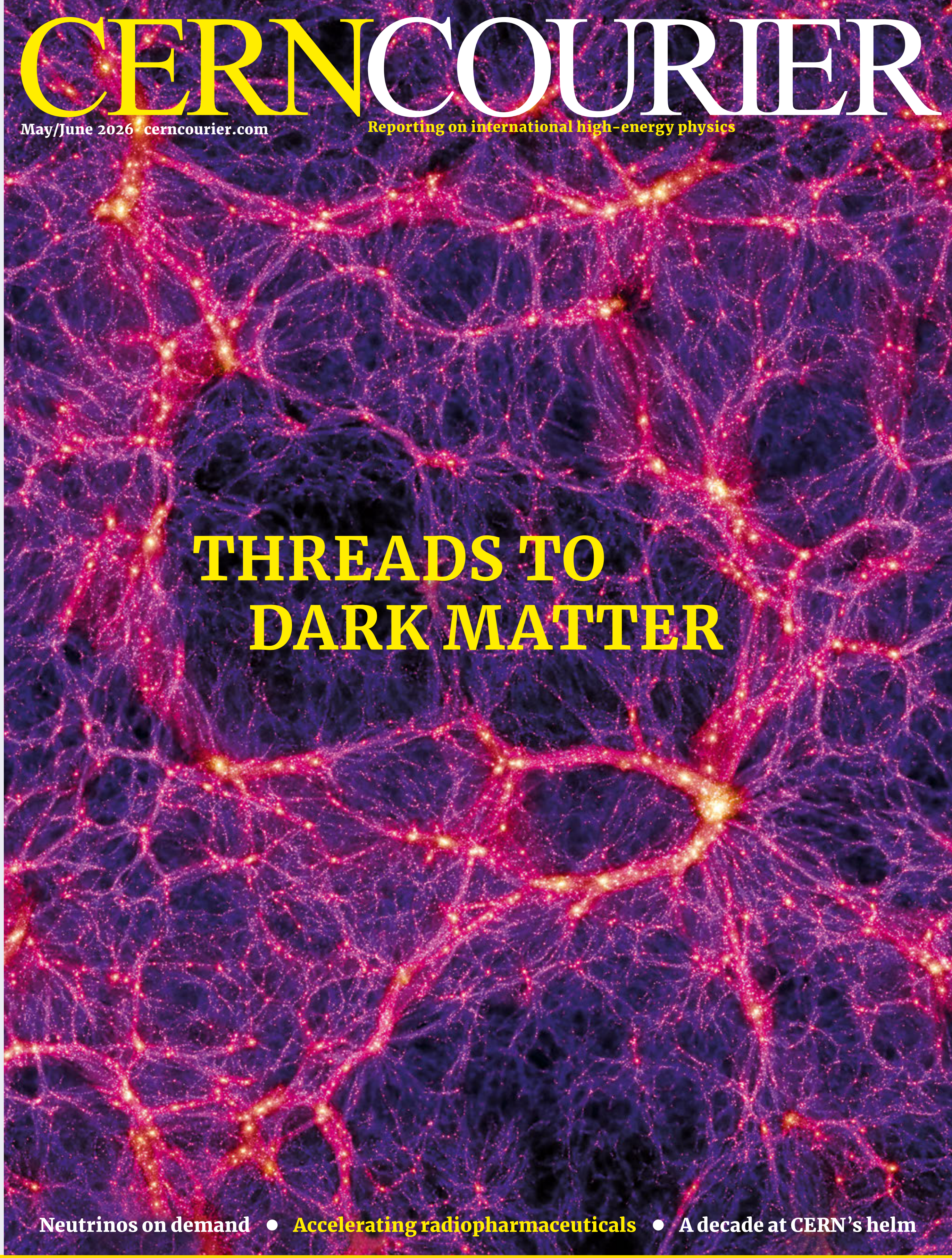
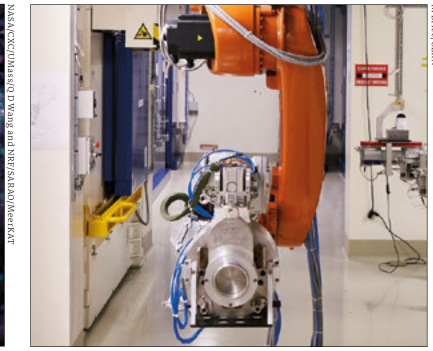
ASSOCIATE EDITOR: DAVIDE DE BIASIO



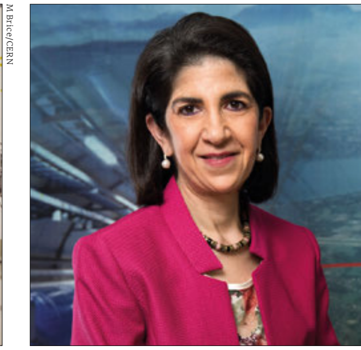
IN THIS ISSUE

Volume 66 Number 3 May/June 2026

Galactic clocks *A radio survey of the galactic centre found a lone pulsar candidate.* **11**



Radioactive medicine *Particle physics is helping scale the supply of medical radionuclides.* **30**



Looking back *Fabiola Gianotti reflects on two terms as CERN Director-General.* **43**

FROM THE EDITOR

A stack of signals

Davide De Biasio
Associate editor

Most of the universe is void. Of the rest, most is invisible. Yet it weaves the sprawling thread-like structure pictured on this issue's cover – a snapshot from the Millennium Simulation – lit at its nodes by clusters of galaxies. Stack many cluster pairs and a faint radio glow appears between, brighter than diffuse inter-galactic gas alone can account for. Theorist Elena Pinetti explains how the excess may set new constraints on dark-matter models (p35).

A more earthly web threads Europe, carrying vital radio-pharmaceuticals for modern cancer therapy. Produced in accelerators, reactors and mass separators, isotopes must reach their destination before they decay (p30). The machinery serving clinics was built first for nuclear and high-energy physics, and the supply chain that now sustains them began as an instrument of fundamental science.

Antimatter, by contrast, stays in the lab. Or does it? In March, 92 antiprotons completed a 30-minute loop around CERN's Meyrin site in the first controlled transport of antimatter beyond its production point (p7). The technique opens a path to high-precision tests of CPT symmetry at dedicated facilities, far from the noisy environment of CERN's Antimatter Factory.

This issue also explores neutrino tagging, a potential technique to overcome a precision barrier to next-generation oscillation experiments. In 1979, Bruno Pontecorvo conceived a way to match each neutrino in a beam to its parent decay, allowing the reconstruction of its energy and direction. A dedicated CERN facility has been proposed to do this at scale (p23), employing the same fast-timing technology used by NA62 to hunt for rare kaon decays (p9).

In December, the European Strategy Group recommended the FCC-ee as CERN's next flagship collider. Alain Blondel, one of the earliest advocates of a circular Higgs factory, traces the case back half a century (p41). Elsewhere on these pages: takeaways from Moriond Electroweak (p17), a conversation with former CERN Director-General Fabiola Gianotti (p43), the latest results from the LHC experiments (p13), and much more.

Mark upheld with grace the unspoken pact between the *Courier* and its readers

Twelve covers *The issues of* CERN Courier *edited by Mark Rayner, the first (bottom right) jointly with Matthew Chalmers.*

In the service of physics

A page of *CERN Courier* is a small unit of this field's memory. For almost 70 years, its editors have worked with the community to present the breadth of high-energy physics, and to hold each edition to the standards of rigour, accuracy and integrity the field expects of itself.

In his tragically all-too-short time at the helm, Mark Rayner led the *Courier* as a physicist and editor of the highest calibre (p51). He was a warm and discerning mentor to his team, an impeccable judge of physics, and a relentless worker who carried out his role with dignity. He had a flair for the image as much as for the word, and the covers he chose will forever bear his artistic sensibility. More importantly, he understood that a page outlives the day it goes to press.

Mark upheld with grace the unspoken pact between the *Courier* and its readers. The issues he edited are now part of the historical memory of high-energy physics.

Reporting on international high-energy physics

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NEWS ANALYSIS

ANTIMATTER

Antimatter hits the road

In transit *The BASE–STEP transport truck on CERN's Meyrin site on 24 March 2026. Inside, 92 antiprotons sit in a one-tonne portable trap.*

Take a bunch of antiprotons. To stop them annihilating, seal them inside a near-perfect vacuum, suspended in the bore of a superconducting magnet, and superimpose an electric field. Load them onto a truck, and drive off. On 24 March 2026, the BASE collaboration sent 92 antiprotons on a test loop around CERN's Meyrin site, achieving the first controlled and reversible transport of antimatter. The trip is the culmination of years of work to move antimatter precision measurements out of CERN's noisy Antimatter Factory, where BASE operates (*CERN Courier* January/February 2025 p6).

The collaboration's main target is CPT symmetry. Charge conjugation (C), parity inversion (P) and time reversal (T), taken together, are expected to leave physics invariant. Matter and antimatter must therefore have identical masses and magnetic moments of equal magnitude, with charges of opposite sign. BASE tests CPT directly on protons and antiprotons, confined in electromagnetic traps, by measuring their cyclotron and spin-flip frequencies. "At low energies, measurements usually use only matter systems, on the assumption that antimatter behaves the same way without testing it," says Christian Smorra, leader of the collaboration's transportable-trap project BASE–STEP. "Antiprotons are the only stable antibaryons that can be produced and trapped at low energies, enabling precise frequency measurements."

Noisy fields

So far, BASE results on proton and antiproton charge-to-mass ratios agree to 16 parts per trillion, and their magnetic moments to 1.5 parts per billion. The measured frequencies, however, scale linearly with the strong magnetic field that confines the particles, so any noise in it directly affects the result. The magnetic environment of CERN's Antimatter Factory now limits how far precision can be pushed.

One natural solution is to move the antiprotons elsewhere. To survive the journey, they must remain in an extreme vacuum, below 10^{-14} mbar, since contact with a single gas molecule means annihilation. "At those pressures, the only way to test the vacuum is to trap antiprotons and see how long they survive," explains Smorra. "We had no way to predict how much the pressure would rise in the room-temperature parts of the system during transport, so we had to rely on calculations and build the best possible setup to limit the gas flow into the trap."

The result is BASE–STEP: a one-tonne portable electromagnetic trap with up to four hours autonomous operation and a persistent superconducting magnet cooled by liquid helium. At those temperatures, the inner walls of the trap freeze out most gas molecules on contact, preserving the vacuum. Three further measures handle what the walls cannot manage alone. A 500 mm-long differential pumping section thins residual gas in the warm part of the system, a specialised valve – now in its third generation – seals the cold interior, and a dedicated pump captures any stray hydrogen.

The first injection of antiprotons, in December 2025, lasted three days. A subsequent run kept them trapped for more than a month, with cumulative experimental lifetimes now reaching two and a half. "Calculations suggest the trap could hold antiprotons for more than a year," says Smorra. "The limit is set by gas slowly accumulating on the cold trap surfaces. Once a single layer has built up, they can no longer trap new molecules, and the vacuum starts to deteriorate."

> **Calculations suggest that the trap could hold antiprotons for more than a year**

The 24 March test demonstrated that BASE–STEP could survive vibration and acceleration without losing its load. The team has now requested a low-magnetic-noise space at CERN to establish methods for transferring antiprotons between the transportable trap and a receiver experiment. Further afield, BASE–HHU at Heinrich Heine University Düsseldorf is being built to receive antiprotons from BASE–STEP and perform precision measurements. "We expect to need only one or two trips per measurement," says Smorra. The Düsseldorf transport will take around 10 hours, longer than the trap can run on its own. A generator on the truck will power a cryocooler to keep the magnet superconducting throughout.

Beyond CPT tests, the approach may prove useful to other precision searches. "We are also studying exotic interactions of antiprotons," comments Smorra, "such as antiproton–axion coupling or collision rates of millicharged particles with trapped antiprotons."

CERNCOURIER
VOLUME 66 NUMBER 3 MAY/JUNE 2026

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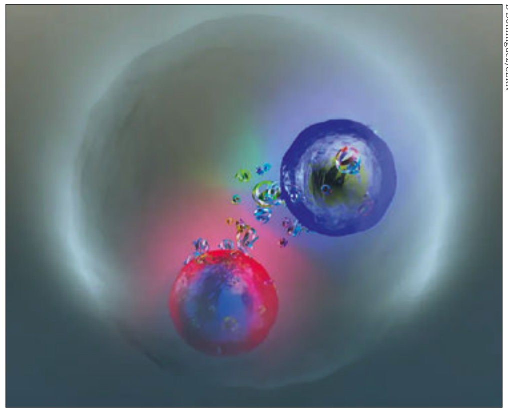
NEWS ANALYSIS

TOP-QUARK PHYSICS

Two channels for the top-antitop excess

The top quark was never meant to bind. And yet a year ago, CMS reported an excess of top-quark–antiquark pairs in dilepton events near the production threshold, consistent with the fleeting formation of a top-quark–antiquark quasi-bound state: toponium. ATLAS confirmed the effect just a few months later, rejecting a pure perturbative QCD interpretation at 7.7σ (*CERN Courier* September/October 2025 p9). CMS has now extended the case to an independent decay process.

The analysis, presented at this year's Rencontres de Moriond, looks at events in which one top decays into a charged lepton, a neutrino and a bottom quark, and the other into jets. In 138 fb^{-1} of Run 2 data at 13 TeV, the enhancement exceeds the pure-QCD prediction by more than five standard deviations, with an excess cross section of 5.1 ± 0.9 pb.



D Dominguez/CERN

A fleeting pair *Artist's impression of a top quark and an antiquark at the production threshold, where they may briefly form a quasi-bound state.*

"Establishing a signal in both channels was very important," says Regina Demina, who leads the University of Rochester CMS group. "The lepton + jets channel has higher statistics, thanks to the larger hadronic branching ratio of the W boson, and a single neutrino makes the kinematics easier to reconstruct. The systematic uncertainties differ from those in the dilepton channel."

The charm and bottom quarks live long enough to bind tightly with their antiparticles, and the resulting mesons appear as sharp, narrow peaks in the cross section. The top quark, by contrast, decays too quickly, with a width comparable to the binding energy that would hold a top-quark–antiquark system together. Any such state would manifest as a broad threshold enhancement, smeared over the smooth QCD continuum.

"The formation of bound states of charm or bottom quarks is a well-established effect, which allowed theorists to refine our understanding of the QCD binding potential," says Yu-Heng Yu, a graduate student at the University of Rochester who worked on the analysis. "Yet it came as a surprise that, given the very short lifetime of top quarks, such a quasi-bound state still manages to form in a small fraction of events."

The lepton + jets channel demanded two methodological adjustments. The first replaces the invariant mass of the top-quark–antiquark pair, whose resolution is limited near threshold, with their relative velocity as the discriminating observable. "If they form a bound state, the relative velocity should be much smaller than when they are produced independently," says Otto Hindrichs, also at Rochester. The second concerns the parity-sensitive observables that distinguish a pseudoscalar from a scalar interpretation of the bump. "These variables require a reconstruction method that identifies the down-type jet from the hadronic W decay," explains Hindrichs. "To achieve this, we developed a machine-learning technique that improves the correct identification of the top-quark decay products."

Some puzzles remain. The 5.1 pb cross section sits below the 8.8 pb measured in dilepton events, and the non-relativistic QCD reference of about 6.4 pb. "We do observe somewhat different signal strengths in the lepton + jets and dilepton channels, and we are actively investigating this difference," says Yu.

"With the current sensitivity, interpretations beyond the Standard Model cannot be excluded," Hindrichs adds. "A pseudoscalar heavy Higgs decaying into top-quark pairs would interfere strongly with the continuum, creating a characteristic peak-dip structure in the invariant $t\bar{t}$ mass. With enough statistics, this feature could be used to differentiate it from a quasi-bound state."

The top-quark–antiquark threshold enhancement in e^+e^- collisions was analysed by Fadin and Khoze in 1987, and extended to hadron colliders by Fadin, Khoze and Sjöstrand in 1990, before the 1995 discovery of the top quark at Fermilab. The standard assumption was that any signal would have to wait for a next-generation e^+e^- collider reaching the threshold, which would provide the cleanest measurement of the top-quark mass. "Even with Run 3 data, we will not be able to resolve the structure of the threshold region itself, because the resolution on both the invariant mass and the relative velocity is too limited," says Demina. "But the increased statistics should allow us to probe the spin-parity content of the bump, testing whether it carries scalar or vector contributions alongside the pseudoscalar one."

Further reading

CMS Collab. 2026 CMS-PAS-TOP-25-002.

BREAKTHROUGH PRIZE

Breakthrough honours g–2

The 2026 Breakthrough Prize in Fundamental Physics recognised the multi-decade programme to measure, with ever-increasing precision, the muon's anomalous magnetic moment ("g–2"). Announced in Los Angeles on 18 April, the $3 million award is shared among the living co-authors of the key publications from the muon g–2 collaborations at CERN, Brookhaven National Laboratory and Fermilab. Five further Breakthrough prizes recognised work in theoretical physics, dark-matter searches and cosmology.

The story of the g–2 began at CERN in 1959

As a charged particle with spin, the muon behaves like a tiny magnet whose strength is set by a dimensionless factor close to, but not exactly, two. The deviation, known as the anomalous magnetic moment, encodes virtual loop corrections from all sectors of the Standard Model (SM), and comparing it with theoretical predictions is among the most stringent tests of the theory.

Following initial measurements at Columbia University in 1957, the story began at CERN in 1959 with a small magnet borrowed from the University of Liverpool and Leon Lederman's idea to test quantum electrodynamics using the muon. The idea was to place muons in a uniform external magnetic field and observe their spin precession frequency, which depends on the strength of the field and the muon's magnetic moment. By 1962, a dedicated 6 m magnet at the Synchrocyclotron had enabled the CERN team to pin down the anomalous magnetic moment with a precision of 0.4%. Two storage-ring experiments at the Proton Synchrotron followed. The third reached a precision of 7.3 parts per million by 1979, and pulled hadronic effects into view for the first time.

K Morse/Breakthrough Prize

Celebration *From left to right: John Hill (Brookhaven), Chris Polly (Fermilab), Bradley Lee Roberts (Boston University), Young-Kee Kim (Fermilab), Mark Thomson (CERN), David Hertzog (University of Washington) and William M Morse (Brookhaven) at the Breakthrough Prize ceremony on 18 April 2026.*

Brookhaven's E821 experiment took over at the Alternating Gradient Synchrotron, reaching 540 parts per billion in its final 2006 report. The measurement stood 2.2–2.7σ above the SM evaluations of the day. In the summer of 2013, the experiment's 14 m-diameter superconducting storage ring travelled by road and barge from Long Island to Batavia, where Fermilab's more intense and pure muon beam awaited.

The final Fermilab measurement, announced in June 2025, reached a precision of 127 parts per billion: 30,000 times better than the first g–2 results (*CERN Courier* July/August 2025 p7). The theory side has moved as sharply. By August 2023, the discrepancy with respect to the 2020 prediction of the Muon g–2 Theory Initiative, an international consortium tasked with delivering a consensus SM value, had reached 5.1σ. Its 2025 update, which drops data-driven inputs to the hadronic vacuum polarisation in favour of a lattice-QCD consensus, sits within roughly 1σ of the measured value. The shift between the two predictions is itself about 3σ, reflecting an unresolved tension (*CERN Courier* January/February 2026 p41).

The 2026 Special Breakthrough Prize in Fundamental Physics went to David Gross (KITP, UC Santa Barbara) for a lifetime of contributions to theoretical physics. In 1973, Gross and his graduate student Frank Wilczek at Princeton, and independently David Politzer at Harvard, found that the strong nuclear force becomes weaker as quarks approach one another, a property known as asymptotic freedom. The three shared the 2004 Nobel Prize in Physics.

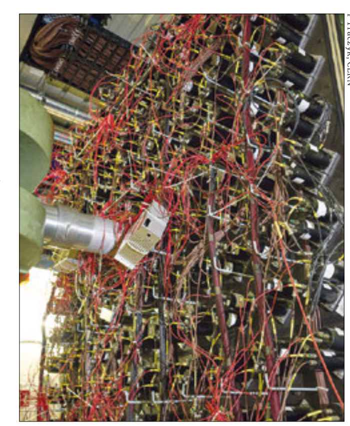
The inaugural Vera Rubin New Frontiers Prize went to Carolina Figueiredo (Princeton University). With Nima Arkani-Hamed and collaborators, she showed that the scattering amplitudes of three apparently unrelated theories, describing gluons, pions and a simplified scalar toy model, are generated by a single function, related by a simple shift of the kinematics. The result emerges naturally from a geometric formulation known as surfaceology.

Among the New Horizons in Physics Prize recipients, Benjamin Safdi (UC Berkeley) was recognised for his contributions to axion searches. Clay Córdova (University of Chicago), Thomas Dumitrescu (UCLA), Shu-Heng Shao (MIT) and Yifan Wang (New York University) shared a New Horizons in Physics Prize for the development of generalised symmetries in quantum field theory, with applications ranging from condensed-matter physics to string theory. A third New Horizons in Physics Prize recognised Dillon Brout (Boston University), J Colin Hill (Columbia University), Mathew Madhavacheril (University of Pennsylvania), Maria Vincenzi (University of Oxford), Daniel Scolnic (Duke University) and W L Kimmy Wu (Caltech) for analyses of cosmic microwave background data and Type Ia supernova samples, delivering tight constraints on the expansion and composition of the universe.

FLAVOUR PHYSICS

The kaon stays on script

Less than one in 10 billion positively-charged kaons decay into a pion and a neutrino–antineutrino pair. The NA62 experiment has now measured the rate of this rare process with an uncertainty 40% smaller than its previous result and a central value closer to the Standard Model (SM) prediction (*CERN Courier* November/December 2024 p11).



P Traczyk, CERN

Wired for rarity *Photomultiplier readout on the MUV3 detector at NA62, designed to study the $K^+ \to \pi^+\nu\bar{\nu}$ decay against an overwhelming background.*

"The $K^+ \to \pi^+\nu\bar{\nu}$ decay is a golden mode of flavour physics," says NA62 spokesperson Giuseppe Ruggiero. "It is highly suppressed in the SM, but its branching ratio can be predicted to better than 10% precision. The decay is also highly sensitive to new physics, with many models predicting dramatic changes to the branching ratio. Such modifications may come from indirect effects of new physics at or above the 100 TeV scale."

The scarcity of the decay called for a kaon factory. At NA62, a high-intensity proton beam from the Super Proton Synchrotron strikes a beryllium target, producing around 500 million secondary particles per second. About 6% are positively charged kaons. From that flux, the experiment must isolate the signal against backgrounds many orders of magnitude larger. The first 5σ observation, on data collected through 2022, was reported in 2024. The branching ratio came out at $(13.0^{+3.3}_{-3.0}) \times 10^{-11}$, consistent within 1.7σ with the SM prediction of around 8×10^{-11}, despite a central value about 50% higher. Two ▷

CERNCOURIER
VOLUME 66 NUMBER 3 MAY/JUNE 2026

years of additional data have now doubled the signal sample, and the central value has come down to $(9.6^{+1.9}_{-1.8}) \times 10^{-11}$, reaching a sub-20% precision.

Two new machine-learning techniques drove the increase in precision. "Reconstructing beam particles in the harsh environment of up to a gigahertz of incoming particles is challenging," says Joel Swallow of CERN, lead data analyst of the study. "To tackle this, we deployed a transformer encoder to pick out a kaon as it enters the experiment. Meanwhile, a combined convolutional and feed-forward neural network was developed for pion identification, which effectively uses images of the energy deposits in the calorimeters to more efficiently and accurately identify pions."

Two new machine-learning techniques drove the increase in precision

"Had the central value stayed where it was, the precision of the new measurement would have been sensitive to a 3σ excess," says Ruggiero. "If there had been an excess that large, this measurement was perfectly positioned to find it. Evidently, nature is a bit more subtle."

The new result tightens constraints on beyond-SM scenarios that would have predicted larger branching ratios, including those involving leptoquarks or heavy Z′ bosons. Still, the dominant uncertainty remains statistical, and additional data from 2025 and 2026 will improve the precision further.

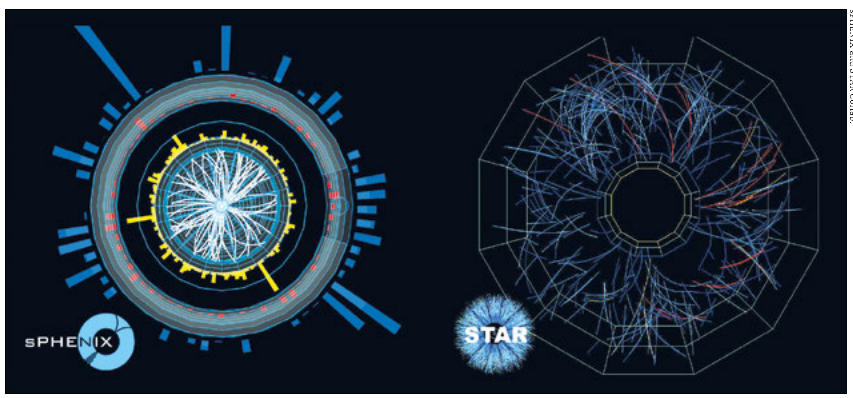
The neutral counterpart, $K_L \to \pi^0 \nu \bar{\nu}$, has yet to be observed. The current upper limit on its branching ratio, set by Japan's KOTO experiment at J-PARC, sits two orders of magnitude above the SM prediction. "Measuring both the charged and neutral modes is important," says Ruggiero. "Together, they enable a fully independent reconstruction of the unitarity triangle from kaon decays alone. Even if, in the end, the charged mode is consistent with the SM, it does not rule out significant enhancements from new physics to the neutral mode." The proposed KOTO-II, at J-PARC, is targeting a measurement of $K_L \to \pi^0 \nu \bar{\nu}$ in the 2030s.

Further reading

NA62 Collab. 2026 arXiv:2604.12649.

Accelerators

Final collisions for the RHIC



sPHENIX and STAR Collab.

Last drop *Oxygen–oxygen collisions recorded by the STAR and sPHENIX detectors on 6 February 2026, closing 25 years of RHIC operations.*

On 6 February 2026, beams of oxygen ions circulated through the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory for the last time. A leading facility in the study of hadronic matter and the strong force since 2000, RHIC now hands its tunnel and many of its components to its successor, the Electron–Ion Collider (EIC).

"Experiencing the challenges of first trying to get beams to circulate during commissioning in the fall of 1999, one could not have dreamed how far the performance of this machine would come," said Wolfram Fischer, chair of Brookhaven's Collider-Accelerator Department. "We've pushed well beyond the original design in terms of the number of collisions we can produce, the energy range of those collisions, the variety of ions we've collided, and our ability to align the spins of protons and maintain a high degree of this alignment or polarisation."

RHIC was conceived above all to study the quark–gluon plasma (QGP). In QGP, quarks and gluons, normally confined inside protons and neutrons, roam free under extreme temperature and density. The early universe is thought to have existed in this state for a fraction of a second after the Big Bang, before cooling into the ordinary matter around us.

Theorists had expected this primordial soup to behave as a weakly coupled gas of quarks and gluons. Gold–ion collision data from RHIC's four original detectors, BRAHMS, PHENIX, PHOBOS and STAR, found instead a strongly coupled liquid. By 2005 the collaborations had concluded that they were producing one of the lowest-viscosity substances ever observed, a nearly "perfect" liquid. Later runs traced how this extreme state of matter swirls, flows and cools, and revealed that even small collision systems can briefly form tiny droplets, overturning earlier ideas about how QGP forms.

"RHIC transformed nuclear physics by demonstrating the remarkable consequences of 'boiling the vacuum,'" said theorist Raju Venugopalan, paraphrasing T D Lee's description of matter governed by quantum chromodynamics.

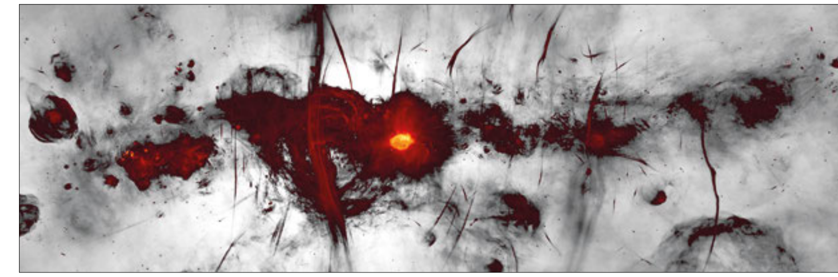
Beyond QGP, STAR and PHENIX measurements in polarised proton–proton collisions established that gluons carry a significant share of the proton's spin. In the final run, sPHENIX, the faster successor to PHENIX, became the first detector to record a continuous streaming dataset from RHIC's spin-polarised proton collisions – thus eliminating the need for triggers.

RHIC transformed nuclear physics by demonstrating the remarkable consequences of 'boiling the vacuum'

The final run also gave a sense of the scale of modern physics data: sPHENIX alone recorded more than 200 petabytes of raw data, more than every previous RHIC dataset combined, including 40 billion gold–ion collision events. Analysis of RHIC data will continue for at least another decade. Much of RHIC's infrastructure will then live on in the EIC, including its ion sources, pre-accelerator chain and one of its superconducting storage rings. A new electron ring will share the tunnel, crossing the ion beam at points where polarised electrons and ions will collide. The EIC will enable precision measurements that reveal how quarks and gluons are organised within protons or atomic nuclei, helping physicists to understand how mass, spin, and nuclear structure emerge from the strong force.

Astrowatch

On the hunt for cosmic clocks



I Heywood/SARAO

Where the clocks hide *The galactic centre, as seen at 1.28 GHz by the MeerKAT radio telescope. The bright spot at the centre marks the Sagittarius A* black hole, while the dense gas and radio filaments trace the extreme environment that complicates the search for pulsars.*

The galactic centre (GC) is one of the most extreme places we know – a dense stellar cluster filled with turbulent plasma, orbiting the four-million-solar-mass black hole Sagittarius A* (Sgr A*). For decades, astronomers have expected this region to host a rich population of pulsars. Yet only a handful have been detected, and none within a parsec of Sgr A*. A deep survey with the Green Bank Telescope, part of the Breakthrough Listen (BL) programme, has now delivered both a stringent non-detection of the expected population and an intriguing millisecond pulsar candidate near Sgr A*.

Pulsars are rapidly rotating, highly magnetised neutron stars, whose periodic radio emission sweeps across Earth like a cosmic lighthouse. Their stable periods make them among the most precise clocks in nature. Ever since Jocelyn Bell Burnell's 1967 detection of the B1919+21 pulsar, more than three thousand have been catalogued in our galaxy.

Many should populate the GC. The region hosts a dense concentration of massive stars that evolve and die in supernovae, leaving behind neutron stars. Population-synthesis models estimate the number of pulsars within the central parsec at hundreds, perhaps thousands. Moreover, the 2013 discovery of a magnetar (J1745–2900) just arcseconds from Sgr A* confirmed that neutron stars can survive, and be detected, in this environment.

Delving deep

Why, then, are they so elusive? Radio pulses are scattered by clumps of ionised gas along the line of sight, blurring them in time. The effect is severe everywhere, but worse near the dense GC, where it can stretch millisecond pulses to seconds at standard observing frequencies. Higher frequencies are scattered far less, and so pass through more cleanly. The BL GC survey took advantage of this, focusing on high radio frequencies of 8–12 GHz, well above the band typically used for pulsar searches. The observations total more than 20 hours between 2021 and 2023, with 11 hours on the innermost 1.4 arcminutes around Sgr A*. The result is one of the deepest pulsar searches ever performed in this region.

At the achieved sensitivity, the survey should have detected roughly 10% of the millisecond pulsars, rotating hundreds of times per second, and up to half of the slower, canonical pulsars expected if the GC population resembled that of the wider galaxy. It came up empty – almost.

In a one-hour scan, the survey identified a candidate consistent with an 8.19 millisecond pulsar, dubbed the Breakthrough Listen Pulsar (BLPSR). The signal was coherent across both time and frequency throughout the observation, with statistical tests on randomised data giving a chance occurrence rate of roughly one in a thousand (about 3σ) from its statistical properties alone, and closer to one in a million (approaching 5σ) when its coherent signal power is included.

These figures make a chance-origin unlikely on a single trial, though they are not, on their own, sufficient to establish a pulsar. The candidate did not reappear in subsequent observations, and a much stronger case is required before asserting an astrophysical origin. If confirmed, BLPSR would be the first millisecond pulsar found in the immediate GC environment, and an encouraging sign that more may yet lurk in the central parsec, just below current detection thresholds.

Still, the shortage of detections raises real questions. GC pulsars could be intrinsically fainter, older, or differently distributed than expected. Strong scattering may persist at higher frequencies through complex, localised structures in the interstellar medium. Selection effects, including long periods and unfavourable beaming geometry, could also play a larger role than usually assumed.

Millisecond pulsars are extraordinarily stable rotators, and serve as precision clocks for measuring gravitational effects. A confirmed millisecond pulsar in close orbit around Sgr A* may open a new window on strong-field gravity, allowing precision tests of general relativity in the immediate vicinity of a supermassive black hole.

The connection to fundamental physics extends further. Wide-band, high-resolution radio data of the kind used here have also been turned to the search for axion dark matter, where axion-to-photon conversion in stellar magnetic fields would imprint narrow spectral features. Modern radio surveys are increasingly designed for this kind of breadth, with the same observations used to search for pulsars, signatures of dark matter, and potential signs of extraterrestrial technology.

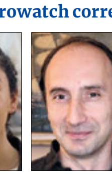
The path forward needs deeper, more sensitive searches, supported by advances in instrumentation and analysis. The Square Kilometre Array and the next-generation Very Large Array promise to overcome the current sensitivity and frequency limitations. Open data are equally important. By releasing GC observations publicly, BL enables the broader community to pursue independent analyses and complementary science cases.

If confirmed, a millisecond pulsar near Sgr A* would be a step forward in our understanding of the GC, and a potential new probe of physics in its most extreme regimes.

Further reading

K I Perez *et al.* 2026 doi:10.3847/1538-4357/ae336c.
J M Cordes and T J W Lazio 1997 doi:10.1086/303569.
R P Eatough *et al.* 2021 doi:10.1093/mnras/stab2344.

Guest Astrowatch correspondents



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CERNCOURIER
Volume 66 Number 3 May/June 2026

NEWS DIGEST


CERN

Chile's representative Claudia Fuentes Julio with CERN Director-General Mark Thomson.

Chile becomes associate member

On 2 April 2026, Chile officially became an Associate Member State of CERN, the second in the Americas after Brazil and the 11th overall. Cooperation between CERN and Chilean institutions dates to 1991, with current participation spanning ATLAS, CMS, LHCb, SND@LHC, NA64, SHiP and ISOLDE. Associate membership grants Chile a voice in the laboratory's governing bodies, opens CERN's graduate programmes and limited-duration staff positions to Chilean nationals, and allows Chilean firms to bid for procurement contracts.

Doubly charmed, again

At the Moriond Electroweak conference, the LHCb collaboration reported the first observation of the doubly charmed baryon Ξ_{cc}^{+} (LHCb Collab. 2026 arXiv:2603.28456), the first new particle from the upgraded LHCb detector. With quark content ccd, the new state is the isospin partner of the Ξ_{cc}^{++} (ccu) discovered by LHCb in 2017 (*CERN Courier* July/August 2017 p8), completing the lightest doubly-charmed doublet. Discovered in 6.9 fb^{-1} of 13.6 TeV proton–proton collisions recorded in 2024, the signal has a significance exceeding seven standard deviations. The mass is measured to be 3619.97 ± 0.83 (stat) ± 0.26 (syst) +1.90/−1.30 (lifetime) MeV, in agreement with theoretical expectations. Although the d quark is heavier than the u, the central value of the Ξ_{cc}^{+} mass falls about 1.8 MeV below that of its doubly charged partner, due to the different electromagnetic interaction between the light quark and the heavy diquark.

Chips to the Moon

On 1 April 2026, NASA's *Artemis II* mission launched on the first crewed lunar journey since 1972, carrying six Timepix chips developed at CERN within the Medipix2 collaboration (*CERN Courier* September/October 2024 p37). The chips, derived from the same hybrid-pixel technology used to track particles at the LHC, register individual particle hits in real time and reconstruct the type, energy and direction of incoming radiation. They are arranged in three-chip modules across two sensor units of NASA's Hybrid Electronic Radiation Assessor (HERA), inside the *Orion* spacecraft. Astronauts on the 10-day mission, which travelled through the Van Allen belts and beyond Earth's geomagnetic shield, were expected to receive tens of millisieverts of radiation, roughly 10 times the typical annual exposure on Earth. The data will be used to characterise radiation exposures inside the Orion spacecraft.


NASA

Artemis II *lifts off.*

New record for SuperKEKB

On 19 March 2026, the SuperKEKB electron–positron collider at Japan's KEK laboratory achieved a peak instantaneous luminosity of 5.24×10^{34} cm^{-2}s^{-1}, the highest value ever reached by a particle collider. The achievement extends a series of upward steps from 4.71×10^{34} cm^{-2}s^{-1} in June 2022 and 5.1×10^{34} cm^{-2}s^{-1} in December 2024. SuperKEKB feeds the Belle II detector with large amounts of B and D mesons and tau leptons near the ϒ(4S) resonance at 10.58 GeV, allowing precision tests of the Standard Model in the flavour sector. The luminosity gain rests on the nano-beam scheme, in which a large horizontal crossing angle and extreme vertical focusing squeeze the beams at the interaction point to a few hundred nanometres. Belle II has now accumulated 763 fb^{-1} of integrated luminosity.


S.Takahashi/KEK

The Belle II detector.

DESI calls time

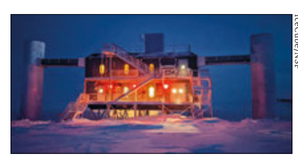
The Dark Energy Spectroscopic Instrument (DESI) completed its five-year survey ahead of schedule, with a final tally exceeding 47 million galaxies and quasars plus 20 million stars. Operating from the 4 m Mayall Telescope at Kitt Peak in Arizona, DESI assembled the largest 3D map of the universe yet, tracing cosmic structure back 11 billion years. Earlier, DESI data hinted that dark energy may evolve slightly with cosmic time (*CERN Courier* May/June 2025 p11), thereby deviating from the standard model of cosmology. The survey will continue into 2028 and expand its map from 14,000 to 17,000 square degrees of sky.

Robot down the LHC

A compact robot developed jointly by CERN and the UK Atomic Energy Authority will inspect regions of the LHC beamline that human operators cannot reach. Named PipeINEER, the device measures 3.7 cm in width and 20 cm in length, and can travel through the beam pipe under battery power for distances up to 6 km. Its target is the roughly 2000 plug-in modules that absorb the beam pipe's expansion and contraction through repeated thermal cycling. Each module relies on thin radio-frequency fingers to maintain electrical contact across the joint, where even slight deformations can obstruct the beam. Onboard cameras, combined with a machine-learning classifier trained on real LHC images, flag abnormalities, and the robot autonomously returns to its launch point to report the defect's location. Performance trials over 60 km are planned for 2026, ahead of operator deployment in 2027.

Seyferts in the south

On 24 March 2026, the IceCube collaboration reported the first evidence from the southern sky for high-energy neutrino emission from X-ray bright Seyfert galaxies, a class of active galaxies powered by accretion onto a supermassive black hole and typically lacking strong relativistic jets (IceCube Collab. 2026 arXiv:2602.10208). The result extends the 2022 evidence of TeV neutrinos from the nearby Seyfert galaxy NGC 1068 in the Northern Hemisphere (*CERN Courier* January/February 2023 p10). Using 10 years of IceCube data and a sample of 14 X-ray bright galaxies, the collaboration found a combined signal of $6.7^{+4.0}_{-3.2}$ excess neutrino events, inconsistent with background at 3σ. Gamma rays from the central regions of galaxies are absorbed by the dense radiation field surrounding their supermassive black holes, while neutrinos pass through unimpeded, offering a direct probe of the high-energy processes taking place there.


IceCube/NSF

The IceCube Observatory.

CERNCOURIER.COM

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

A sharper probe of a rare B_s decay

The $B_s \to \phi\mu^+\mu^-$ process, in which a bottom quark decays into a strange quark and a pair of oppositely charged muons, is a powerful probe of physics beyond the Standard Model (SM). For the first time, the CMS collaboration has measured its branching fraction as a function of q^2, the squared invariant mass of the dimuon pair. In the low-q^2 region, from 1.1 to 6 GeV^2, the result lies 4.2σ below SM predictions obtained from a range of form-factor calculations.

In the SM, the weak nuclear force is mediated by the heavy gauge bosons W^+, W^- and Z^0. Transitions mediated by the Z^0 boson in which fundamental particles, such as quarks, change their flavour without altering their electric charge are known as flavour-changing neutral current (FCNC) processes. These transitions are absent at tree level in the SM and can only happen via complex, higher-order "penguin" or "box" loop diagrams. Moreover, the Glashow–Iliopoulos–Maiani mechanism ensures that contributions from the up-type quarks in the loop largely cancel, heavily suppressing FCNCs. As a result, these rare processes provide a sensitive probe for physics beyond the SM.

The $B_s \to \phi\mu^+\mu^-$ decay is an FCNC transition where a bottom quark decays to a strange one, with the intermediate loop dominated by a top quark. Recent studies of similar processes have revealed tensions between experimental measurements and theoretical predictions for both the branching fraction and angular observables. Specifically, using 9 fb^{-1} of data collected at 7, 8 and 13 TeV centre-of-mass energies, the LHCb collaboration observed that the $B_s \to \phi\mu^+\mu^-$ branching fraction lies 3.6σ below the SM prediction (*CERN Courier* September/October 2021 p15).

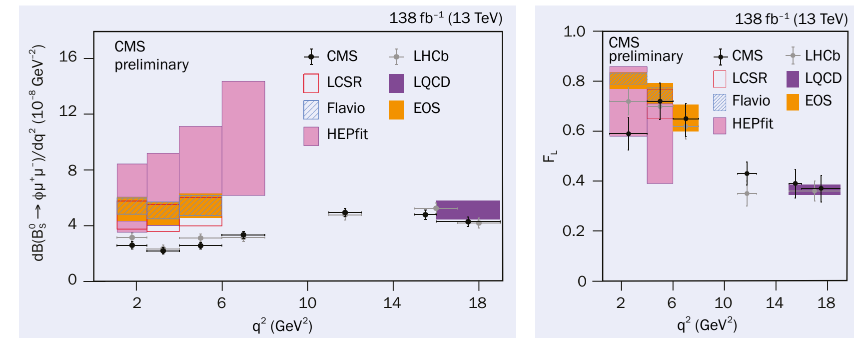


Fig. 1. *Differential branching fraction (left) and angular observable F_L (right) for the $B_s \to \phi\mu^+\mu^-$ process as functions of q^2, compared with SM predictions. The branching fraction lies 4.2σ below Flavio expectations in the low-q^2 region.*

In this new result, the CMS collaboration reports its first differential measurement of the branching fraction of the $B_s \to \phi\mu^+\mu^-$ decay as a function of q^2, using 138 fb^{-1} of data collected at 13 TeV centre-of-mass energy. The B_s-meson candidate is reconstructed in the $K^+K^-\mu^+\mu^-$ final state by requiring soft-muon identification and high-purity hadronic tracks. The two hadron tracks, assigned the kaon mass hypothesis, are paired to form the φ-meson candidate. The narrow natural width of the φ resonance enables a clean selection with low background.

The analysis reveals a 4.2σ tension between the measured branching fraction and SM predictions

Signal events are extracted from extended, unbinned maximum-likelihood fits to the $K^+K^-\mu^+\mu^-$ invariant mass distribution over various q^2 intervals. The branching fraction is then measured relative to the normalisation channel $B_s \to J/\psi\phi$, which shares the same final state, allowing many systematic uncertainties to cancel. The angular observables F_L and A_6 are extracted in each q^2 bin, from an unbinned maximum-likelihood fit to the three-dimensional distributions of the B_s candidates' invariant mass and two angular variables.

While the angular observables F_L and A_6 are consistent with expectations, the analysis reveals an up to 4.2σ tension between the measured branching fraction and SM predictions (see figure 1). Still, the current sensitivity is limited by statistical constraints. The inclusion of Run 3 data will significantly reduce these uncertainties, yielding the improved precision required to address the persistent anomalies in the beauty quark sector.

Further reading

CMS Collab. CMS-PAS-BPH-23-003.

ALICE

Jets boost nuclear coalescence

The production mechanism of light (anti) nuclei in hadronic collisions has been studied in several experiments over the past decades, but is still not fully understood. One candidate mechanism is baryon coalescence, in which nuclei can form only if preexisting nucleons only if they are close in phase space. The ALICE collaboration has now reported the first measurement of deuteron production in and out of jets in p–Pb collisions at a centre-of-mass energy per nucleon pair of 5.02 TeV. The results are consistent with the enhancement expected from coalescence models.

The results are consistent with the enhancement expected from coalescence models

Jets, the collimated emission of hadrons produced by the hadronisation of high-energy quarks, are a natural testing ground for coalescence, as the nucleons they contain are typically close in phase space. Comparing yields inside and outside jets can then test the mechanism directly. In the ALICE analysis, the coalescence probability is investigated by calculating the coalescence parameter B_A, defined as the ratio between the nucleus invariant yield and the proton invari- ▷

CERNCOURIER
Volume 66 Number 3 May/June 2026

ant yield raised to the mass number A of the nucleus. This quantity is calculated both in (B_A^{jet}) and out of jets (B_A^{UE}, where UE represents the underlying event). In the latter, the density of produced particles is expected to be lower, and thus coalescence should be less likely. If proximity in phase-space affects the coalescence probability, B_A^{jet} should therefore exceed B_A^{UE}. Otherwise, the two should be similar.

Three regions of equal width are used to study the jet-correlated production: "toward", "away" and "transverse" to the jet axis, with the direction approximated by the highest-transverse-momentum particle in the event. The in-jet contribution is obtained from the toward region by subtracting the underlying event, captured by the transverse region. B_2^{jet} appears to be enhanced with respect to B_2^{UE} (see figure 1), as expected from coalescence models.

Compared to previous studies in pp data, the system formed in p–Pb collisions is slightly larger and produces more particles, providing additional constraints on coalescence. The enhancement of B_2^{jet} with respect to B_2^{UE} is found to be larger in p-Pb than in the corresponding pp measurement at 13 TeV. This difference could be explained by the different source sizes and, possibly, by different particle-species compositions of the jets.

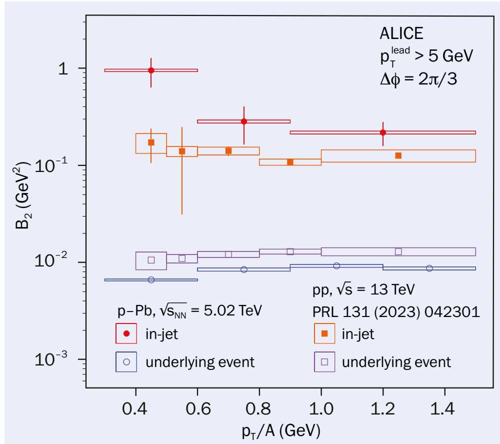


Fig. 1. *Deuteron coalescence parameter B_2 in jets (full markers) and out of jets (open markers) in p–Pb collisions at a centre-of-mass energy per nucleon pair of 5.02 TeV (circle markers), compared with the measurements in pp collisions at a centre-of-mass energy of 13 TeV (square markers).*

Further investigations of the coalescence parameter in and out of jets will be carried out with data from Run 3 of the LHC, which includes software-triggered pp data samples up to three orders of magnitude larger than those collected in Run 2. The full exploitation of this data will allow for the inclusion of A = 3 nuclei (^{3}He, triton) and the extension of the transverse momentum coverage to higher values, providing additional information to constrain the processes behind the formation of light (anti)nuclei.

Further reading

ALICE Collab. 2026 arXiv:2602.22880.
ALICE Collab 2023 *Phys. Rev. Lett.* 131 042301.

ATLAS

Two new CP tests for Higgs couplings

The origin of the observed asymmetry between matter and antimatter in the universe, of the order of one part in 10 billion, is one of the open questions in particle physics. In 1967, Andrei Sakharov showed that one of the necessary conditions to generate such an imbalance in the early universe is the violation of the combined charge-conjugation and parity (CP) symmetry. In the Standard Model (SM), CP violation arises from a complex phase in the quark mixing matrix, but this contribution is too small to account for the observed asymmetry. Additional sources of CP violation are therefore required, such as contributions from the neutrino sector or from other sources beyond the SM.

The discovery of the Higgs boson has opened a new sector in which to search for additional CP-violating interactions. The ATLAS experiment at the LHC recently reported the results of two new analyses that probe the CP properties of Higgs-boson interactions with electroweak gauge bosons, including the structure of its couplings to longitudinally and transversely polarised W and Z bosons.

The first comes from a measurement of Higgs production through the vector boson fusion mechanism (VBF), with the Higgs boson decaying into two photons. It is the first ATLAS measurement to use Run 3 data, collected between 2022 and 2024, to probe CP violation in the interaction between the Higgs boson and electroweak gauge bosons.

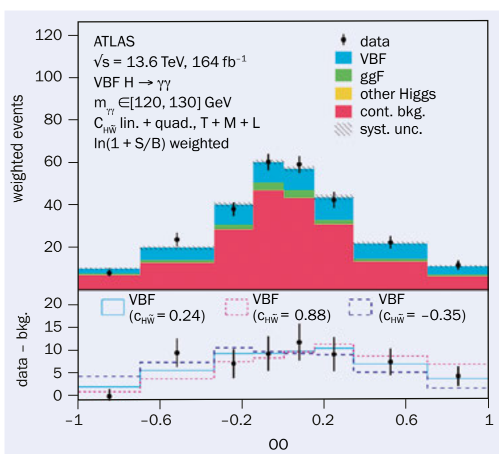


Fig. 1. *Distribution of the optimal observable (OO) in the VBF H → γγ analysis. Events are weighted by ln(1 + S/B), where S and B are the best-fit signal and background yields. The lower panel shows the background-subtracted data compared with the best-fit VBF result ($c_{H\tilde{W}}$ = 0.24) and two CP-violating scenarios, corresponding to two values of the $c_{H\tilde{W}}$ coefficient excluded at 95% CL by shape-only fits.*

The Higgs decay into two photons provides a clean experimental signature with a large sample of Higgs events. The analysis exploits CP-odd observables, which change sign under a CP transformation, and whose average over the full phase space vanishes in the absence of CP violation. Any observed asymmetry would therefore signal a violation of CP symmetry. One such quantity, used in this analysis, is the optimal CP-odd observable. It is constructed from the per-event ratio of the CP-odd SM–BSM interference term to the SM matrix element squared, evaluated from the reconstructed four-momenta of the Higgs boson and the two jets.

No asymmetry was observed (see figure 1), and results were interpreted in the Standard Model effective field theory (SMEFT) framework. SMEFT provides a systematic, model-independent parameterisation of potential new-physics effects at energy scales beyond those directly accessible at the LHC, by extending the SM Lagrangian with higher-dimensional operators parameterised by Wilson coefficients. Constraints on these coefficients are broadly reinterpretable across a wide class of BSM scenarios. This new result improves the Run 2 limits by more than a factor of two.

The second result combines measurements from several Higgs-boson decay channels and production modes recorded during Run 2 to extract even stronger limits on possible CP-violating interactions. This combination uses the full Run 2 results from VBF H → ττ, H → WW*, VBF H → γγ, H → ZZ* and WH with H → $b\bar{b}$. A strategy similar to that of the Run 3 VBF H → γγ analysis was employed in all the single channels by looking for asymmetries in CP-odd observables and interpreting the results in terms of SMEFT. In addition to constraining individual sources of CP violation, the combination disentangles the effects from multiple sources, since different channels probe different combinations of operators. This allows simultaneous limits to be set on three CP-violating Wilson coefficients, yielding the most stringent constraints to date (see figure 2).

These new results highlight the breadth of the ATLAS programme aimed at understanding the CP properties of the Higgs boson and its interactions with electroweak gauge bosons. They also demonstrate the growing potential of the Run 3 dataset to address open questions in the Higgs sector of the SM.

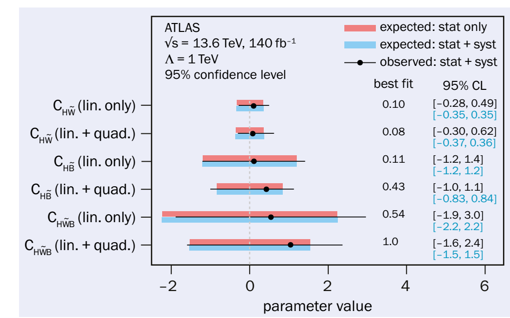


Fig. 2. *Best-fit values and 95% CL intervals for three CP-violating Wilson coefficients, from a simultaneous fit combining all Run 2 CP analyses sensitive to the Higgs coupling to electroweak gauge bosons. The results are shown for both the linear and the linear-plus-quadratic scenarios, with the latter yielding tighter but less theoretically clean limits. Expected limits with statistical uncertainties only are shown for comparison.*

Further reading

ATLAS Collab. arXiv:2603.20087.
ATLAS Collab. arXiv:2603.20117.

LHCb

An upgraded take on CP violation

The LHCb collaboration has announced its first Run 3 measurement of the CKM angle γ, a key parameter describing CP violation in the quark sector. The measurement, consistent with previous results, yields γ = (68.1 ± 6.7)°, and will provide an important input to the world average.

The matter–antimatter asymmetry in the universe remains one of the central puzzles in physics, and violation of the combined charge-parity (CP) symmetry is a prerequisite for it. Within the Standard Model (SM), the only established source of CP violation is the complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) matrix, which governs the weak transitions between quarks of different flavour. Precise experimental tests of the CKM framework thus play a central role in understanding CP violation and weak interactions.

Among the CKM parameters, the angle γ is central to testing the SM paradigm. Its direct determination through B → DK decays provides a clean theoretical environment and is largely insensitive to physics beyond the SM. Indirect determinations, obtained from global fits to other CKM observables under the assumption of CKM unitarity, currently achieve higher precision, but involve loop-level processes where new physics could enter, and are limited by challenging theoretical uncertainties. A precise direct determination of γ is therefore essential to compare the two approaches and provide a stringent test of the CKM picture.

LHCb is the best-positioned experiment to produce such a determination. Its highly efficient tracking system, excellent vertex resolution and powerful particle-identification capabilities allow it to reconstruct large samples of B → DK decays. As a result, LHCb measurements currently dominate the world average on γ, with a recent combination yielding γ = (62.8 ± 2.6)°. After a major upgrade of the detector from 2019 to 2022, the experiment now records data at five times the previous luminosity and operates with a highly-efficient, fully software-based trigger, significantly increasing its physics reach.

The matter–antimatter asymmetry in the universe remains one of the central puzzles in physics

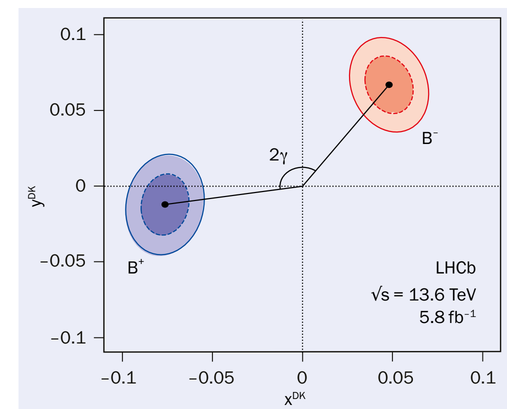


Fig. 1. *Two-dimensional likelihood contours of the CP-violating observables x^{DK} and y^{DK}, measured separately for B^+ (blue) and B^- (red). Shaded areas indicate the 68% and 95% confidence levels from profile-likelihood scans, while the dashed and solid lines are obtained from two-dimensional Gaussian approximations. The two vectors differ by a relative rotation of 2γ.*

LHCb has now measured the CKM angle γ in the golden channel $B^{\pm} \to DK^{\pm}$, with $D \to K_S^0 h^+h^-$, using data collected by the upgraded LHCb detector between July and October 2024, corresponding to an integrated luminosity of 5.8 fb^{-1}. The decay $B^{\pm} \to D\pi^{\pm}$ is included to help control detector-induced effects and reduce the dependence on simulation, leading to a high-precision measurement. About 16,000 $B^{\pm} \to DK^{\pm}$ and 240,000 $B^{\pm} \to D\pi^{\pm}$ signal candidates were observed by inspecting their invariant-mass spectra.

Despite using only four months of Run 3 data, corresponding to a lower integrated luminosity than the combined Run 1 and Run 2 dataset, the signal yield is 17% larger. This illustrates the substantial gain in performance from the upgraded detector and reoptimised software trigger system. CP-violating observables are extracted through a simultaneous analysis of data across the decay phase space (see figure 1). A clear signature of direct CP violation is visible as the opening angle between the B^+ and B^- vectors: the two differ by a relative rotation of 2γ, directly encoding the CP-violating phase. Interpreting these observables in terms of the underlying physics parameters yields γ = (68.1 ± 6.7)°.

Excellent precision has already been achieved with a small fraction of the LHCb Run 3 dataset. The full dataset, projected to increase the sample size by a factor of four, is expected to produce the most precise direct measurement of γ. The planned LHCb Upgrade II, with its much larger dataset and enhanced detector capabilities in the HL-LHC era, will further strengthen the tests of the SM through increased sensitivity to CP violation.

Further reading

LHCb Collab. arXiv:2605.03501.

CERNCOURIER
Volume 66 Number 3 May/June 2026

FIELD NOTES

Reports from events, conferences and meetings

RENCONTRES DE MORIOND: ELECTROWEAK INTERACTIONS & UNIFIED THEORIES

Rencontres de Moriond turns 60

For 60 years, Rencontres de Moriond has brought theorists and experimentalists in high-energy physics into close, sustained contact. The 2026 Electroweak session, held in the Alpine town of La Thuile, Italy, from 15 to 22 March, gathered around 140 participants for a week covering flavour, neutrinos, dark matter, Higgs and beyond-the-Standard Model physics.

Several updates came from the flavour sector. The LHCb collaboration presented the first measurement of the CP-violating angle γ using a small fraction of the Run 3 dataset (see p15). This result, compatible with previous determinations, demonstrated the improved sensitivity of the upgraded trigger. LHCb also reported the observation of a new doubly charmed hadron, the Ξ^{+}_{cc}. The BES III collaboration showed many new measurements in charm and tau physics, while Belle II presented an updated measurement of $R(D^*)$ – a test of lepton-flavour universality comparing τ leptons with electrons and muons in the $B \to D^* \ell \nu$ decay. This new result, with its improved precision, is consistent with both the Standard Model (SM) at 1.5σ and the world average at 1.3σ. The growing LHCb Run 3 dataset and the record peak luminosity reached by SuperKEKB will enable several interesting results in B-physics.

Branching out

NA62 presented a new result based on 2023–2024 data for the very rare decay $K^+ \to \pi^+ \nu \bar{\nu}$ (p9), whose SM branching ratio of order 10^{-10} makes it highly sensitive to new physics. Combined with previous NA62 data, the new result determines the branching ratio with a precision of about 20%, in agreement with the SM prediction.

In neutrino physics, new results addressed the sterile neutrino anomalies ($\Delta m^2 \sim 1\,eV^2$). The MicroBooNE experiment, using a combination of data from the Booster Neutrino Beam and the NuMI beam at Fermilab, excluded essentially all the parameter space favoured by the MiniBooNE and LSND anomalies at 95% confidence level. Similarly, the KATRIN experiment showed new results excluding almost all the parameter space

C Tavila

Anniversary photograph *Participants of the 60th Rencontres de Moriond form the figure 60 on the snow above La Thuile, Italy.*

The limits from the LHC experiments provide strong guidance for theorists when building new models

favoured by the Gallium anomaly. The 3 + 1 sterile-neutrino explanation of the anomalies now seems to be excluded (see *CERN Courier* January/February 2026 p8), although new-physics alternatives are still under scrutiny. The JUNO experiment, which measures antineutrinos from nuclear reactors, released its first results based on 59 days of data-taking. With this small fraction of the target exposure, it has already achieved world-leading accuracy on the θ_{12} and Δm^2_{21} mixing parameters. The main goal of JUNO is to establish the ordering of the three neutrino masses, and it should achieve 3–4σ significance in about six to seven years of data-taking, with detector performance already close to the design.

New results from direct searches for dark matter in the 1 GeV–10 TeV range were presented by the LUX-ZEPLIN, XENONnT and DarkSide-50 experiments. The exclusion limits for the WIMP spin-independent cross-section are now approaching $10^{-48}\,cm^2$ for masses in the ~30–70 GeV region. In addition to the "standard" analyses, optimised for WIMPs above 10 GeV, dedicated techniques have been developed to cover the lower WIMP mass region (1–10 GeV). XENONnT and LUX-ZEPLIN are now entering the "neutrino fog", an irreducible background from coherent elastic neutrino–nucleus scattering, and both report first signals from ^{8}B solar neutrinos.

Many searches for phenomena beyond the SM at the LHC were presented by the ATLAS and CMS collaborations. In addition to the "classical" high-energy signatures, the experiments are now investing large resources to investigate the more challenging phase-space regions characteristic of models with feebly interacting particles and compressed-SUSY scenarios. New trigger strategies, such as scouting and trigger-level analyses, parked data and delayed streams, and end-of-fill triggers, have been developed to address these complicated topologies, while dedicated reconstruction, calibration and machine-learning techniques help identify non-conventional signatures. Despite great efforts, no significant signals have been found – but the limits from the LHC experiments provide strong guidance for theorists when building new models.

Golden era

The ATLAS and CMS collaborations presented several new results on Higgs-boson physics. New total and differential cross-section measurements in the "golden" $H \to ZZ^* \to 4\ell$ channel were shown, using about half of the LHC Run 3 data set (2022–2024). With this subset of the total collected data, the two experiments have already reached a precision on the total cross-section of less than 10%.

A new ATLAS measurement reached, for the first time, 3σ evidence for the inclusive $H \to bb$ production with transverse momentum above 450 GeV. When the detectors were designed, this process was considered unobservable due to the large QCD dijet background. The achievement comes from developing and calibrating *in situ* a new algorithm based on graph neural networks, optimised to identify boosted objects decaying into heavy-flavour jets. ▷

CERNCOURIER
VOLUME 66 NUMBER 3 MAY/JUNE 2026

Concerning di-Higgs (HH) production, which provides critical information about the Higgs boson self-couplings and constraints on its potential, ATLAS and CMS presented their legacy Run 2 combination. The measured signal strength is $\sigma/\sigma_{SM} = 0.8^{+0.9}_{-0.7}$, showing sensitivity to the SM signal at better than 1σ. The performance gains already seen with Run 3 data point to possible evidence for the process by combining the two experiments' Run 2 and Run 3 datasets, assuming the SM production rate.

The research programmes at existing and planned facilities point to strong progress in the coming years

Thanks to the large collected datasets, ATLAS and CMS are now able to explore very rare processes in top-quark and multi-boson production. The latter are very powerful at constraining new-physics interactions in the framework of effective field theory, and several new results were presented, including top + boson, top + diboson and three-top production. It is also worth highlighting the first measurement of the $|V_{cb}|$ CKM element using on-shell W bosons from top-quark decays presented by ATLAS.

In summary, Moriond Electroweak 2026 demonstrated steady experimental improvements in addressing the fundamental open questions in particle physics. Although the experimental challenges are arduous, the research programmes at existing and planned facilities point to strong progress in the coming years.

Fabio Cerutti *LBNL.*

CHAMONIX WORKSHOP

Scaling new heights towards Long Shutdown 3

The Chamonix Workshop is the annual strategic meeting of the CERN Accelerator and Technology Sector (ATS), a long-standing tradition dating back to 1991. Initially dedicated to the performance of the LEP collider, the workshop shifted its focus to the LHC in 2001 and, since 2024, has covered the entire CERN accelerator complex as well as future projects.

Final stretch *Participants of the 2026 Chamonix Workshop, the last before Long Shutdown 3.*

CERN

The 28th edition took place at the Majestic conference centre in Chamonix from 2 to 5 February, with around 130 participants from CERN attending, along with international guests. This year's workshop was quite unique, as it covered not only the operational aspects of the accelerator complex until the end of Run 3, but also the tasks and challenges facing the sector for Long Shutdown 3 (LS3), which will start in July for the LHC and on 31 August for the rest of the injector complex (the ISOLDE facility and AWAKE experiment have already started their LS3 activities). There was also discussion of the 2026 update to the European Strategy for Particle Physics, and its implications for future activities at CERN.

Record-breaking

2025 was yet another year of records for the CERN accelerator complex. The LHC integrated a proton–proton dataset of 125 fb^{-1}, the highest to date for a single year, and produced physics collisions with neon and oxygen ions for the first time. The Proton Synchrotron Booster delivered record intensities to the ISOLDE facility, as did ELENA to the AD experiments, while the SPS North Area received 20% more spills than targeted. Operation in 2026 was discussed at length, in particular the strategy for settings management and the tests still to be performed before LS3. These include reliability runs in the LHC injectors to ensure that the beams planned for the High-Luminosity LHC (HL-LHC) are operationally ready in the injector chain, and a high-intensity test scheduled in the LHC for the last two weeks of Run 3. This is unknown territory for beam physics and probes the limits of existing LHC equipment, which was designed for "ultimate" intensities of 1.7×10^{11} protons per bunch, against the 2.3×10^{11} expected for the HL-LHC.

The second and third days of the workshop focused on LS3 activities. The first priority is the HL-LHC project, which aims to produce 10 times more physics data than the LHC. Progress towards the HL-LHC was reviewed in detail, and significant advancements were noted on all fronts, as the project prepares to transition to the installation phase in the LHC tunnel. Installation activities are proceeding well in the new HL-LHC technical galleries, with the major cryogenic refrigerator installations nearly complete.

Progress with the inner triplet (IT) magnet string test in the SM18 test hall received particular attention. The test stand has since reached a vital operational milestone: cool-down began on 9 March and reached 1.9 K just eight days later, with the first powering tests following on 20 April. This is a major achievement that will allow the collective behaviour of the different systems in the final-focus zone of the HL-LHC to be validated. Lessons learnt from the IT string installation have already led to design changes that will greatly facilitate the work in the LHC tunnel.

2025 was yet another year of records for the CERN accelerator complex

In 2025, some technical challenges required mitigation actions to ensure the timely readiness of certain components. ATLAS and CMS also experienced some technical difficulties, which are being addressed to minimise their impact.

Other LS3 projects include an intensity and energy upgrade for ISOLDE, with major works to replace the current beam dumps; consolidation of the SPS North Area to renovate this fixed-target experimental area after 47 years of operation; and its preparation for the high-intensity ECN3 project, in view of the Beam Dump Facility and the recently approved SHiP experiment.

A solid plan for LS3 is now established, with all the main activities scheduled and only details to be finalised. On the critical path ahead lies the upgrade of the experimental insertions at points 1 and 5, where the LHC equipment will be removed to make way for the HL-LHC. The "safety first, safety always" message was clear. The successful and timely ▷

completion of LS3 will rely on the expertise, ingenuity, commitment and dedication of all the CERN teams involved.

The last day of the workshop was dedicated to the Laboratory's longer-term future. It opened with how the FCC programme fits into the CERN strategy for 2026–2030, followed by talks on its organisation and an initial look at the workforce required for its implementation. The baseline accelerator design concepts for the FCC-ee and its injector complex, as well as the FCC-hh, were also discussed. The final session covered the development of an ATS roadmap for common accelerator-control hardware and software, advances in magnet and radio-frequency acceleration technologies, and the future fixed-target physics landscape.

A solid plan for LS3 is now established

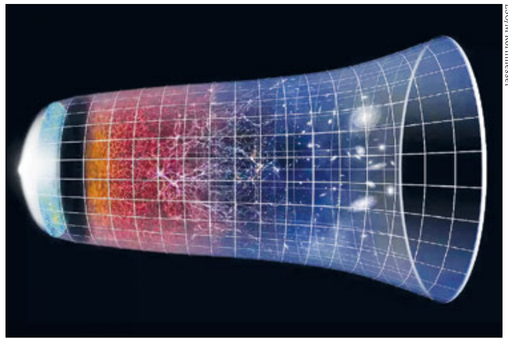
Bringing together colleagues from across the ATS sector and beyond, the workshop was once again an excellent opportunity to take stock of the breadth of activities across the CERN accelerator complex and to finalise preparations for LS3.

Oliver Brüning, Hector Garcia Gavela *and* **Giulia Papotti** *CERN.*

HIGH ENERGY, COSMOLOGY AND ASTROPARTICLE PHYSICS WORKSHOP

Drilling down on dark matter

The High Energy, Cosmology and Astroparticle Physics (HECAP) Abu Dhabi Workshop, held at New York University Abu Dhabi on Saadiyat Island from 13 to 15 January, brought together more than 30 researchers to discuss some of the deepest mysteries in fundamental physics.



ESO/M Kornmesser

Cosmic evolution *Dark matter and the early universe were central topics at the HECAP Workshop in Abu Dhabi.*

A central theme was the effort to unravel the nature of dark matter (DM) and understand its production mechanisms, both in the early universe and in laboratory experiments. The traditional freeze-out paradigm, in which DM was once in thermal equilibrium with ordinary matter and froze out as the universe expanded and cooled, was contrasted with freeze-in scenarios, where DM is never in equilibrium and is produced through extremely weak interactions. In particular, Andrzej Hryczuk (NCBJ) analysed the production of multi-component dark sectors, including non-equilibrium effects such as conversions and cannibalisation processes, and Hyun Min Lee (Chung-Ang University) explored gravity-mediated DM scenarios. Complementary perspectives on DM phenomenology were presented by Nuria Rius (IFIC/UV), who discussed scenarios with warped extra dimensions where DM interacts gravitationally with Standard Model (SM) particles.

Search and research

The possible signatures of dark sectors at colliders were discussed by Giovanna Cottin (UC Chile), who emphasised that dark-sector particles may be long-lived and produce displaced vertices or other unconventional signatures at the LHC. The importance of dedicated searches and of reinterpreting existing LHC data was highlighted, together with the prospects offered by future facilities such as the Future Circular Collider.

A recurring theme was the connection between the origin of matter and the nature of dark matter. Cosmological observations directly establish a quark–antiquark asymmetry, conventionally identified with a baryon asymmetry under the assumption that the dark sector carries no compensating baryon number. Whether this assumption holds, and what its breakdown would imply, was a recurring question. Pilar Hernández (UV) discussed the link of this puzzle to neutrino masses, while a complementary scenario was presented in which the observed quark–antiquark asymmetry predicts the existence of DM, stabilised by the same symmetry that prevents proton decay.

Several presentations focused on the early universe as a probe of new physics. Javier Rubio (Universidad Complutense de Madrid) discussed Hubble-induced phase transitions triggered by the evolution of the scalar component of spacetime curvature after inflation, which can amplify field fluctuations, generate transient topological defects, and potentially lead to observable gravitational-wave signals. The role of early-universe dynamics in uncovering new physics was also highlighted by Basabendu Barman (SRM University), who discussed how cosmological observations may provide unique information about physics beyond the SM.

Closely related to these questions is the study of vacuum decay in scalar field theories. José Ramón Espinosa (IFT) showed that the standard semiclassical "bounce" picture can be extended to include pseudo-bounce and antibounce configurations, revealing a richer structure of vacuum decay channels than previously considered.

Thermal history

The reheating epoch following inflation was also discussed as a crucial stage in the thermal history of the universe, when it evolved from a nearly empty state to a hot radiation-dominated plasma. The details of this transition can significantly affect DM production and enlarge the viable parameter space for DM candidates, as discussed by Yann Mambrini (Université Paris-Saclay) and Kuldeep Deka (NYU Abu Dhabi).

Gravitational waves provide an important observational probe of these early-universe processes. Antonio Junior Iovino (NYU Abu Dhabi) discussed gravitational-wave signatures from primordial black holes across a wide range of frequencies and the prospects for detecting them with experiments ranging from pulsar timing arrays to the LIGO–Virgo–KAGRA network. Related aspects of gravitational-wave production in the early universe were addressed by Xunjie Xu (IHEP), who discussed the thermal generation of a cosmic gravitational-wave background.

The workshop also covered precision tests of the SM. Yosef Nir (WIS, Rehovot) presented recent developments in flavour physics, including the puzzling measurement of the branching fraction of $B_s \to K^0 K^0$, which appears to be in tension with SM expectations based on flavour-symmetry relations. The decay proceeds dominantly through loop diagrams and is therefore sensitive to ▷

CERNCOURIER
VOLUME 66 NUMBER 3 MAY/JUNE 2026

virtual contributions from new heavy particles. In addition, measurements of CP asymmetries in $B \to J/\psi\,\pi$ decays were discussed, as they help refine the determination of the CKM parameter $\sin(2\beta)$.

Alberto Casas (IFT) discussed how high-energy experiments can test fundamental aspects of quantum mechanics, including quantum entanglement and Bell non-locality, at unprecedented energy scales. In addition, Juan José Gómez Cadenas (DIPC) reviewed the status of searches for lepton-number violation and the progress of the NEXT experiment in probing neutrinoless double-beta decay.

Overall, the workshop provided an excellent forum to discuss recent developments at the interface of particle physics, cosmology and astroparticle physics, in particular in the search for physics beyond the SM. Many of the discussions illustrated how progress in understanding DM, the early universe and fundamental interactions increasingly relies on the interplay between theoretical work, laboratory experiments and astrophysical observations.

A recurring theme was the connection between the origin of matter and the nature of dark matter

Alejandro Ibarra *TUM.*

FCC Physics Workshop

Garching gathers for the FCC

MPP

FCC in focus *Hundreds of theorists and experimentalists assembled at the Max Planck Institute for Physics in Garching for the ninth edition of the Future Circular Collider Physics Workshop.*

From 26 to 30 January 2026, the Max Planck Institute for Physics in Garching, near Munich, hosted the 9th FCC Physics Workshop, a major gathering of theorists and experimentalists advancing the physics case, addressing the experimental challenges and developing detector-concept candidates for the proposed Future Circular Collider (FCC). The event brought together hundreds of scientists from Europe and beyond to discuss the FCC and the broader strategy for the field after the LHC and its high-luminosity phase.

European physicists have recently recommended the electron–positron FCC (FCC-ee) as the preferred next flagship project in the ongoing update to the European Strategy for Particle Physics, with a final decision on construction anticipated around 2028 (*CERN Courier* January/February 2026 p7). This endorsement followed years of extensive design and feasibility studies, and provided an important backdrop to the Munich workshop, where participants worked to align physics goals with technical feasibility and long-term sustainability considerations.

The meeting marked a visible shift in tone and substance for the FCC programme, with conceptual exploration giving way to operational, benchmark-driven studies. Five days of discussion converged on a common message: if the FCC is to deliver as the next flagship collider at CERN, precision must be engineered at every level, from beam energy calibration and theoretical predictions to detector granularity, reconstruction algorithms, analysis software and governance structures.

The FCC's first stage, FCC-ee, is conceived as a high-luminosity electron–positron collider operating at multiple centre-of-mass energies, including the Z pole, WW threshold, Higgsstrahlung maximum around 240–250 GeV and the top-quark pair threshold. The physics case has long emphasised unprecedented precision in electroweak observables, Higgs couplings and top-quark properties, alongside sensitivity to rare and exotic processes. What was striking in Munich was the degree to which this ambition is now translated into quantitative requirements and structured work plans.

The meeting marked a visible shift in tone and substance for the FCC programme

The Physics Studies work package presented a coordinated strategy across electroweak, Higgs, flavour, QCD, top and beyond-the-Standard Model (BSM) groups. The workshop highlighted the need for consistent benchmark processes, shared uncertainty frameworks and global fit strategies capable of combining hundreds of measurements into coherent constraints on new physics.

At FCC-ee luminosities, statistical uncertainties on many observables would improve by up to three orders of magnitude over previous electron–positron colliders. This shifts the limiting factor toward systematic effects: beam energy calibration, luminosity normalisation, detector alignment, flavour-tagging biases, uncertainties in higher-order calculations and parton-shower modelling. Matching this statistical power with equally ambitious control of systematics is a prerequisite for turning per-mil measurements into probes of new physics well beyond the direct kinematic reach.

The workshop made clear that the FCC physics case cannot be decoupled from detector performance. Precision Higgs and electroweak measurements demand excellent tracking momentum resolution and minimal material budgets to control multiple scattering and secondary interactions. Heavy-flavour and tau-physics programmes hinge on vertexing and impact-parameter resolution, with b- and c-tagging joined by emerging capabilities such as strange-quark tagging. Multi-jet final states from W, Z and Higgs decays bring jet-energy resolution to the fore. Meeting these goals favours highly granular calorimetry and particle-flow reconstruction, which combines information from all subsystems to identify and measure each particle in the event.

Beyond precision

At the same time, the programme also extends beyond canonical precision channels. Sensitivity to long-lived particles and feebly interacting states motivates continuous tracking and hermetic calorimetric coverage. Ultra-precise luminosity measurements at the 10^{-5} level are integral to the detector architecture, and particle-identification capable of K/π separation over wide momentum ranges supports flavour and QCD studies.

Four detector concepts – ALLEGRO, CLD, IDEA and ILD – are under active development, exploring complementary technologies toward shared performance goals. A fifth, ALFA, has recently emerged, and the workshop encouraged further proposals. The timeline outlined in Munich foresees optimisation studies through 2027, system demonstrators by around 2030, scalable prototypes in the early 2030s, and conceptual design reports in 2033. While ▷

the final political decision is still pending, detector R&D is advancing in lockstep with physics requirements.

The Physics Software and Computing (PSC) work package presented its vision for supporting physics and detector studies. At its core is Key4hep, a community-driven framework for HEP experiments, prototyped by FCC together with other future collider projects and increasingly adopted by related R&D efforts. Key4hep provides modularity, interoperability and long-term sustainability, integrating past work from linear-collider facilities and current CEPC and EIC work. In Munich, updates were presented on full simulation geometries for several detector subsystems, integrated digitisation and reconstruction chains, and improved user workflows.

Large-scale production campaigns, data-management strategies and distributed-analysis frameworks are being aligned with CERN IT services and GRID tools, with machine-learning methods increasingly embedded in reconstruction and analysis workflows. Realistic simulation studies, incorporating beam-induced backgrounds and detailed geometries, are gaining importance, alongside the development of robust analysis algorithms that can be validated across simulation levels.

Core contributors

The PSC session also addressed human infrastructure. Recognising computing experts as core scientific contributors – with appropriate career paths and visibility – was considered essential to the long-term success of a data-intensive programme like the FCC.

One of the most distinctive aspects of the Munich workshop was the visible role of early-career professionals. The FCC Early Career Forum presented a draft document synthesising discussions from FCC Week 2025 and subsequent exchanges. Its focus on sustainability, communication, careers and governance resonated across sessions.

One of the most distinctive aspects of the workshop was the visible role of early-career professionals

Sustainability emerged as a central design consideration: environmental, economic and social aspects must be integrated from the earliest design phases through operation and decommissioning. Participants stressed the importance of engaging local and regional communities, and of clearly articulating how the FCC could contribute to broader societal goals.

The Munich workshop made clear that the FCC programme is entering a new phase of maturity and consolidation. With coordinated efforts across physics, detectors, computing and accelerator physics, the community is laying the groundwork for a project that promises to extend our understanding of fundamental interactions and prepare particle physics for its next frontier.

Panos Charitos *CERN.*

Research and Technology Infrastructures Summit

Big Science and industry meet in Copenhagen

How can Europe turn its world-leading capabilities in Big Science into industrial and societal impact? The conclusion of the Research and Technology Infrastructures (RTIs) Summit 2025 was clear: Europe has the skills, partners and ambition, but progress is slowed by fragmentation and lack of consistent funding.

Held in Copenhagen on 22–23 October 2025, and hosted under the Danish EU presidency, the RTI Summit brought together leaders from across Europe to shape the future of research and technology infrastructures and to discuss how to implement the new European strategy in this field, launched by the European Commission at the event.

Danish Technological Institute

Common ground *Panellists at the RTI Summit 2025 in Copenhagen discuss how Europe can turn scientific and technological advances into industrial applications.*

A dedicated session on accelerators and superconducting magnets examined today's best practices and the steps needed to build a reliable route from lab to market. Several European strengths are already visible. Pierre Vedrine (CEA Saclay) showed how open technology infrastructures, such as Synergium, accelerate innovation from materials and components to full systems, including superconducting MRI magnets. Clean rooms, assembly platforms and large-scale testing shorten development cycles and enable close collaboration between scientists, industry, and small and medium-sized enterprises (SMEs). Martina Bauer (GSI/FAIR) presented the Hi-Acts platform, which offers companies a single-entry point into Helmholtz competencies to find contacts, access beamtime and services, and obtain guidance on cooperation.

The I.FAST EU-funded project coordinated by CERN, presented by Maurizio Vretenar, provided another example of co-innovation: involving SMEs in R&D from the outset supports earlier adoption of industrial standards, faster prototype improvement and lower costs. I.FAST brings together 49 partners, including 17 companies as co-innovation partners to develop technologies common to many accelerator platforms, from high-efficiency klystrons and thin-film superconducting RF cavities to new beam-window materials and energy-efficiency strategies. Industry presentations confirmed the long-term payoff of Big Science engagement: Julio Lucas (Elytt Energy) showed how experience from ITER tooling translated to CERN magnet systems and FAIR dipoles, while Torben Ekvall (Mark & Wedell) described how one-off contracts opened doors to the private fusion market.

Despite this progress, familiar obstacles persist. Access rules, intellectual property (IP) practices and internal priorities still vary by country and facility. Funding and support mechanisms exist but are difficult to navigate across borders. Funding cycles are often too short for hardware-heavy, low-TRL (technology readiness level) development – four-year projects rarely suffice to reach robust prototypes and market adoption, keeping the so-called "valley of death" wide. At the same time, administrative procedures overwhelm smaller companies without dedicated grant management. Talent retention is another pressure point: SMEs struggle to match big-company salaries and maintain niche competencies during long project gaps.

The Big Science market also presents a challenging risk profile for SMEs. Long projects offer few invoicing milestones against unavoidable upfront spending on engineering, tooling, quality systems and certification. Specialised skills must be maintained through periods of low order volume, and key experts are hard to replace in tight labour markets. Markets are lumpy and project-based, with long gaps between tenders and highly customised solutions that do not always translate to other buyers. Cross-border collaboration adds further complexity. Strategically, firms often enter ▷

early-stage R&D without a clear view of the post-project market, and risk over-dependence on a single facility.

A panel discussion with Pierre Vedrine (CEA), Julio Lucas (Elytt Energy), Raffaella Geometrante (KYMA Undulators and co-chair of the Accelerator Science and Technology Industry Permanent Forum), Sabine Brock (Hi-Acts) and Elena Hoffert (French Ministry of Higher Education and Research) converged on a set of practical remedies.

First, early and structured co-innovation should become the norm. When SMEs participate from low-TRL levels, roles and milestones can be defined up front, risk shared more evenly, and manufacturability feedback integrated before costs escalate.

Second, Europe would benefit from a more coherent access and IP framework. Building on models such as Hi-Acts, Europe could connect companies to testbeds, services and expert brokers without forcing them to relearn procedures in each country. Harmonised IP principles would help: open, royalty-free academic research, clear commercialisation pathways for industry, and standard terms agreed upfront rather than under time pressure.

Longer, steadier funding is equally important, as hardware-centric deep-tech needs time. Extending funding horizons beyond four years would match development realities, while dedicated technology-transfer funds – combining public and private capital – could bridge feasibility, prototyping and first deployments. Targeted instruments such as vouchers or match funding can reduce the barrier to SME participation in pilot projects, test campaigns and certification.

Markets matter

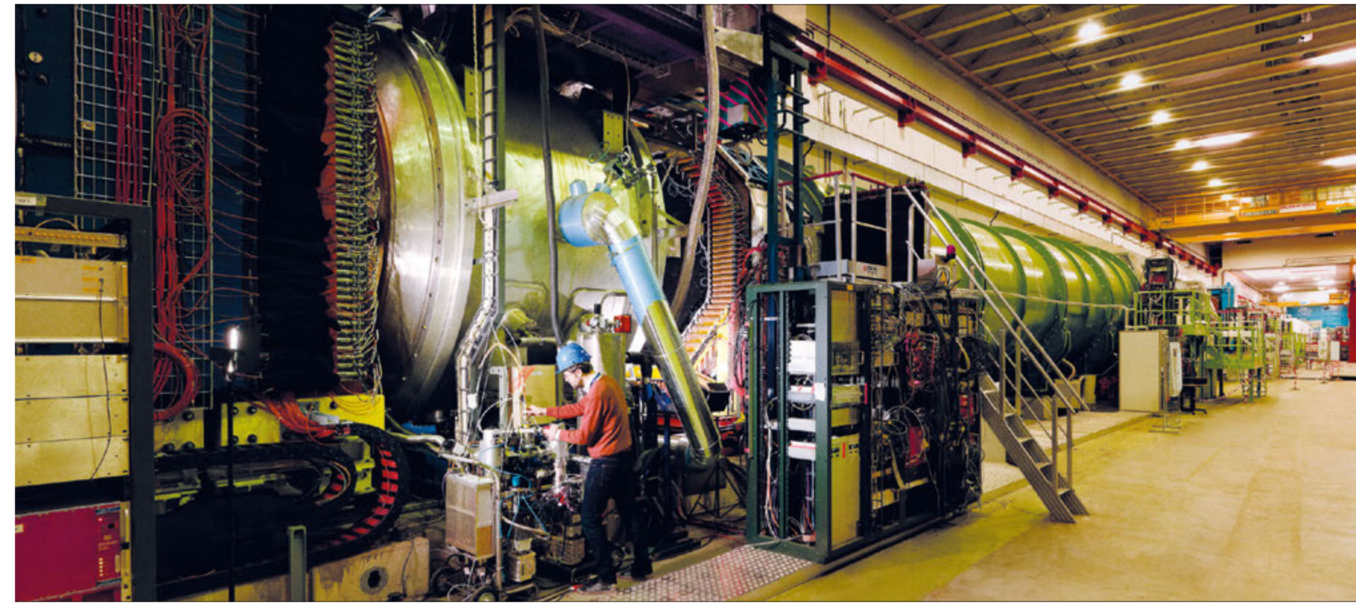
Market signals matter too: if facilities publish procurement roadmaps and use framework agreements, SMEs can plan capacity and recover innovation costs by selling validated solutions to multiple sites. Standardised specifications and qualification across facilities would increase portability and reduce repeated rework.

People remain the backbone of deep-tech translation. Mobility programmes and joint appointments between RTIs, universities and SMEs can spread know-how and create shared cultures. Embedding training and student pipelines within projects turns RTIs into talent multipliers. Temporary support to retain key teams between projects can prevent hard-won competencies from dissipating during inevitable times of low market demand.

Administrative simplification and lasting coordination would further lower barriers. SME-friendly procedures, template agreements and faster feedback make participation less daunting. Permanent, lightly funded structures can maintain continuity and provide a platform for roadmapping and collaboration. Securing the industry perspective in long-term strategies is essential, with the AIPF Forum being one such initiative.

In the end, the session's messages were well aligned. Europe has the infrastructure, excellence and entrepreneurial SMEs to lead globally in Big Science technologies. By turning its diversity into a strength, through coordinated standards, simpler access to facilities, more continuous funding and earlier industry engagement, it can move technology transfer from a by-product to a central objective. This will allow SMEs to recover development costs and invest in people and in durable collaboration structures that keep the know-how alive. Europe could then ultimately accelerate the translation of Big Science into societal and industrial impact.

Henrik Bak Jeppesen, Katrine Hjort *and* **Nikolaj Zangenberg**, *Danish Technological Institute.*



A game of tag *The NA62 experiment in CERN's North Area. Designed to catch an ultra-rare kaon decay, it also delivered its first "tagged" neutrino candidate, matching it to its parent process and pinning down its energy to 0.3%. Credit: V Moncorgé/CPPM/CNRS Images*

NEUTRINOS ON THE CLOCK

Neutrino beams lack the precision that modern oscillation experiments demand. Laura Munteanu, Mathieu Perrin-Terrin and Stephen Dolan describe how neutrino tagging, proposed in 1979 and demonstrated at CERN, promises to close the gap.

Born of one kind, a neutrino can die another. Its three flavours, electron, muon and tau, do not correspond to states of definite mass, but to quantum superpositions of three distinct masses. As neutrinos propagate, the mixture reshuffles and the flavour at arrival can differ from the one at production. None of this is predicted by the Standard Model, making the observation of neutrino oscillations one of the clearest signals of physics beyond it.

Neutrino oscillations provide a unique probe of new physics, acting as an interferometer that is sensitive to neutrino mass differences down to the sub-eV level. Precise measurements at the next-generation accelerator-based oscillation experiments, Hyper-Kamiokande in Japan and DUNE in the US, are poised to answer several critical questions. What is the ordering of the three neutrino masses, given their two measured mass-squared differences? Do neutrinos and antineutrinos oscillate differently? Are there additional, as yet undetected, neutrino states? These long-baseline neutrino facilities, in which a beam of neutrinos is sent to a detector hundreds of kilometres away, will produce much larger datasets than current-generation experiments. However, they suffer from a fundamental limitation: we do not know the precise energy or intensity of the neutrino beams when they set out. Reaching ultimate precision on neutrino-oscillation parameters is therefore no longer a matter of statistics, but one of messy nuclear-physics questions related to the details of weak-interaction cross sections and proton-induced hadron production.

Modern neutrino beams use the famous "magnetic horn" design, developed by Simon van der Meer at CERN

THE AUTHORS

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CERNCOURIER
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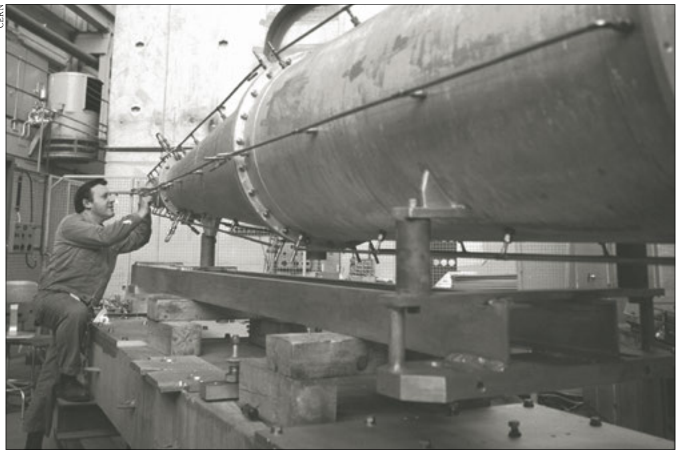
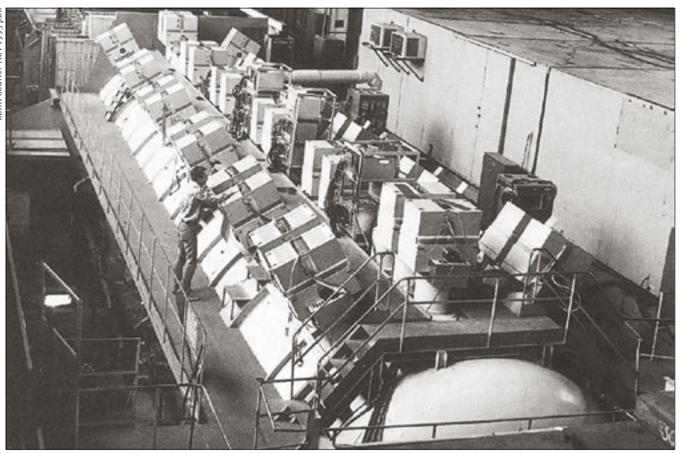
CERN



In focus *A magnetic horn installed in the beamline that fed CERN's Gargamelle bubble chamber, where neutral currents were discovered in 1973. Invented by Simon van der Meer, the device uses a pulsed current to focus charged pions into a beam. The pions decay in flight to produce neutrinos.*

CERN Courier Nov 1993 p28



Dream, deferred *The neutrino detector of the Tagged Neutrino Facility at the Serpukhov accelerator in Protvino, Russia. Built in the early 1990s, the facility was the first to attempt neutrino tagging and collected a handful of candidate events in a short pilot run. The dissolution of the Soviet Union ended the programme before it could mature.*

in 1961 (see "In focus" image). Protons strike a target to produce pions, which the horn focuses into a volume for them to decay to neutrinos and leptons. The trouble is, the resulting neutrino beam covers a wide range of energies (about 0.5 GeV and 2.5 GeV for Hyper-K and DUNE, respectively), with a shape and intensity that depend on the details of tough-to-model proton–nucleus collisions. To make matters worse, the broadband neutrino flux forces the neutrino energy to be estimated from the products of neutrino–nucleus interactions, which are notoriously difficult to model accurately. Together, these challenges form a barrier to ultimate precision in neutrino-oscillation measurements.

There is, in principle, a way around both problems: neutrino tagging. Proposed by Bruno Pontecorvo in 1979, this technique associates a measurement of the four momenta of the pion and muon in a $\pi^+ \to \mu^+\nu_\mu$ decay with a measurement of a neutrino in a downstream detector. Four-momentum conservation then fixes the neutrino kinematics event-by-event. As a result, the neutrino energy is known for each interaction and the flux is perfectly constrained, nullifying the key challenges for neutrino-oscillation experiments and producing well-controlled muon, pion and kaon beams as byproducts. The idea was first attempted in the 1990s at the dedicated Tagged Neutrino Facility (TNF) at the Serpukhov accelerator in Protvino (see "Dream, deferred" image). TNF recorded two candidate events in its brief pilot run, before the dissolution of the Soviet Union brought the work to a halt.

The downside with neutrino tagging is one of scale: for every neutrino seen in a massive, 100-tonne detector close to the beam, there are about 10^{13} pion decays. To collect a reasonable 10^5 neutrino interactions per year, one would therefore need to identify at least 10^{11} individual muons per second and successfully identify the minute fraction of them that are associated with observed neutrinos. Such a measurement demands beamline detectors with timing resolutions of 10 to 100 ps and a neutrino detector with sub-ns timing resolution, with the beamline detectors operating in a high-radiation environment.

Promising performance

These challenges proved too much for the 1990s, and the idea lay dormant for three decades after the closure of TNF. However, a revolution in detector and electronics technology has since changed what is possible (see "The fast-timing revolution" panel) – beginning with the NA62 experiment at CERN.

In order to study the very rare kaon decay $K^+ \to \pi^+\nu\bar{\nu}$, the NA62 collaboration faced a similar timing challenge in the late 2010s. At the time, pixel detectors, mainly developed for experiments at the LHC, were only recording the position of particles, their time being given by the proton bunch crossing (50–25 ns). New R&D was started to face the challenge of integrating timing capabilities into every pixel (of which there are more than one thousand per cm^2). Within a few years, the "TDCPix" chip was designed (see "Pixel timekeeper" image), achieving a hit time resolution of 130 ps and starting a new field of 4D tracking (measuring particle trajectories in space and time). The price to pay for this performance was a significant increase in the power density absorbed by the pixel, exceeding 2 W/cm^2. Absorbing this power required developing an innovative cooling technology: a 200 µm-thin silicon plate integrating a dense microfluidic cooling circuit. These two innovations led to the GigaTracker beam spectrometer (see "Fourth dimension" figure) – the first 4D tracking detector in high-energy physics, which has been in operation since 2015.

With the GigaTracker in hand, the NA62 collaboration achieved the main goal of measuring the $K \to \pi\nu\bar{\nu}$ decay, and was able to put neutrino tagging to the test. The facility's high-intensity kaon beam also serves as a neutrino source, since the kaons predominantly decay as $K^+ \to \mu^+\nu$. Due to the intensity of the neutrino beam and its mean

The fast-timing revolution

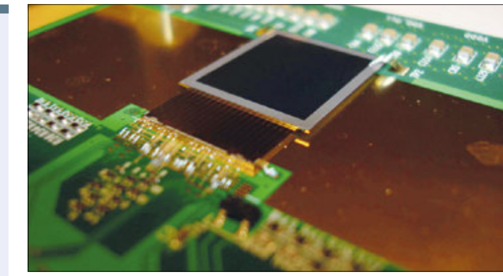
R&D for the high-luminosity phase of the LHC are expected to push fast-timing sensors beyond the performance of NA62's GigaTracker. With bunches crossing every 25 ns and up to 200 proton collisions in each, the ATLAS and CMS upgrades require timing resolutions below 50 ps to disentangle overlapping vertices. In a silicon detector, incoming particles release small electric charges, with internal electric fields then steering them toward electrodes to be collected and measured. Faster timing demands more charge, a shorter drift for the signal to form quickly and smaller collection electrodes for sharper and stronger pulses. In conventional planar sensors, these requirements are often in conflict with one another. Since the collected charge is proportional to the sensor thickness, which also sets the drift distance, thinner sensors give faster signals but fewer carriers. Potential solutions span a wide range of architectures. Low-gain avalanche detectors (LGADs), for instance, combine thin, 50 µm sensors with a gain layer to amplify charge, compensating for the lower number of carriers produced in a thin substrate while preserving a short drift. They achieve resolutions of 20 to 50 ps and will equip the new ATLAS and CMS timing layers.

Many roads to fast timing

For the upgrade of the LHCb vertex locator, which must resist radiation levels of 10^{16} to 10^{17} 1 MeV neutron equivalents per cm^2 (n_{eq}/cm^2), a gain layer would erode too quickly. Three-dimensional sensors sidestep the problem geometrically. Their electrodes run along the sides of each pixel rather than on the top and bottom surfaces, so charges move sideways over distances below 50 µm while the sensor remains thick enough to generate large signals. Initially developed for radiation-hard pixel detectors for ATLAS and CMS, these sensors were later redesigned for timing and have reached resolutions as good as 10 ps. The remaining challenge lies in the electronics. Readout chips must match the sensors' speed and radiation tolerance, and recent prototypes in 28 nm CMOS have achieved 30 ps resolution over areas of a few mm^2. Large-area designs are currently underway.

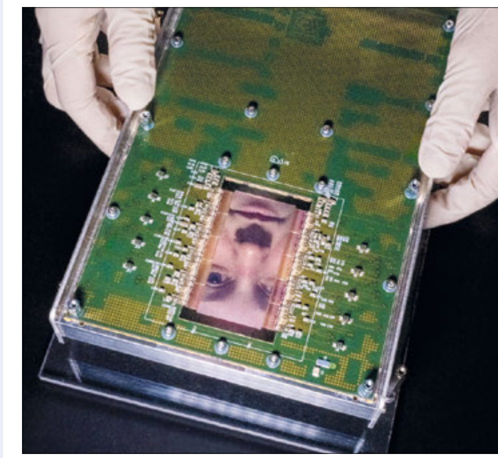
Depleted monolithic active pixel sensors integrate the sensor and readout electronics on the same chip. With resolutions of 10 to 200 ps and pixels smaller than $100 \times 100\,\mu m^2$, they are much cheaper than three-dimensional sensors and LGADs, and therefore better suited to instrumenting large surfaces and achieving a lower material budget. Some R&D initiatives are also exploring the use of Cherenkov radiation to detect charged particles, a process much faster than ionisation in silicon. In these detectors, the prompt Cherenkov light is converted into photoelectrons and amplified in a thin gaseous detector, producing signals with time resolutions of a few tens of picoseconds. While highly promising, extending this approach to finely segmented detectors operating at very high rates remains an open problem. All these new tracking technologies offer promising perspectives beyond high-energy physics, for example in real-time monitoring of the proton and ion beams used in cancer therapy.

NA62 collaboration



Pixel timekeeper *A single TDCPix readout chip is connected to its silicon sensor and wire-bonded to a readout card. Each chip contains 1800 pixels of $300 \times 300\,\mu m^2$, with a built-in time-to-digital converter that timestamps particle hits with a resolution of 130 ps. Ten chips tile each GigaTracker station.*

V Moncorgé/CPPM/CNRS Images



Fourth dimension *One of the stations from NA62's GigaTracker, the first 4D tracking detector for high-energy physics. Designed to track around 10^9 beam particles per second, the detector has operated in the NA62 beamline since 2015. Reflected in its surface is Zuzana Kučerová, GigaTracker's deputy project leader.*

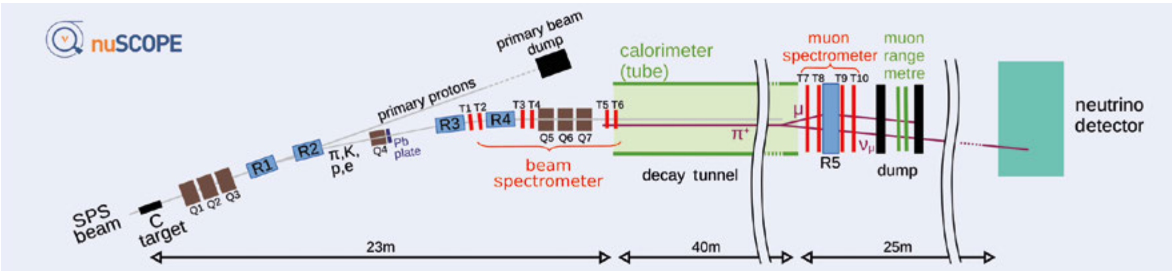
energy of 40 GeV, a non-negligible number of neutrinos interact in the experiment's electromagnetic calorimeter, a 20-tonne volume of liquid krypton. The analysis of data collected in 2022 revealed one neutrino interaction candidate that could be matched to a detected parent decay. The neutrino's energy was estimated to be 52 GeV, with a record relative precision of 0.3%. For reference, with a few exceptions (such as pion and kaon decays at rest), neutrino energies from conventional neutrino beams are known with an uncertainty of at least 10%, and not event-by-event.

NA62's proof-of-concept for neutrino tagging, combined with the broader advance of fast-timing detectors, have together made it possible to revisit the original TNF idea. Developed in parallel with the first tagged-neutrino analysis by NA62, the NuTag collaboration investigated the conditions under which a tagged beam would enable measurements inaccessible with conventional neutrino beams. These efforts have led to the proposed nuSCOPE facility at CERN, which emerged within CERN's Physics Beyond Colliders study group by combining the tagged-beam concept from NuTag with the slow-extraction-driven monitored neutrino beam pioneered by the ENUBET collaboration. Rather than using a pulsed magnetic horn, the ENUBET setup relies on slow extraction from the SPS and lines the decay tunnel with particle detectors that identify the charged leptons produced with neutrinos, constraining the flux at the percent level.

Legacy measurements

The idea of nuSCOPE echoes that of TNF (see "Beam to neutrino" figure). The first step is to direct a slow-extracted proton beam from the SPS onto a target to produce secondary pions and kaons that are then momentum-selected, using a series of dipoles and quadrupoles, to form an 8.5 GeV meson beam with a narrow momentum range. The mesons then traverse a set of ultra-fast detectors before decaying to predominantly muons and neutrinos. The muons reach a

A revolution in detector and electronics technology has changed what is possible



Beam to neutrino *The layout of the proposed nuSCOPE facility at CERN. SPS protons produce a secondary beam of kaons and pions, which are momentum-selected and tracked before entering a 40 m decay tunnel. There, they may decay into a muon and a neutrino. The muon is reconstructed in a downstream spectrometer, while the neutrino interacts in a dedicated detector further on.*

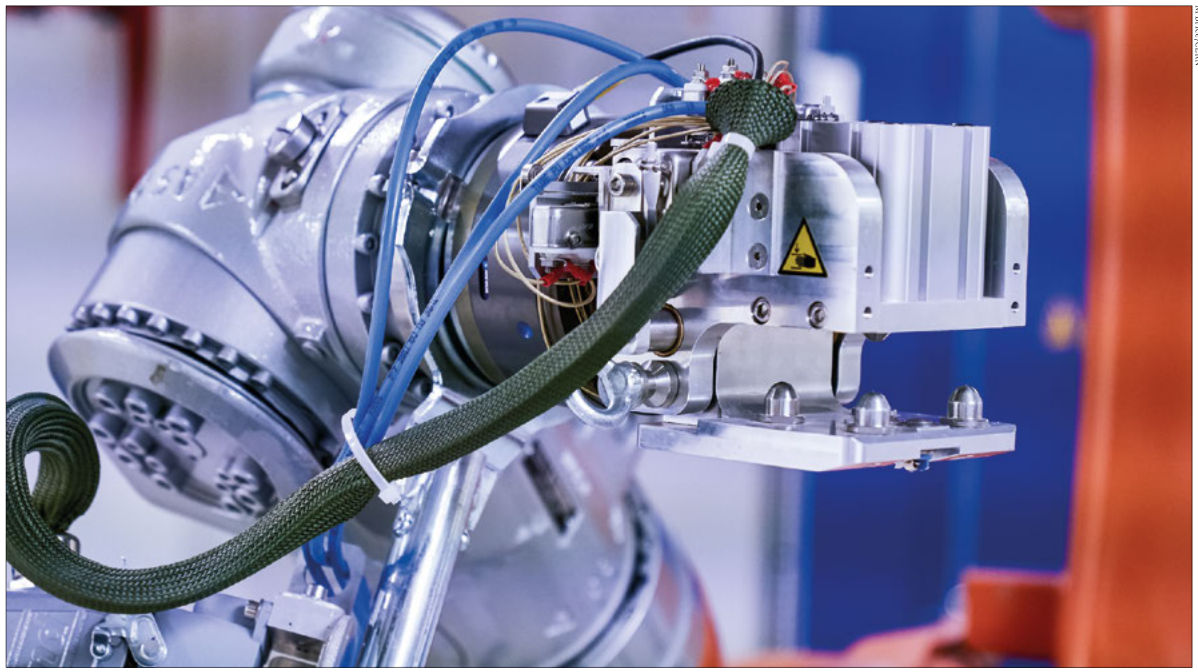
second set of fast detectors, whilst a few neutrinos interact in a dedicated detector 25 metres downstream. With sufficient timing and spatial resolution, each neutrino interaction can be associated with a measured individual meson decay. For the first time, the energy of the incoming neutrino would be known at the sub-percent level on an event-by-event basis. Measurements of neutrino cross sections, currently the dominant source of systematic uncertainty projected for DUNE and Hyper-Kamiokande, may then reach an accuracy of about 1%. Such datasets could serve as reference, "legacy" measurements for neutrino physics for decades to come.

The techniques might reshape future long-baseline experiments

The implications extend well beyond standard oscillation physics. Short-baseline oscillations induced by sterile neutrinos, for instance, could produce rapid patterns that would get washed out by energy smearing in conventional beams. The facility would also deliver intense, well-characterised muon and pion beams, opening additional avenues for rare process searches and precision measurements. Looking further ahead, one can even imagine how such techniques might reshape future long-baseline experiments. Depending on what DUNE, Hyper-Kamiokande and the reactor-based JUNO experiment in China will discover, the next leap in precision may not come just from higher intensities, but from beams whose properties are known with exquisite accuracy. •

THE AGE OF THE BLOCKBUSTER-SCALE RADIOPHARMACEUTICAL

Radiopharmaceuticals based on novel radionuclides have, for the first time, reached blockbuster proportions. Thierry Stora explains why high-energy physics has an essential role to play in scaling up a life-saving technology.



M Brice/CERN

Hands off *A robot at CERN-MEDICIS transfers irradiated targets in and out of the radiologically controlled area, where short-lived medical radionuclides are mass-separated and collected. The isotopes are then dispatched to partner hospitals and research centres across Europe.*

While radioactivity and radionuclides have been used in medicine for decades, radiopharmaceutical drugs have only recently reached the rank of a pharma blockbuster, with more than one billion US dollars in annual sales. The clearest example is lutetium-177-based therapy, which has moved into routine use for prostate and neuroendocrine cancers, is being investigated as a first-line treatment and generates revenues previously unseen in nuclear medicine (see "How radiopharmaceuticals work" panel).

On the production side, accelerators are a key source of innovation beyond the long-established nuclear reactors. Scaling up these technologies, however, remains challenging. No single laboratory can combine megawatt beams, advanced target engineering and full radiological infrastructure, and the products literally decay on the shelf.

Many of the technologies now limiting medical radionuclide supply – high-power targets, isotope separation, beam reliability – were originally developed for nuclear and high-energy physics (HEP). These fields will remain essential not because they created today's tools, but because future medical radionuclide production pushes those tools into regimes that only nuclear physics and HEP routinely explore.

THE AUTHOR

Thierry Stora
CERN.

Physicists must address four bottlenecks to meet the growing demand for radiopharmaceuticals, each of which cuts differently across the European accelerator landscape (see "The European landscape" figure). Overcoming these bottlenecks would stabilise the supply of existing treatments and open the door to R&D for entirely new diagnostic and therapeutic isotopes. In that sense, the infrastructure choices made today will shape what kinds of cancer treatments are possible a decade from now.

1. Targets that cannot survive megawatt beams

Large-scale accelerator facilities push beams to extreme power densities in order to generate secondary particles or rare isotopes, placing materials under intense thermal and radiation stress. This regime is familiar from spallation neutron sources, neutrino-production targets and radioactive-ion beam facilities, where target integrity and remote handling are central design challenges rather than secondary considerations. As medical radionuclide production scales up, it increasingly operates in this same regime, where target survivability under sustained continuous-wave irradiation becomes the primary limiting factor. Beyond a certain point, targets degrade, deform or fail faster than they can be replaced, turning material endurance, target design and monitoring – rather than accelerator capability – into the dominant constraint on production.

In practice, this challenge unfolds in two forms, depending on whether a single- or a two-stage target is used. In the two-stage configuration, an intense primary beam is first converted into neutrons or photons, and those secondary particles then irradiate production targets from which the desired radionuclides are generated.

At the very front end of the supply chain, these spallation targets and beam converters – which transform protons into neutrons or electrons into photons – are among the most demanding components in the entire supply chain, because their performance and lifetime cannot be decoupled from beam power. A prominent example is the European Spallation Source (ESS) in Lund, Sweden, which will soon operate the world's most intense long-pulse neutron beams, where a rotating, helium-cooled tungsten target enables sustained high-power operation (see "Under the beam" image). The pulsed regime introduces additional challenges from shock waves and material fatigue, which must be addressed to ensure safe operations. Likewise, the IFMIF-DONES facility in Granada will combine a 5 MW deuteron beam with a fast-flowing liquid lithium target to generate intense fast-neutron fluxes. While their primary missions lie in fundamental, material and multidisciplinary research, the extreme beam powers and neutron fluxes of these facilities also make them potentially capable of supporting radionuclide production as a secondary, but societally important, application.

Similarly, single-stage targets used for radionuclide production must withstand extreme heat loads and power densities, with geometries that depend on the type and energy of the incident particles. Active cooling, using either gases or liquids, is essential to remove heat, and careful optimisation of both beam delivery and target design can translate directly into higher radionuclide production yields.

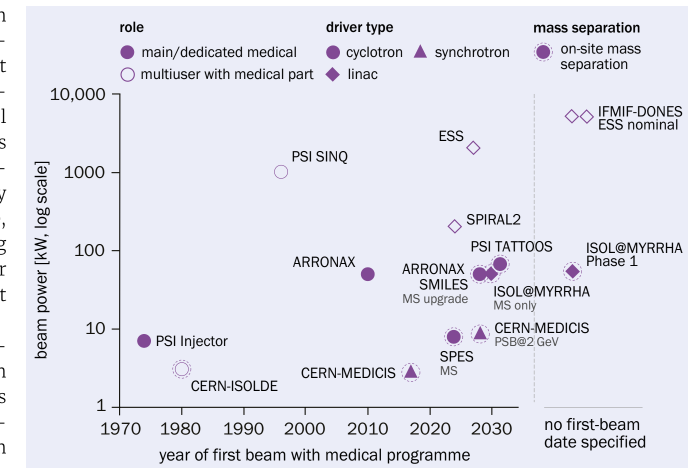
A good example is the development of high-power bismuth targets, in either liquid or solid form, such as those proposed at RIKEN in Japan, which can handle alpha beams of around 10 kW and enable the production of At-211 in batches approaching 100 GBq – far beyond the gigabecquerel-scale batches typical of present-day facilities. RIKEN is Japan's largest comprehensive research institute, operating major accelerator and nuclear-physics facilities with a long-standing programme in medical radionuclide production. In Europe, comparable facilities are under construction, such as SPIRAL2 in Caen, France, or at SCK CEN in Mol, Belgium, where ISOL@MYRRHA will deliver a 100 MeV proton beam of up to 500 μA onto a target dedicated to the production of medical and research radionuclides (see "Sorting the haul" figure).

Additional challenges arise for highly radioactive targets such as Ra-226, a long-lived precursor used in the production of the alpha-emitting medical isotopes Ac-225 or

How radiopharmaceuticals work

Modern radiopharmaceuticals combine a radioactive isotope with a biologically active molecule that targets specific cells in the body. The compound is typically injected into the bloodstream, where the biological component guides it to a tumour by binding to a particular protein expressed on cancer cells. Once attached, the radioactive isotope delivers a highly localised dose of radiation that damages or destroys the targeted cells while largely sparing surrounding tissue.

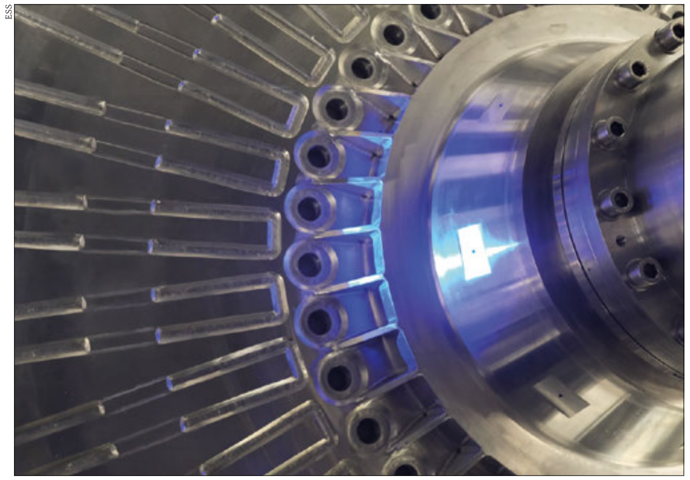
The type of radiation emitted determines how the compound is used. Gamma rays and photons from positron annihilation can escape the body and be detected externally for diagnostic imaging, while Auger electrons, beta particles or alpha particles deposit their energy over very short distances, making them effective for therapy. Increasingly, the same isotope–molecule combination can be used both to image disease and to treat it – an approach known as theranostics.



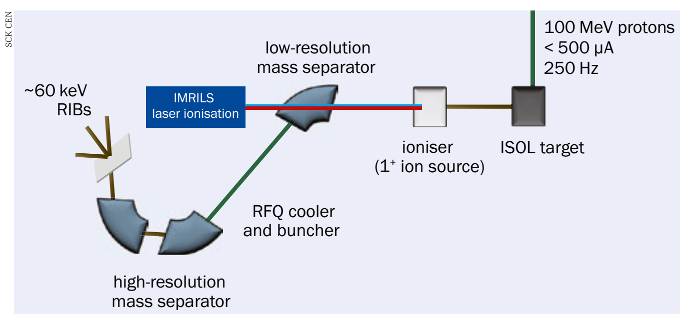
T Stora

The European landscape *Accelerator facilities producing medical radionuclides across Europe, plotted by year of first beam against beam power. A dotted halo flags on-site mass separation, essential for the most demanding therapeutic isotopes. Three projects with announced power but no first-beam date appear on the right.*

CERNCOURIER
VOLUME 66 NUMBER 3 MAY/JUNE 2026



Under the beam *The ESS target wheel. Blocks of tungsten fitted into the radial channels absorb the 5 MW proton beam and release neutrons via spallation. Continuous rotation and helium cooling prevent any single point from melting under the load.*



Sorting the haul *The layout of the future ISOL@MYRRHA facility at SCK CEN in Mol, Belgium, with the beam line running from right to left. A 100 MeV proton beam strikes a thick target to produce rare radioactive nuclei. These are extracted as singly charged ions, selectively excited by the ISOL@MYRRHA Resonant Ionization Laser Source (IMRILS), cooled and bunched in a radiofrequency quadrupole cooler-buncher (RFQ), and mass-separated to deliver pure radioactive ion beams (RIBs) for research and medical applications.*

Ra-224, or for targets designed for high-power operation and mass separation, which must remain structurally and chemically stable at temperatures approaching 2500 °C.

Even when targets survive extreme beam power, increased production immediately creates a second constraint: the radionuclides they produce are only useful if they can be isolated in the required purity – a challenge that defines the next bottleneck.

2. Radionuclides that cannot be separated

When radioactive products are chemically indistinguishable from unwanted isotopes, separation must rely on their mass rather than on their chemical properties. Without such separation, many promising medical radionuclides cannot be used at all, regardless of how efficiently they are produced, because they remain too dilute or come with long-lived impurities. This challenge is familiar from isotope production for nuclear and particle physics, where ion sources, mass separators and laser techniques are used to extract rare species from intense backgrounds.

A dedicated collaborative infrastructure was established at CERN with the creation of CERN-MEDICIS, which received support from the CERN & Society Foundation and pioneers isotope mass separation for medical applications. Commissioned in 2017, MEDICIS brings together expertise in target production, purification, radiopharmaceutical development and clinical use, linking large-scale physics infrastructure directly to biomedical research.

Building on techniques originally developed at ISOLDE, the MEDICIS programme has adapted isotope mass separation specifically for medical needs. This has enabled access to radionuclides that are otherwise unavailable, or available only at insufficient purity, achieving high molar activities essential for theranostic and therapeutic applications.

In contrast to radiochemical separation, which typically achieves efficiencies above 95%, mass-separation efficiencies vary widely, ranging from a few percent to around 70%, depending on the isotope and production route. As a result, scaling up production by mass separation is not a matter of incremental optimisation: gains in yield must be traded against beam power, target lifetime and radiation handling, placing practical limits on what facilities can deliver for many isotopes.

Significant progress has nevertheless been achieved through advances in target design, compact ion sources and resonant laser ionisation, with efficiencies above 50% now considered high performance for these physics-driven separation processes. Operating at higher beam intensities further opens the possibility of separating radionuclides directly from reactor or cyclotron targets, but doing so requires accelerator conditions and radiation handling capabilities that are only available at large-scale research infrastructures. Because mass separation is both technically demanding and intrinsically inefficient, access to purified radionuclides cannot be scaled locally, making coordination across large research infrastructures unavoidable.

In Europe, this need for coordination has been addressed through a networked approach rather than a single flagship facility. The PRISMAP programme (H2020 grant #101008571), and its follow-up PRISMAP+, bring together accelerators, reactors, isotope separation facilities and biomedical hubs across national borders, allowing researchers to access purified radionuclides that no single site could reliably supply on its own (see "Special delivery" figure). By pooling infrastructure, expertise and scheduling through competitive calls, PRISMAP has lowered the barrier for biomedical researchers to work with non-conventional radionuclides, while preserving the efficiency and safety constraints imposed by large-scale physics infrastructure. It is becoming the European medical radionuclides programme that biomedical research lacked.

The same mismatch between research-scale tools and medical-scale demand reappears in accelerator design itself – the focus of the next bottleneck.

3. Machines optimised for experiments, not production

Accelerators developed for fundamental research are typically optimised for peak performance, flexibility and discovery-driven operation. Medical radionuclide production, by contrast, demands continuous, predictable delivery, exposing a growing mismatch between machines designed for experiments and those required for routine isotope production. In practice, the requirements of medical radionuclide production change dramatically between exploratory research and routine clinical supply, shifting the emphasis from flexibility and peak performance towards reliability, uptime and predictable delivery.

Improving multi-user operation and reducing maintenance downtime can already deliver substantial gains in effective output, even without higher beam power. Intense beams of light ions and electrons are available today using cyclotrons and linear accelerators, while new concepts are being developed to better match medical needs, including synchrotrons for alpha particles and high-power electron sources for photon-based production routes.

Even when suitable accelerators exist, however, delivering medically usable radionuclides depends on meeting regulatory, dosimetric and logistical constraints that lie beyond the machine itself.

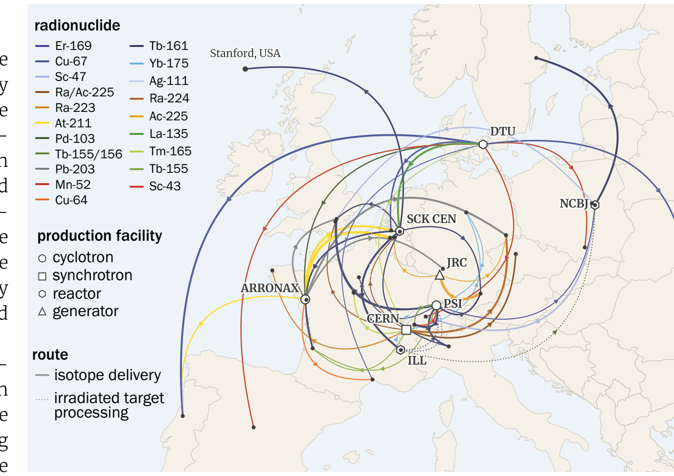
4. Production without regulatory viability

Unlike research isotopes, radiopharmaceuticals must meet strict regulatory, dosimetric and logistical requirements. Even small uncertainties in nuclear data, impurity levels or processing routes can prevent a radionuclide from reaching patients, regardless of its therapeutic promise. At this stage, scale is limited not by beam power or yield, but by whether a radionuclide can be licensed, transported and used safely in the clinic.

The case of lutetium-177 (Lu-177) illustrates both the challenge and the opportunity. Its success has been central to the emergence of modern radiotherapeutic drugs, with compounds targeting prostate and neuroendocrine cancers now used routinely in clinical practice. This success rests not only on biological targeting, but on a carefully controlled production chain that meets pharmaceutical standards.

The mode of production of Lu-177 – either by direct neutron capture on Lu-176 or via an indirect route through Yb-176 – highlights the complexity of aligning nuclear physics, infrastructure and regulation. Choices made upstream determine radionuclidic purity, waste streams and processing requirements downstream, all of which feed directly into licensing and clinical acceptance. Lu-177's physical and radiological properties, including its suitability for both imaging and therapy, and a half-life of about 6.64 days that is compatible with existing medical logistics, have helped it integrate into an established supply-chain organisation. This combination has enabled treatments to reach large patient populations and commercial scale.

Meeting these requirements demands substantial investment beyond irradiation itself. Facilities must support radiochemical processing, quality control, dosimetry and specialised logistics, often in shielded hot-cell environments. Recent upgrades to such infrastructure have shown that production capacity can increase significantly once these downstream constraints are addressed. At the same time, improved nuclear and biological data have revealed that even modest discrepancies in decay properties or radiation dose can have major consequences for treatment planning, licensing and waste management.



Special delivery *Flows of medical radionuclides within the PRISMAP network. Production facilities ship purified isotopes to biomedical hubs across Europe and on to users as far as the US. The diversity of species and routes reflects the fact that no single site can supply biomedical research with every radionuclide it needs.*

Programmes such as PRISMAP+ have begun to address this bottleneck by providing access to novel treatment radionuclides, including beta emitters that extend established therapies such as Lu-177. By generating data on production quality and radiochemical behaviour early in development, these programmes help determine which radionuclides can realistically progress from research to routine clinical use. Crucially, regulatory constraints feed back into accelerator choice, target design and separation strategy: decisions taken at the level of beam energy, target material and purification method determine whether a radionuclide can ever meet clinical purity, waste and licensing requirements.

Taken together, these constraints show why regulatory viability is itself a bottleneck. Scaling radiopharmaceuticals requires not only new radionuclides, but integrated infrastructures in which production, processing, regulation and clinical deployment are addressed together. As radiopharmaceuticals move further into mainstream oncology, success will depend on sustained collaboration between large-scale research infrastructures, regulators, clinicians and industrial partners – none of which can solve the problem alone. ●

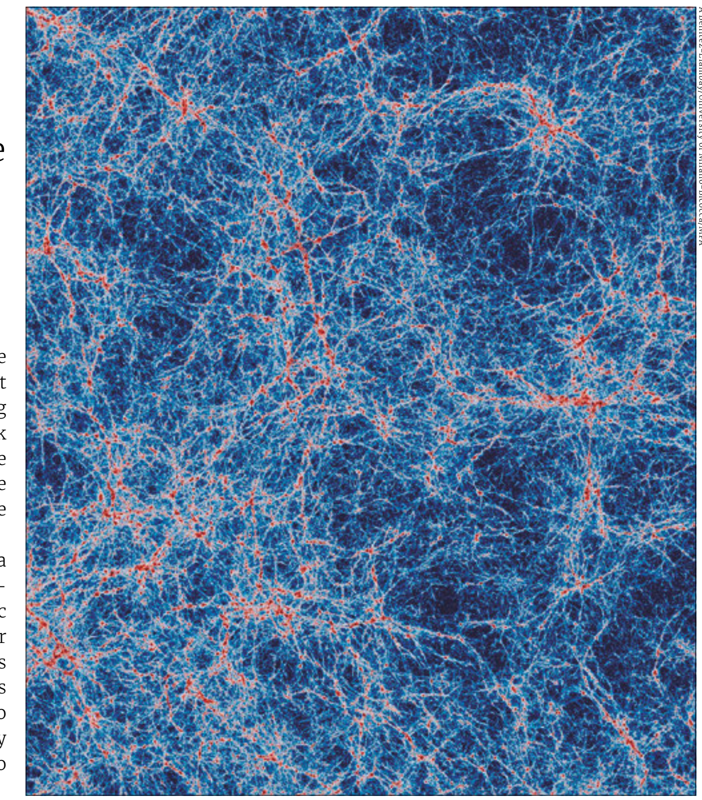
The author dedicates this article to the memory of Mark Rayner, who shaped its structure and much of its prose.

Scaling requires not only new radionuclides, but integrated infrastructures

CERNCOURIER
VOLUME 66 NUMBER 3 MAY/JUNE 2026

WELCOME TO THE DARK WEB

The universe is a cosmic web, woven from vast filaments that connect galaxies and clusters. Elena Pinetti explains how these elusive threadlike structures are opening a new window on the nature of dark matter.



A Benítez-Llambay/University of Milano-Bicocca/MPA

Cosmic web *The bright nodes (red) correspond to galaxy clusters, threaded together by cosmological filaments (white), while the vast regions between them are cosmic voids.*

Cosmological filaments form the backbone of the cosmic web, the vast, interconnected network that defines the universe on the largest scales. Stretching across tens to hundreds of millions of light-years, they link galaxies and galaxy clusters along the pathways where matter assembles under gravity. They may also hold the key to one of the deepest questions in modern physics: the nature of dark matter.

For astrophysicists, filaments first drew attention as a potential reservoir of missing baryons. Big Bang nucleosynthesis and precision measurements of the cosmic microwave background agree on how much ordinary matter the universe should hold, but the census of stars, galaxies and hot gas comes up short. The leading explanation is a warm, diffuse gas permeating cosmic filaments, too faint to detect in any single observation but increasingly accessible through statistical techniques at X-ray and radio wavelengths.

More recently, dark-matter hunters have begun to recognise the potential of filaments as probes of new physics. Filaments are not only vast but overwhelmingly dark-matter-dominated, with lower astrophysical backgrounds than traditional search targets such as the galactic centre. New simulations are pinning down their dark-matter density profiles with enough precision to make quantitative predictions, and recent theoretical work has opened detection channels that could turn these structures into laboratories for physics beyond the Standard Model.

Dark matter and the cosmic web

Our scientific understanding of stars and the structures they inhabit has grown remarkably over the past century. We now know that galaxies are vast collections of stars, and clusters are collections of galaxies. These immense systems do not float randomly; they are woven into an intricate "cosmic web" resembling that of a spider. Gravity shapes this web and governs the motion of the celestial bodies within it. Yet many observations defy expectations. Galaxies rotate too quickly, clusters bend light too strongly, and the cosmic web holds together with more gravitational pull than visible matter would allow. Something unseen must be at work. A new, invisible "dark matter" component must dominate the mass of the universe.

Dark matter accounts for roughly 85% of the matter in the cosmos and dictates how cosmic structures form and evolve.

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Dark-matter candidates in the spotlight

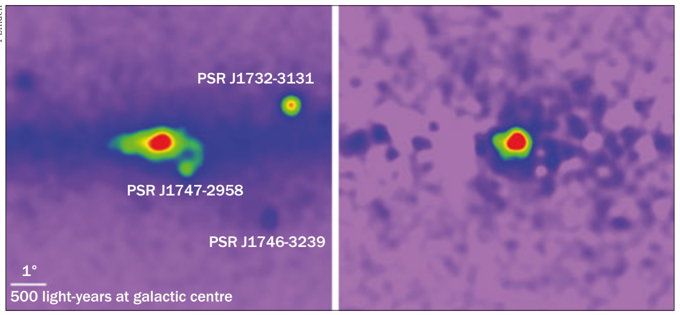
Dark matter accounts for roughly 85% of the matter in the cosmos, and about 27% of its content once dark energy is included, yet its nature remains unknown. Several well-motivated candidates have emerged, each predicting distinct signatures that indirect searches, including those targeting cosmic filaments, could probe. Weakly interacting massive particles, sterile neutrinos, primordial black holes and axions are among the most prominent.

Weakly interacting massive particles These hypothetical particles naturally arise in several extensions of the Standard Model and possess two defining features: they are massive, and they interact only through gravity and the weak force.

Sterile neutrinos Unlike the three known active neutrino species, they do not interact through the weak force. Their existence is motivated by extensions of the Standard Model that aim to explain both neutrino masses and the matter–antimatter asymmetry of the universe.

Primordial black holes Unlike stellar black holes, which form from collapsing stars, primordial black holes are hypothetical relics of the early universe, born from the collapse of exceptionally dense regions of matter moments after the Big Bang.

Axions Originally proposed to solve the strong CP problem, axions are hypothetical particles whose production mechanism can account for the observed dark-matter abundance, elegantly linking two of modern physics' greatest mysteries.



Gamma-ray excess *Since its launch in 2008, the Large Area Telescope of the Fermi Gamma-ray Space Telescope (Fermi-LAT) has observed an excess of gamma rays from the galactic centre. A map of 1.0–3.16 GeV gamma rays is shown unprocessed on the left, and with known sources removed on the right.*

Progress depends on close collaboration between particle physicists, astrophysicists and cosmologists

Yet, despite decades of international effort and extraordinary experimental ingenuity, its nature remains a puzzle. The Standard Model of particle physics, describing all known fundamental particles, can't account for the observational effects of dark matter. In response, theorists have proposed a wide range of models that include dark-matter candidates (see "Dark-matter candidates in the spotlight" panel). A well-motivated dark-matter theory, one that truly excites theorists, typically meets three criteria. First, it accounts for the observed cosmic abundance of dark matter. Second, it yields clear, testable predictions. And third, it resolves multiple open questions in fundamental physics.

Rich landscape

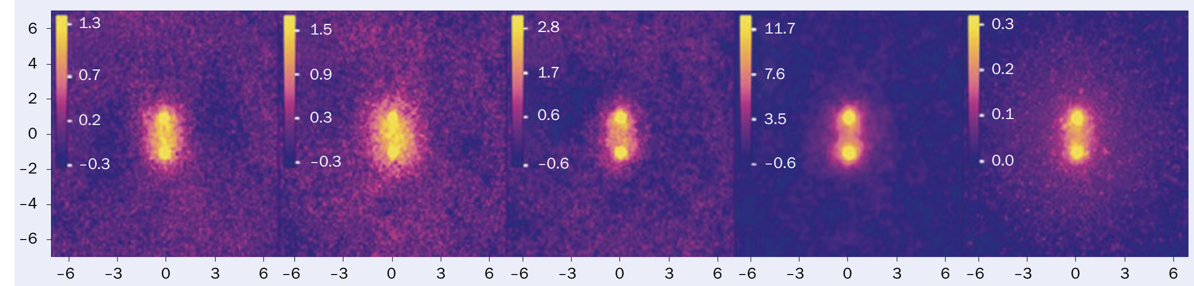
While the theoretical landscape is rich, testing it requires identifying cosmic environments where dark matter's signatures might be detectable. One of the most powerful strategies is indirect detection – the search for faint cosmic messengers produced when dark matter annihilates, decays or interacts with ordinary matter. These signatures may appear as electromagnetic waves, neutrinos or charged cosmic rays. Observing these messengers requires high sensitivity and careful modelling of both the dark-matter signal and the astrophysical backgrounds. Progress, therefore, depends on close collaboration between particle physicists, astrophysicists and cosmologists, integrating theoretical predictions with multi-messenger observations.

Choosing optimal targets is crucial for indirect dark-matter searches. Traditional efforts have focused on the galactic centre and on dwarf satellite galaxies of the Milky Way. The galactic centre is expected to host the highest dark-matter density, but it also contains intense and complex astrophysical backgrounds, which is why the origin of a long-debated gamma-ray excess observed by Fermi-LAT remains uncertain (see "Gamma-ray excess" figure). Dwarf galaxies, by contrast, are dark-matter-dominated and relatively free of astrophysical emission. However, their stellar populations are orders of magnitude smaller than that of the Milky Way. This limits the available kinematic tracers – observables whose spatial distribution correlates with the underlying matter density field – and leads to sizable uncertainties in the predicted signals.

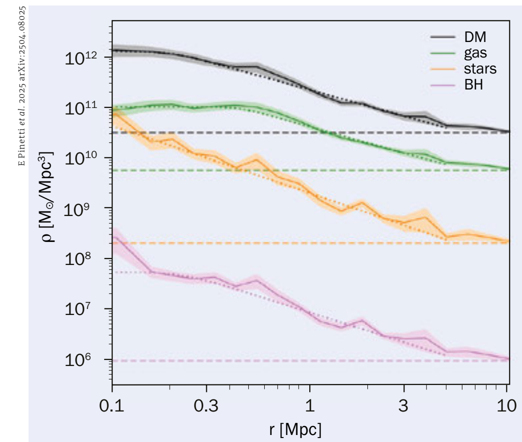
Unconventional environments

Recently, unconventional but promising probes have gained attention, such as cosmological filaments. Filaments are a natural outcome of anisotropic gravitational collapse in an expanding universe. Matter can collapse under gravity in some directions while still expanding in others, producing elongated structures that are bound across their width but continue to grow along their length. Not all cosmic filaments are alike. Some lie within galaxy clusters, linking individual galaxies over relatively short distances. Others extend far beyond cluster boundaries, forming vast inter-cluster bridges that connect galaxy clusters and even superclusters across tens and hundreds of megaparsecs. The longer the filament, the thinner and more diffuse it tends to be. This reflects the way gravity draws matter out of underdense regions and funnels it into elongated bridges between massive nodes.

Together, galaxy clusters and the diffuse filaments that connect them form the cosmic web and make up most of the baryonic matter. Yet the very properties that make filaments so fundamental to cosmic structure also make them extraordinarily difficult to observe. Their emission is faint, diffuse and easily overwhelmed by brighter astrophysical sources, posing a major challenge for direct detection across the electromagnetic spectrum.



Stacked maps *From left to right, the panels show radio maps from the GLEAM survey at 154, 118 and 88 MHz, radio data from OVRO–LWA at 73 MHz and X-ray emission from ROSAT in the 0.1–2.4 keV band. The x and y axes are the normalised pair separation unit and the colour bars indicate brightness temperature (in kelvin) for the radio maps and count rate for the ROSAT data. The two bright dots in all five panels represent the pair of stacked luminous red galaxies, connected by the stacked filamentary emission.*



ν [MHz]	T_b^{obs} [K]	T_b^{DM} [K]
154	0.10 ± 0.04	0.10
118	0.22 ± 0.06	0.22
88	0.44 ± 0.09	0.51
73	1.1 ± 0.2	0.85

Simulations, observations and theory *Left: radial density profiles in cosmological filaments for dark matter (black), gas (green), stars (orange) and black holes (pink), derived using the EAGLE simulations. Solid lines indicate the mean density profiles inside filaments, dotted lines the corresponding "β-model fits", and dashed lines mark the mean density of each component in the full simulation volume. Above: observed and expected dark-matter-induced radio emission at four frequencies, assuming the benchmark scenario of 30 GeV dark matter decaying into electron–positron pairs and producing synchrotron radiation in filamentary magnetic fields.*

To overcome this limitation, astronomers have turned to a statistical technique known as "image stacking". In stacking analyses, many observations of similar systems are superimposed. Any emission associated with filaments then adds coherently, while random noise and unrelated astrophysical signals average away. The result is a significant enhancement in sensitivity, allowing extremely weak, extended emission to emerge that otherwise would remain invisible.

A potent technique

The power of this approach relies on numbers: the larger the sample that can be stacked, the stronger and more reliable the resulting signal. Image stacking is therefore a potent but data-hungry technique, one that becomes increasingly effective as modern surveys deliver ever-larger datasets. This requirement poses a particular challenge for filaments, whose precise locations are generally unknown. Since cosmological filaments connect massive structures, a natural strategy is to use galaxy clusters as signposts: by stacking observations of regions between pairs of clusters, the faint emission from the filamentary bridges that link them can be statistically enhanced.

Cluster catalogues have expanded dramatically over the past decade. Today, surveys based on optical imaging, weak gravitational lensing and the Sunyaev–Zel'dovich effect, in which scattering with high-energy electrons distorts the cosmic microwave background, collectively identify tens of thousands of clusters across the sky. While progress is remarkable, it may still fall short of what is needed to robustly detect the extremely faint emission expected from typical filaments. This limitation motivates the search for alternative tracers. A reliable proxy for galaxy clusters available in far greater numbers, potentially in the millions, would enormously increase the statistical power of stacking analyses.

Particularly effective proxies for galaxy clusters are luminous red galaxies (LRGs). These massive, early-type galaxies have been observed and catalogued for decades and are known to be excellent tracers of the large-scale structure of the universe. LRGs typically reside in, or near, the centres of galaxy clusters, making them reliable signposts of the densest regions of the cosmic web. Pairs of LRGs that are close to one another in the sky and in physical distance can therefore be used as proxies for

Luminous red galaxies typically reside in, or near, the centres of galaxy clusters, making them reliable signposts of the densest regions of the cosmic web

CERNCOURIER
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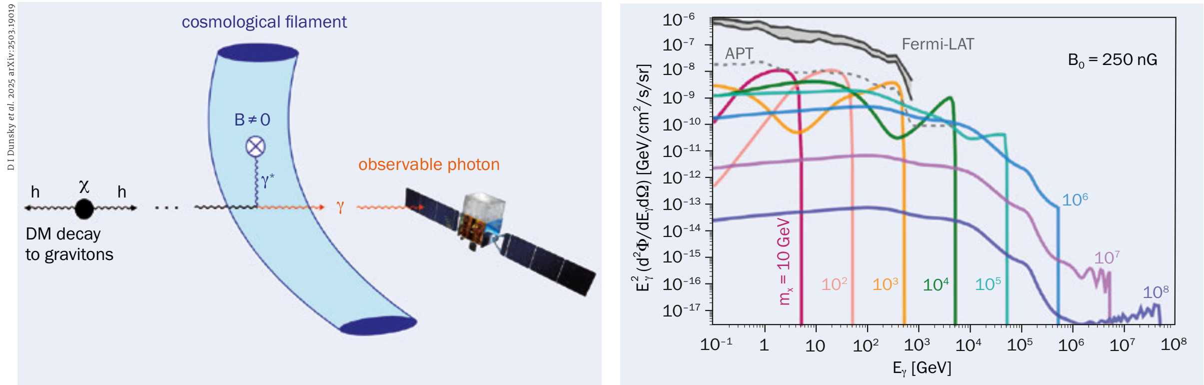

Graviton-to-photon *Illustration of a novel dark-matter search strategy: dark matter decays into gravitons, which propagate through magnetised cosmic filaments and convert into photons (left panel). This process generates a diffuse photon signal (right panel, for 250 nGauss magnetic fields). Different coloured curves correspond to different dark-matter masses, compared with the Fermi-LAT isotropic gamma-ray background (grey band) and the projected sensitivity of the Advanced Particle-astrophysics Telescope (APT, dashed).*

nearby cluster pairs. Statistically, such pairs are likely to be connected by inter-cluster bridges or filaments, even if the filaments themselves cannot be directly identified in individual observations.

By applying this stacking technique to pairs of LRGs drawn from the Sloan Digital Sky Survey, whose catalogues contain millions of such galaxies, together with radio maps from the GLEAM and OVRO-LWA surveys, researchers have identified an intriguing anomaly. The radio emission associated with stacked filaments (see "Stacked maps" figure) exceeds theoretical predictions for diffuse filamentary gas by more than an order of magnitude.

One possible interpretation is that this excess arises from secondary radiation produced by dark matter (see "Simulations, observations and theory" figure). In this scenario, weakly interacting massive particles with masses of a few GeV decay into electrons, which then spiral through filament magnetic fields and emit synchrotron radiation at radio wavelengths. For the magnetic field strengths inferred in the stacking analysis, the amplitude of the observed signal is consistent with that expected from a dark-matter flux of this kind.

As with other anomalies, this interpretation remains debated. A more conventional explanation attributes the emission to astrophysical particle acceleration in strong accretion shocks, generated as matter falls into filaments and galaxy clusters. While shocks can in principle produce radio synchrotron emission, reproducing the observed excess appears to require acceleration efficiencies higher than those typically assumed in simulations. Significant uncertainties persist in filament properties, such as their magnetic field strengths and shock characteristics, which complicate the modelling of expected signals and remain an active area of research.

Cosmic filaments may also open a window onto more exotic dark-matter scenarios. Recent work has shown that if heavy dark matter decays into gravitons – the hypothetical quantum carriers of the gravitational interaction – these can convert into photons via the Gertsenshtein effect (see "Graviton-to-photon" figure), closely analogous to the Primakoff conversion of axions, as they propagate through the large-scale magnetic fields threading filaments. This process generates an irreducible extragalactic gamma-ray background, allowing such scenarios to be constrained with Fermi-LAT data and offering promising sensitivity for future gamma-ray observatories.

A bright future for the dark universe

For millennia, humanity has been inspired by the starry sky. Philosophers, poets and scientists alike have gazed upward, their minds filled with questions, joy and awe. Dante, one of Italy's greatest poets, expressed this enduring fascination in the closing line of *Inferno* in *The Divine Comedy*:

"*E quindi uscimmo a riveder le stelle*"

"And thence we came forth to see again the stars"

Centuries after Dante, the sky continues to guard many of its secrets. However, we are now entering a golden era for indirect dark-matter searches. Future facilities, most notably the Square Kilometre Array (SKA), currently under construction in South Africa and Australia, will deliver unprecedented sensitivity to the diffuse structures of the cosmic web, and may soon be capable of directly imaging large filaments, characterising their properties and turning these vast structures into powerful probes of physics beyond the Standard Model.

These observational advances are being matched by progress on the theoretical front. Cosmological simulations are reaching new levels of realism, while the growing use of machine-learning and artificial-intelligence techniques is beginning to transform how filamentary structures are identified, modelled and interpreted. These developments promise a far more precise characterisation of filament properties, sharpening their role as laboratories for fundamental physics. The cosmic web may not keep its secrets much longer. ●

Further Reading

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CERNCOURIER
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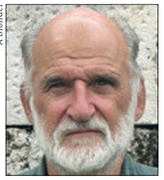
OPINION
VIEWPOINT

The FCC, half a century on

The European Strategy has recommended the FCC-ee as CERN's next flagship collider. The case for it, Alain Blondel argues, rests on 50 years of inventions and discoveries.


A Blondel

Alain Blondel *is emeritus director of research at LPNHE-CNRS, Paris, and an honorary professor at the University of Geneva.*

The community has spoken: the electron–positron Future Circular Collider (FCC-ee) is the preferred next flagship project for CERN. As an initiator of the concept of a circular Higgs factory in 2011, I was elated by this outcome. But it also made me wonder: why did it take so long? To answer this, we need to travel back 50 years.

1976 was an eventful year for particle physics. The open charm was discovered at SPEAR, while the J/ψ earned Burton Richter and Samuel Ting their Nobel Prize. The same year, Richter authored both the first yellow report on a large e^+e^- (LEP) colliding ring and the first paper proposing a linear e^+e^- collider. Gargamelle's measurement of the ratio of Z-induced over W-induced neutrino interactions had allowed the Standard Model (SM) – by then a familiar name – to predict the masses of the W and Z bosons. And Carlo Rubbia, synergy wizard, proposed to undercut the e^+e^- aficionados by converting the SPS into a proton–antiproton collider. The W and Z bosons were duly discovered in 1983.

In 1987, following the La Thuile Workshop on Physics at Future Accelerators and before LEP had even been completed, Rubbia called a general meeting in CERN's main auditorium to discuss the future beyond LEP. Two contenders stood out: a 5 TeV e^+e^- linear collider in a new 30 km tunnel (CLIC), or a 20 TeV pp collider (LHC) with the advantage of fitting in the already financed and nearly finished LEP tunnel. The relative physics merits of the two machines were compared on supersymmetry and Higgs compositeness. The LHC was chosen, and CLIC became a priority R&D programme.

We had a whale of a time at LEP, establishing that light neutrinos are exactly three, measuring the Z mass to six digits and predicting the top-quark mass through radiative corrections a few months before its Tevatron discovery.

By 1996, the LHC was approved and a small group at CERN was considering what could follow it. The listed options were a high-energy future LHC (FLHC), CLIC, and a 4 TeV muon collider. A first 0.5–1 TeV linear collider (LC) was assumed to be done elsewhere. In that context, a circular e^+e^- machine was mentioned only as a top factory add-on to the FLHC programme, with a design extrapolated from LEP and a performance well below the LC. The prevailing assumption was that the LHC would detect the Higgs boson and supersymmetry, if either existed.

A breakthrough came in 1999, when the asymmetric B factories PEP-II and KEKB, with separated e^+ and e^- rings and continuous top-up injection, demonstrated luminosities orders of magnitude higher than LEP. Meanwhile, LEP Higgs-hunted fiercely until the end of 2000, setting a lower mass limit at 114.5 GeV, while precision measurements set an upper mass limit of about 180 GeV.

The hunt is on

Come the summer of 2011, the LHC experiments were taking data at 7 TeV. The hunt for the Higgs and the supersymmetric particles was on, and the first limits already constrained the Higgs mass below that of a W pair. That clarified the required centre-of-mass energy of a Higgs factory: a relatively low-energy e^+e^- collider would do. Locating it in the LEP/LHC tunnel was an obvious possibility, and had already been discussed in the corridors of the EPS-HEP conference in Grenoble that July. Five months later, applying the B-factory design principles, a Higgs factory fitting in the LHC tunnel was evaluated. "LEP3" offered luminosity significantly higher than the linear collider, and the advantage of running several experiments simultaneously. On the downside, its maximum energy fell short of the top-pair-production threshold… and the LHC tunnel was already occupied.

Presented with this evaluation, some members of the CERN Scientific Policy Committee suggested that an e^+e^- Higgs factory more than triple the size of LEP would make a great initial step towards a higher-energy version of the LHC, which was already under consideration. Inserting the Higgs factory in a 100 km tunnel did magic. With its large bending radius, the machine reached the top-pair threshold while covering a wide range of energies and luminosities. It delivered large statistics at the Z pole, with 6×10^{12} visible Z decays, and transverse polarisation for exquisite energy calibration up to the W-pair threshold. Those were key ingredients in achieving a vertiginous potential for statistical and systematic improvement, by up to a factor of 500 or more over the old LEP precision measurements. The Z run, it was later realised, would turn FCC-ee into a flavour factory for b and tau precision studies, and also enable unique searches for feebly coupled particles in the 5–80 GeV mass range.

None of this was a straight line. It took 15 years for the physics to make the case on its own terms

What lies beyond

When the Higgs came, it did so at 125 GeV – too high for most incarnations of supersymmetry, too low for theories of a composite Higgs, and consistent with an unchanged SM up to very high energies. It raised the question of what lies behind the SM and at which energies, making it essential for the future of particle physics to include an extensive programme of precision measurements, in the hope of detecting deviations from the SM that could guide the next steps. The Higgs itself was also of obvious interest, and a lepton collider the natural way to study it.

These arguments were summarised in two contributions to the 2013 update of the European Strategy and led to the recommendation of a costed design study of FCC-hh and FCC-ee. The 2020 update continued it as a feasibility study, which led in turn to the 2025 recommendation.

None of this was a straight line. It took 15 years for the physics to make the case on its own terms, and the conversation had been on, in one form or another, for 35 years before that. The Higgs mass, the absence of supersymmetry and the precision reach all pointed to a machine in the best CERN tradition, where the most is made of the resources through a strong synergy between infrastructure planning and physics opportunities.

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Directing a decade

Looking back on two terms as CERN Director-General, Fabiola Gianotti discusses some highlights of her tenure, the opening of CERN to private philanthropy and the case for science as a force for peace.

CERN

At the helm *Fabiola Gianotti served as CERN Director-General from January 2016 to December 2025. During her mandate, she oversaw the approval of the High-Luminosity LHC, the work on the Future Circular Collider, including the raising of one billion US dollars in private pledges, and the realisation of the CERN Science Gateway.*

What would you say were CERN's scientific and technological highlights of the past 10 years?

I would start by highlighting the excellent performance of the accelerator complex, the experiments and the computing infrastructure, all of which have gone well beyond forecasts. Thanks to these achievements, and to the increasing sophistication of the data analyses, the Laboratory's scientific output has far surpassed what one could have anticipated, both in breadth and depth. The diversity of results across all our facilities is impressive, and physics sensitivities have exceeded even the most optimistic expectations. Notably, some studies originally foreseen for the High-Luminosity LHC (HL-LHC) phase are already being carried out today.

Secondly, the approval of the HL-LHC by the CERN Council in June 2016 marked a major milestone for the future of the LHC programme, and paved the way for substantial progress in upgrading both the accelerator complex and the experiments. As a first step, the successful Long Shutdown 2, carried out during the challenging COVID-19 period, enabled significant upgrades to the injectors and the completion of the Phase-1 upgrades of the four experiments.

Following the establishment of the Physics Beyond Colliders (PBC) Study Group in 2016, we have strengthened the Laboratory's programme of physics complementary to the LHC, notably with the approval of new experiments and projects such as FASER, SND@LHC and a high-intensity beam-dump facility at the North Area. The Neutrino Platform has remained a focal point for the neutrino community in Europe and beyond, enabling key detector R&D, technology demonstration and prototyping activities, as well as the construction of two large cryostats for the DUNE experiment at the Long-Baseline Neutrino Facility in the United States.

The extraordinary work towards the FCC has laid the foundations for a brilliant long-term future for CERN

The extraordinary work towards the Future Circular Collider (FCC) over the past 10 years, culminating in the highly successful Feasibility Study, laid the foundations for a brilliant long-term future for CERN and the field, and served as a key input to the ongoing update of the European Strategy for Particle Physics. In December 2025, the European Strategy Group recommended the FCC-ee as the next flagship facility at CERN, a pivotal step for the future of particle physics. Chapeau to the entire CERN community for these extraordinary achievements!

You were CERN's first female Director-General. When you first took on the role, did you find the focus on your gender a bit frustrating?

I cannot say that I found it frustrating. What surprised me was that people would tell me I was a role model. I did not consider myself a model of anything, so I was somewhat embarrassed by that description. But then I told myself that, if the fact that a woman held the position of CERN

Director-General could encourage young women to pursue a career in science, I was happy to play that role.

Did your experience as Director-General differ from what you expected?

From the outset, it was an extraordinary experience, far broader than I had expected. I had to deal with a myriad of matters: not only scientific and technical ones, but also finances and human resources, environment and sustainability, relationships with governments, the public and the media, as well as the daily management of a laboratory as complex as CERN.

Fortunately, I was surrounded by an excellent management team of directors, department heads and project leaders, and could count on the support, competence, enthusiasm and dedication of the entire CERN community. I am very grateful to the CERN Member States for the unique opportunity to serve as Director-General for two terms, and for their sustained support and trust throughout the 10 years.

There is one thing I would never have imagined I would need to do: raise substantial funding from the private sector. As a physicist, that was entirely outside my experience…

Despite that, you announced one billion US dollars of private funding for FCC shortly before the end of your tenure. How did you approach donations?

When I started my first term as CERN Director-General, I had no experience whatsoever with donations. I had not raised a single penny in my entire life!

I remember that, in the context of the Science Gateway, I considered hiring a professional fundraiser at some point. But then I realised that the salaries of these people were astronomical, so I abandoned the idea.

Over the years, I learned a lot from experience. I learned that fundraising is very much a matter of personal connections, and I was lucky enough to have some very good ones before becoming CERN Director-General. I also learned that donors love bold, ambitious projects like the FCC, projects that enable major progress for humanity. Finally, donors engage if they trust the institution, in this case CERN, but also if they trust the person. I think they trusted me.

The Science Gateway was a dream I had from the beginning of my first term

What made you decide to pursue private donations, and how did the policy framework for accepting them come about?

Both the Science Gateway and FCC are extremely challenging projects in their respective areas. I quickly realised that projects of this kind can only be achieved with exceptional levels – and therefore sources – of funding.

The Science Gateway was a dream I had from the beginning of my first term, in 2016. At the time, I realised we could host 150,000 visitors annually, compared with 300,000 requests. That seemed a shame to me. The limitation came from the number of visitor areas, which led to the idea of a new building – a dedicated space that could expand our offer to the public. CERN's budget provides only limited funding for education, communication and outreach initiatives, and the money raised annually through the CERN & Society Foundation was far from enough to cover a 100-million-Swiss-franc project. So we had to undertake a dedicated fundraising campaign.

Then we obtained a 48-million-US-dollar donation from the "Eric and Wendy Schmidt Fund for Strategic Innovation" for the "Next Generation Triggers" project, which primarily supports the development of AI-based algorithms for the high-level triggers of ATLAS and CMS at the HL-LHC. It was the first donation ever made to the CERN budget for a scientific project, and prompted us to develop a policy for this type of contribution. The policy was approved by the CERN Council in December 2024. It provides a robust set of principles and boundaries to harness the potential benefits from private funding while safeguarding the integrity and independence of the CERN scientific programme. I had already begun discussions with potential donors regarding the FCC, and the policy provided a framework for those efforts.

The FCC is an unprecedented project, and it has always been clear to me that the two traditional sources of funding for CERN projects, contributions from Member and Non-Member States, would not suffice. We consequently decided to explore two avenues that are innovative for our field: the European Commission and private donors. Concerning the former, the FCC was the first on a list of potential "Moonshot" projects in the draft Multiannual Financial Framework for the 2028–2034 period, along with a substantial dedicated budget line. As for the latter, we received pledges totalling one billion US dollars from philanthropists in the United States and Europe. I am deeply grateful to them for their generosity, vision and commitment to fundamental research.

I would like to emphasise that the main source of CERN funding has been, is, and must remain the regular contributions from the Member and Associate Member States to the CERN annual budget. Private donations are extremely valuable, but they can never replace the long-term funding stability that these contributions provide, which has been one of the key reasons for CERN's success over the decades.

How did you handle periods of crisis?

The key was teamwork, one of CERN's strongest assets at all levels. As Director-General, I always drew on people's strengths, and I was fortunate enough to work with extremely talented and dedicated collaborators across the entire Organisation. I should also mention that the knowledge of CERN and the experience I accumulated over 30 years as a member of staff proved particularly helpful during those challenging periods.

So we faced crises, from the COVID-19 pandemic to the consequences of the Russian invasion of Ukraine, and the high inflation and energy prices of 2023, in true CERN style: by working together. In the decision-making phase, different experts brought their perspectives, concerns and solutions to the table. In the implementation of measures, the relevant services, departments and units deployed their technical expertise. The approach was always collective. Of course, as Director-General, I had to take the final decision, and sometimes that was tough, especially in the context of budget cuts. But those decisions were always well-informed, grounded in collective thinking and shared expertise.

The serious crises we have experienced over the past 10 years have clearly highlighted the strength and resilience of CERN as an institution and of its community.

Do you think science can still be a force for peace?

Absolutely, because science is universal and unifying. Universal, because it is based on objective facts, the laws of nature, and not on opinions. An apple falls in the same way, whether it falls in Isaac Newton's garden in 17th-century England, or today in Switzerland, China or the United States. Unifying, because the thirst for knowledge and the desire to understand how things work are intrinsic to humanity. Thus, science has no passport, belief or gender, and can help connect people in our fractured world.

In this context, the role of CERN is emblematic. It was founded in 1954, amid the ruins of the Second World War, at a turning point in history, with the dual aim of restoring the continent's scientific excellence and promoting peaceful collaboration among Europe's countries and peoples through science. Today, CERN is not only a world-class scientific facility and the world leader in high-energy particle physics: it is a value system, embracing and promoting knowledge, innovation, training and education, collaboration across borders, inclusion, diversity and open science.

Institutions like CERN show what humanity can achieve when we set aside our disputes and work together for the common good. They give us hope for a better world and are more relevant today than ever.

Does CERN have a responsibility to guide the world in new technologies such as AI?

I do not think that CERN's role is to lead the world in the development of new technologies. Our primary mission is fundamental research, and we develop advanced technologies, in collaboration with our partner institutes in the Member States and beyond, insofar as they are necessary to achieve our scientific objectives.

Machine learning and other AI techniques have been used at CERN for many years, and have proven to be valuable tools in a wide range of applications, from accelerator operation to increasing the sensitivity of physics analyses. However, I do not consider it part of our mission to conduct research in AI as a goal in itself. CERN will, of course, need to develop those aspects of AI that are specific to our field when suitable solutions do not already exist. But we should neither reinvent existing solutions nor transform ourselves into a laboratory dedicated to developing all interesting technologies for their own sake.

There is no way to address today's global challenges without science

What are you planning to do next?

I plan to return to active research, at least for part of my time. I have always loved all areas of physics, but the Higgs boson is particularly intriguing and very close to my heart. We have learned a great deal over the past 14 years, yet this key particle remains quite mysterious. There is a rich, compelling and exciting programme of studies ahead at the HL-LHC and, potentially, at the FCC-ee.

I also plan to continue promoting science in other contexts, including as a member of the Board of Trustees of the World Economic Forum. I believe there is no way to address today's global challenges, from health to climate change, without science.

Interview by **Emma Hattersley** *CERN.*

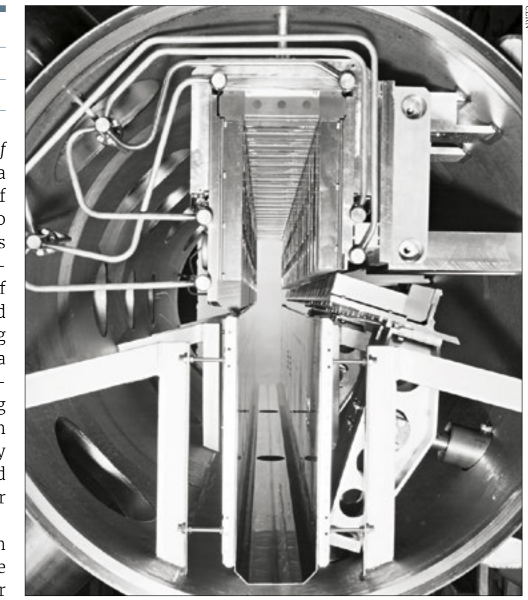
OPINION REVIEWS

Accelerators feel the chill

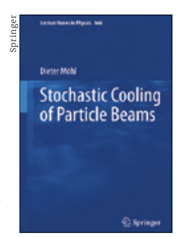
Stochastic Cooling of Particle Beams
By Dieter Möhl
Springer

The monograph *Stochastic Cooling of Particle Beams*, by Dieter Möhl, is a remarkably thorough treatment of a technique that remains central to hadron-beam physics decades after its invention at CERN. In accelerator physics, cooling means reducing the spread of particle positions and momenta around the design orbit, and stochastic cooling does so by sensing each deviation at a pickup electrode and applying a corrective kick downstream. By enabling the accumulation of dense antiproton beams, it paved the way for the discovery of the W and Z bosons, which earned Carlo Rubbia and Simon van der Meer the 1984 Nobel Prize in Physics.

The book grew out of lectures given at the CERN Accelerator School, the laboratory's training programme for accelerator physicists, and it reads that way. The pedagogy is deliberate, building from simplified time-domain models, in which a single particle is followed turn by turn and the corrective kick is derived directly from its measured error, toward progressively more complete descriptions that include the full beam ensemble. There is intentional repetition, which some readers will find slow but newcomers are likely to appreciate, since each pass also tightens the mathematical framework before adding the next layer of complexity.


CERN

Cooling the stack *A kicker inside the Antiproton Accumulator at CERN, where stochastic cooling compressed antiprotons into the dense beams that led to the W and Z discovery.*



Springer

Thorough treatment of a technique that remains central to hadron-beam physics

Of particular interest is the frequency-domain treatment of coasting beams in chapter 4, in which the author constructs the Schottky noise spectrum of an unbunched beam from first principles, starting with the Fourier decomposition of a single circulating particle's current and building up to the full band structure. The main result, that the integrated power of each Schottky band is constant while its bandwidth grows linearly with harmonic number, is laid out clearly.

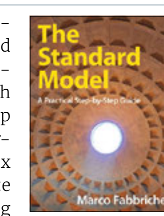
Möhl then extends the treatment to transverse signals, showing how the betatron sidebands, the spectral lines associated with the transverse oscillations of the particles, arise naturally, and how their structure encodes machine parameters such as tune and chromaticity. This is especially relevant in practice, since Schottky signals are often the only non-invasive diagnostic available when the beam is unbunched, and most other instruments are blind. The contrast with bunched beams, taken up among the special applications in chapter 8, is also instructive: cooling depends on particles shuffling between samples, the so-called mixing, and correlated synchrotron motion in bunches undermines exactly that, leading to substantially worse cooling rates.

The book fills an important gap as a self-contained reference on stochastic cooling theory and is well worth reading for anyone working in accelerator physics or interested in the topic.

Borja Rodriguez Mateos *CERN.*

The Standard Model: A Practical Step-by-Step Guide
By Marco Fabbrichesi
Cambridge University Press

This new textbook offers an intermediate-level presentation of the Standard Model (SM). It assumes that students have a knowledge of relativistic quantum mechanics and are comfortable with the Dirac equation, the properties of Dirac spinors, and covariant notation, including how to write Lagrangians in it. It also assumes familiarity with Feynman diagrams in quantum electrodynamics and with the basic application of the Feynman rules. Even so, the book opens with a substantial revision chapter taking up about a quarter of the main text, covering discrete symmetries, the S-matrix and aspects of QED, with a complete calculation of Compton scattering between a photon and an electron. Although the author does not treat phase-space calculations – the integrals over the kinematics of final-state particles that turn a matrix element into a



Cambridge University Press

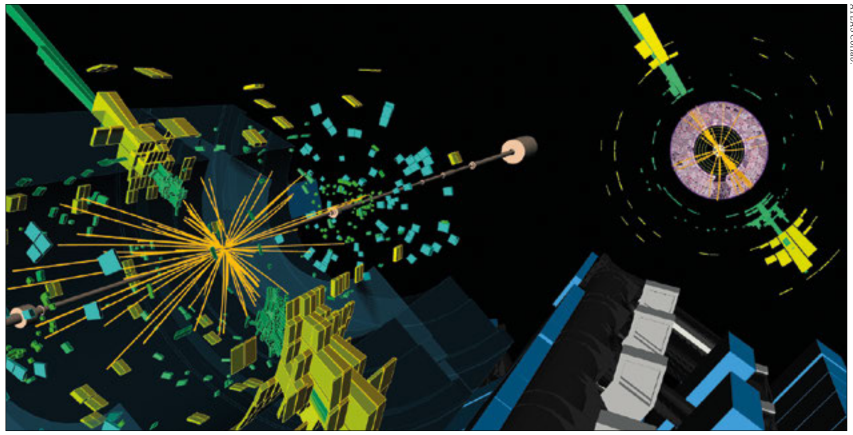
cross section or decay rate – as an independent topic, the complicated example of muon decay is worked out in detail.

A distinctive feature is the inclusion of fully worked-out examples, in which the algebra is carried out at much greater length than in most other textbooks. The effect is that of a blackboard lecture, rather than one of those slide presentations in which all the so-called "trivial" steps – that students rightly find anything but trivial – are omitted. Several of the examples broaden the physical understanding in ways rarely seen ▷

at this level: the hydrogen atom solved with the Dirac equation, coupled oscillators, mechanics problems involving torque, forces and inertia, all pressed into service to illuminate the underlying particle physics.

The heart of the volume is divided into two parts. The first sets out the basic elements of the SM, starting with the electroweak interactions mediated by photons, W and Z bosons, through gauge symmetry, spontaneous symmetry breaking and the Higgs boson, and ending with QCD. The second turns to applications. It includes an accessible treatment of higher-order corrections, flavour physics, flavour-changing currents and the CKM matrix that encodes the mixing between quark generations. It also features a chapter on QCD applications, covering the parton model and deep-inelastic scattering. A more elementary treatment is reserved for hadronisation, the non-perturbative process by which quarks and gluons turn into observable hadrons.

A clean section on the lowest-order calculation of gluon–gluon fusion Higgs-boson production at hadron colliders sits alongside the more standard material. Kaon oscillations, CP violation and neutrino oscillations close the book, alongside a 20-page experimental chapter of the kind one might expect in an introductory course. The book is presumably aimed at students with a stronger grounding in quantum field theory than in particle physics, who are now building from that base toward an understanding of the SM.



ATLAS Collab.

Dominant mode *A Higgs candidate decaying to two b-quarks at high transverse momentum, recorded by ATLAS in 2024. At the LHC, Higgs bosons are produced predominantly through gluon–gluon fusion, an example the book works out at lowest order.*

Overall, the book is faithful to its title. It sticks to the SM and avoids new-physics scenarios, save perhaps for neutrino oscillations, which some already classify as beyond it. Occasional bridges are built nonetheless. For instance, Majorana neutrinos appear in one of the exercises, while an accessible treatment of the θ-QCD term comes a breath away from discussing axions. The author does not shy away from using modern computational tools, with examples drawing on Mathematica, FeynCalc, the event generators MadGraph and Pythia, which simulate hard scattering and the subsequent parton showers and hadronisation, and the detector-simulation package Delphes. Each chapter ends with a small set of problems.

The result is a clear and engaging treatment, carefully tailored to its readership. Its fresh perspective, its unconventional examples and the painstaking attention to algebraic detail, make it a useful resource not only for students but also for instructors teaching introductory particle physics.

Nikolaos Rompotis *University of Liverpool.*

Die Urknallmaschine

By Barbara Warmbein

National Geographic Deutschland

How to explain CERN to someone who's never been there? That's indeed not always easy, but this book can surely help.

The German-language *Die Urknallmaschine* (The Big Bang Machine) by Barbara Warmbein offers an authentic glimpse into the research at CERN and the unique, sometimes extraordinary, environment in which it happens.

Warmbein has a real talent for combining fundamental ideas in physics and engineering at CERN with illustrative analogies. She creates mental pictures that make complex ideas easier to grasp, and much more likely to stick. The level is accessible to anyone with a general interest in physics and remains engaging without becoming overly technical or intimidating. This makes the book a good choice not only for readers without a CERN background, but also for anyone looking for better ways to explain the laboratory to friends, family or visitors.

Both the science and the human side of CERN captured in one stroke

National Geographic Deutschland

Warmbein starts with the big questions, the great mysteries of our universe, and gradually builds a bridge to CERN's research. Along the way, she explores both what we already understand and what remains unknown, often linking these ideas to everyday experiences. She weaves in historical context, reminding us, for example, that around the year 1900 many physicists believed that their work was almost complete, just before quantum mechanics and special relativity changed everything once again.

After roughly 50 pages dedicated to well-pitched basics, Warmbein moves on to accelerators and detectors, before widening the perspective to CERN as an organisation. She traces its development over the past 70 years, highlighting both what happens on site and the global network of institutes and collaborations that make CERN possible.

A nice touch is the inclusion of small but interesting pieces of side information, details that even people working at CERN might not know, in a compact form. This adds an extra layer of discovery, even for long-time insiders. The applications of accelerators outside fundamental research are one such example. Warmbein presents her material in a warm, approachable way, capturing both the science and the human side of CERN in one stroke.

Niklas Herff *CERN.*

Physics with dad jokes

Daniel Whiteson reflects on a career in particle physics at ATLAS, and on building a parallel path in science communication through books, podcasts and children's television.

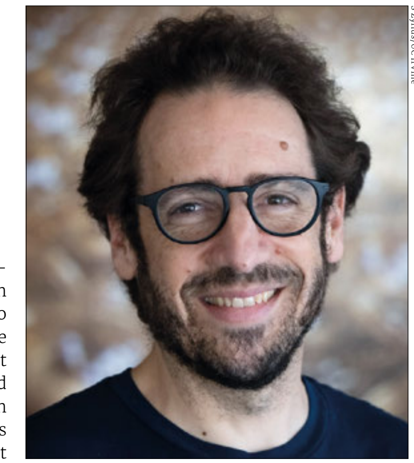
For Daniel Whiteson, professor at the University of California, Irvine, and a researcher on the ATLAS experiment at CERN, there was no obvious path ahead. As an undergraduate, he moved between fields, looking for one that fit. One summer, he tried plasma physics and later moved on to one of those laser labs in which, as he argues, "something is always broken". It was only in particle physics that things eventually clicked. "That's when I realised it's possible to have fun doing research," he recalls. "I also enjoyed the daily work of computer programming and data analysis, not vacuum chambers or optical systems. Particle physics is really personal."

That idea has stayed with him. "We're all interested in the big questions, but what you enjoy doing day-to-day determines where you can actually contribute," he says. Finding that alignment, however, is rarely immediate. "When you're young, you don't know yourself well enough to know what you are going to like," he reflects. "If everybody knew at 20 who they wanted to be at 40, their lives would be much simpler."

Turning point

A second turning point came during his postdoctoral years, when he considered leaving academia. He had no doubt about the science. What worried him, instead, was the life that came with it. Looking at faculty 10 years older, he saw few who seemed happy, and few who had managed a good work–life balance. Luckily, there were exceptions. "I found mentors who seemed to be having healthy patterns and tried to follow their lead," he says. "I thought I could make it work."

Whiteson's research with ATLAS focuses on "breaking down barriers to discovery, by using machine learning to make previously intractable problems tractable", an area he has been working in since the late 1990s. One example is the use of machine-learning algorithms to distinguish rare particle signals from overwhelming background noise in LHC data, improving the sensitivity of searches for new physics beyond the Standard Model.



S Zylius/UC Irvine

Physics, personal *Daniel Whiteson, a professor at UC Irvine and an ATLAS researcher, has built a parallel career in science communication.*

We're all interested in the big questions, but what you enjoy doing day-to-day determines where you can actually contribute

In parallel, he has built a career in science communication. The output spans podcasts, books, such as his recent volume *Do Aliens Speak Physics?* with cartoonist Andy Warner, and the PBS Kids series *Elinor Wonders Why*. Rather than teaching facts, the show portrays the process of science: when the children ask questions, adult characters don't know the answer and show the children how to work it out for themselves.

That journey started alongside cartoonist Jorge Cham. "I always wanted to use cartoons to convey science, because I feel like our field is so abstract that visuals are really important," he says. Humour, too, became central to that approach. "I feel like humour is such an important part of communication. It puts people at ease." As he puts it, "How complicated could this quantum field theory be if there's dad jokes mixed in, right?"

After Whiteson reached out to Cham, the collaboration grew quickly. The first video, on dark matter, reached more than a million viewers on YouTube. A second, on the Higgs boson, was cited in the further-reading materials accompanying the 2013 Nobel Prize announcement. All the while, research did not halt. "I never stopped having students. I never stopped going to CERN. I never stopped writing papers," he says. "My scientific productivity never dropped or dimmed." If anything, communication helped. "I learned physics because I had to describe it for the general public. And that improved my science."

Still, he is candid about the challenges: "The field is not always supportive of those kinds of efforts away from research." He has felt this himself. "It's unfair, but it's also the reality," he says. "There's a tension within the community, and things are changing."

Compelling prose

If there is one skill Whiteson feels is consistently underestimated, it is writing. "Writing is so important and so undervalued, especially in this AI age." Papers are a natural example "If you read a paper, and it's written sloppily, you think maybe the work is sloppy. Whereas if you read a paper, and it's crisp and clear, then you feel grateful to the author for putting in the time to think things through." Grants are another, and here the audience matters too. "Most of the grants submitted have great ideas. If the prose is compelling, it captures that bored grant reviewer and convinces them that you know what you're doing." The same applies to communication more broadly. "The challenge of science communication is not knowing if you understand the material, it's whether you understand where the audience is coming from, and how to guide them."

For early-career researchers, his advice is simple. "Do not get advice from people my age," he says, pointing to how quickly the field is changing. "There's now a path for people who do AI and physics. Thirty years ago, there really wasn't. Even AI was like a side gig for folks like me!" What matters more, in his view, is to be true to oneself. "Do the stuff you find fun," he says. "Because that's where you're going to shine."

Interview by **Caroline Clavien** *CERN.*

CERNCOURIER

Volume 66 Number 3 May/June 2026

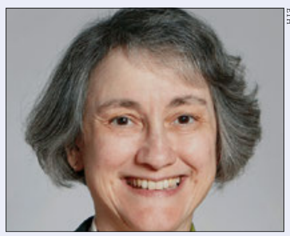
Appointments and awards

D Newbold, STFC

Newbold to co-lead DUNE
Dave Newbold (STFC) has been elected co-spokesperson of the Deep Underground Neutrino Experiment (DUNE), hosted by Fermilab, for a two-year term that began in April. He succeeds Sergio Bertolucci (University of Bologna) and joins continuing co-spokesperson Sowjanya Gollapinni (Los Alamos National Laboratory). Newbold has recently held the position of executive director, national laboratories, science and technologies at STFC, where he had previously served as director of particle physics. He has been involved in DUNE since 2015, contributing to data acquisition and to the UK production of accelerator and detector components. His tenure begins as DUNE enters the final stages of far-detector construction and installation. The experiment will study neutrino oscillations using the world's most intense neutrino beam. Its principal goals include determining the order of the three neutrino masses and searching for lepton-sector CP violation.

Turing win for cryptographers
The Association for Computing Machinery (ACM) has awarded the 2025 A. M. Turing Award to quantum-cryptography pioneers Charles H Bennett (IBM Research) and Gilles Brassard (Université de Montréal), for their foundational work in quantum information science. The $1 million prize recognises the 1984 BB84 protocol, the first practical scheme for quantum key distribution, and their contribution to a seminal 1993 paper on quantum teleportation, which showed how arbitrary quantum states could be transmitted through entanglement and classical communication. BB84 owes its security to a basic fact of quantum mechanics: any attempt by an eavesdropper to measure the transmitted quantum states disturbs them, leaving traces that the sender and receiver can detect. The two have previously been recognised with the Wolf Prize in Physics and the Breakthrough Prize in Fundamental Physics.

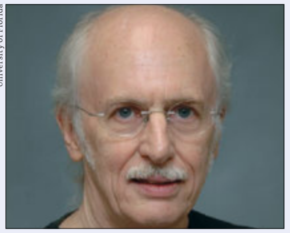
Heyderman wins Charpak–Ritz
Laura Heyderman (ETH Zurich and Paul Scherrer Institute) has been awarded the 2026 Charpak–Ritz Prize of the French and Swiss physical societies. The prize recognises her work on systems with magnets at the mesoscopic scale, from tens of nanometres to a few micrometres. Heyderman, who has held a joint appointment between ETH Zurich and PSI



ETH

since 2013, has, together with her group, demonstrated electrically controlled domain-wall logic in nanomagnetic devices, observed emergent magnetic monopoles in artificial spin ice, and developed synchrotron X-ray magnetic tomography to map three-dimensional magnetic features. The Charpak–Ritz Prize alternates each year between physicists working in France and Switzerland.

Heineman prize for Thorn
Charles B Thorn (University of Florida) has been awarded the 2026 Dannie Heineman Prize for Mathematical Physics of the American Institute of Physics and the American Physical Society. Thorn is recognised "for fundamental contributions to elementary particle physics, primarily the theory of strong interactions and the development of string theory". He co-developed the MIT bag theory of hadrons, which models quarks as confined within a bounded region, and, in collaboration with Peter Goddard, proved the "no-ghost" theorem, establishing the consistency of the dual resonance model (DRM).



University of Florida

Thorn and Goddard showed that the physical spectrum of the DRM contains no states with negative norm, a key step in its reinterpretation as a theory of strings. The $10,000 prize was presented at the APS Global Physics Summit in Denver on 16 March.

New LHCb spokesperson
Tim Gershon (University of Warwick) has been elected spokesperson of the LHCb collaboration for a three-year term starting in July 2026. He succeeds Vincenzo Vagnoni (INFN Bologna) and will be the eighth person to lead the collaboration, which comprises around 2000 members from 109 institutes in 28 countries. Gershon joined LHCb in 2008, served as its physics coordinator in 2012–2013, and has worked throughout on tests of the Cabibbo–Kobayashi–Maskawa picture of CP violation through measurements of B-meson decays. His tenure begins as the LHC enters Long Shutdown 3, during which LHCb will replace the radiation-damaged innermost modules of its electromagnetic calorimeter and the readout electronics of its ring-imaging Cherenkov detectors.

Award for DUNE excavation
The Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE) has received the 2026 Project of the Year Award from the Underground Construction Association in the $100 million to $500 million category. The award recognises the excavation of three large underground caverns at the Sanford Underground Research Facility in South Dakota to house DUNE's far detectors and supporting infrastructure. The two detector caverns each measure some 20 × 28 × 145 m and sit about 1.5 km below the surface. Excavation began in early 2019 and was completed in February 2024, removing 725 million kilograms of rock over more than 1.1 million working hours without lost-time injuries.

Franklin medal to Freedman
Wendy Freedman (University of Chicago) has been awarded the 2026 Benjamin Franklin Medal in Physics by the Franklin Institute, "for scientific investigations that established precision measurements of the expansion rate of the universe, and for leading efforts to make the next generation of these measurements even more precise". Freedman led the Hubble Space Telescope Key Project, which in 2001 produced the first precise measurement of the Hubble constant by fixing distances to nearby galaxies

University of Chicago

with Cepheids – a class of pulsating stars whose intrinsic brightness can be inferred from their pulsation period. She has since pursued independent determinations based on the peak brightness reached by stars at the tip of the red giant branch. The award is one of several she has received in the past two years, including the 2025 US National Medal of Science and the 2024 Georges Lemaître International Prize. The medal was presented at the Franklin Institute on 30 April.

PEOPLE OBITUARIES

Mark Alastair Rayner 1983–2026

A physicist and editor of the highest calibre

It was with profound shock and sadness that we learned of the passing of Mark Rayner, editor of *CERN Courier*, on 23 March due to sudden illness. His love of physics, talent for communication and editorial rigour raised the bar for this magazine.

Mark was born in Hounslow, England, on 7 October 1983 and studied physics at Worcester College, University of Oxford, from 2002 to 2006. In 2005 he spent three months at CERN as a Summer Student working on tests of the ATLAS transition-radiation-tracker end caps. He continued at Oxford with a PhD, participating in the Muon Ionisation Cooling Experiment (MICE) based at the Rutherford Appleton Laboratory. His thesis described the development of a novel technique for characterising the MICE muon beam and demonstrating its suitability for a muon cooling measurement, an essential step on the path towards a possible neutrino factory and muon collider.

In 2011, he moved from accelerator physics to neutrino physics, joining the University of Geneva both as a lecturer and as a researcher working on the T2K, Hyper-Kamiokande and BabyMIND experiments. Over the years, Mark supervised several students. In the process he deconstructed the weaknesses in the T2K detector system, realising that an upgrade of the detector setup at the source was necessary for the long-term programme. An upgrade was proposed, with a much simplified and better geometry, largely using detector techniques developed in MICE. It was approved in 2019 and is now successfully operational.

CERN

Mark's presence brought light to those fortunate enough to know him.

As a physicist, Mark stood out for his care and originality. He liked simplicity and elegance, and to understand the relative causality of correlated observations. He made many important contributions and was happy to do so, without seeking recognition.

A natural educator and communicator, Mark trained as an apprentice physics teacher at Ecole Internationale de Genève in 2018. The following year, he joined CERN as a senior fellow working on the *Courier*, where he played a major role in the launch of the magazine's website and rose quickly to become deputy editor. When his fellowship ended, Mark took his exceptional skills to the World Economic Forum, where he managed the production of a portfolio of publications and tools relating to education, skills and learning, and served as lead author for the *Future of Jobs* report 2023 (see p54).

Mark returned to CERN as a staff member in 2024, as editor of the *Courier*. Over a short period, his eye for design, his mastery with words, and his ability to interpret and display complex information in novel ways sharpened the impact of CERN's flagship publication. He also paid particular attention to improving the visibility of gender diversity in these pages and to developing the magazine's online presence, enabling him to connect particle physics with new audiences. He took great pride in his work and in engaging with authors to shape their stories. He had huge respect for those who devoted their lives to fundamental research in physics and was widely recognised for his dignity and professionalism among members of the international particle-physics community.

Above all, Mark cared deeply about everything he did, and especially about the well-being of others. His pursuit of excellence and his remarkable attention to detail set a standard that inspired those around him, and this is reflected in the deeply motivated team that he built and nurtured. He was highly cultured, played the flute, and sang in the Geneva Gospel Choir.

Mark was a man of great intellect, warmth and spirit, whose presence brought light to those fortunate enough to know him. He will be remembered with great respect and will be profoundly missed.

His friends and colleagues.

Jan Żylicz 1932–2026

An exceptional scholar and teacher

On 16 February 2026, the Polish physics community suffered a painful loss – professor Jan Żylicz, an outstanding nuclear physicist, passed away in Warsaw.

Jan Lubart Żylicz was born on 7 January 1932 in Góra, in the Kashubian region, and completed his studies in physics at the University of Warsaw in 1955, under the supervision of Andrzej Sołtan. His work on beta spectroscopy of strongly deformed nuclei, conducted at the Institute of Nuclear Research, contributed to his 1961 PhD at the University of Warsaw. He continued his research on beta decay of rare-earth nuclei during a stay at the Niels Bohr Institute in Copenhagen from 1963 to 1965. One of his important contributions was the identification of the Coriolis effect's role in rotating atomic nuclei, which served as the basis for his habilitation at the University of Warsaw in 1967.

His research stay at the CERN–ISOLDE facility, from 1970 to 1971, was devoted to the study of nuclides far from beta stability. This topic significantly influenced his subsequent scientific work, and he spent two further research stays in the mass separator group at GSI Darmstadt, from 1978 to 1979 and from 1986 to 1987. The close and long-lasting collaboration with GSI, which Jan initiated, played a crucial role in the scientific development of young scientists in the Warsaw group, many of whom completed postdoctoral fellowships there.

He led several large research projects, including studies of octupole correlations in actinide nuclei. This work was to some extent pioneering and contributed to growing interest in this topic among theorists and experimentalists. He devoted particular attention to exotic nuclides far from the beta-stability line, notably through the extensive research programme on ▷

CERNCOURIER
Volume 66 Number 3 May/June 2026

Gamow–Teller transitions in the region of the doubly magic tin isotope ^{100}Sn, carried out mainly at GSI Darmstadt, but also at the ILL in Grenoble, the University of Jyväskylä and CERN–ISOLDE.

Jan had a talent for initiating valuable research programmes that could be carried out in Poland under the modest experimental conditions available in Warsaw at the end of communism. For example, he developed a new method for measuring the K-shell ionisation by charged particles, which was used for many years at the Warsaw Van de Graaff accelerator and yielded several results of practical importance. He was also interested in phenomena at the interface between nuclear and atomic physics, and proposed a programme to study radiative electron capture in forbidden transitions. Among Jan's most original achievements are his works on the isomeric state of ^{229}Th, and the idea of spin-mixing oscillations in the states of the hydrogen-like ion ^{229}Th^{89+}. This work was ahead of its time – attempts to confirm the phenomena he predicted are currently underway at the ESR storage ring at GSI Darmstadt.

Associated with the University of Warsaw from 1972 to the end of his career, Jan established a new Nuclear Spectroscopy Group, which he headed until 1994, and served as director of the Institute of Experimental Physics from 1994 to 2002. In 2005, the Polish Physical Society awarded him its highest distinction – the Marian Smoluchowski Medal – and the European Physical Society honoured him with the title of EPS Fellow. He was also awarded the Knight's Cross of the Order of Polonia Restituta.


M Baj

Jan Żylicz was a leading figure in Polish nuclear physics and a generous mentor to younger scientists.

Jan was an outstanding educator, whose lectures were valued for their clarity and for the passion with which he explained the essence of a problem. He attached particular importance to mentoring young academic staff, supporting and patiently motivating them. He sent them to international conferences and helped to organise research stays at leading Western institutions, which was especially important at a time when this was not as easy as it is today. He supervised 17 master's theses and 12 doctoral dissertations, with six of his students later becoming professors of physics. Their successes brought him joy and pride, and he considered creating the conditions for the scientific development of his younger colleagues his principal achievement.

Jan Żylicz was a warm and kind man with an extraordinary sense of humour. Working with him gave us a sense of purpose, satisfaction and joy. He will forever be remembered as a model scholar and teacher.

Marek Pfützner *and* **Tomasz Matulewicz** *University of Warsaw.*

Roger Barlow 1951–2026

An illustrious career in particle physics

Roger Barlow passed away suddenly on 1 February 2026 at his home in Wales. Roger had an illustrious career in particle physics and, latterly, also in accelerator physics. He was well known internationally for his work in statistics, in particular for his widely used textbook, *Statistics: A Guide to the Use of Statistical Methods in the Physical Sciences*, published in 1989.

Roger was born on 14 April 1951 in Canterbury. After attending Edinburgh Academy, he obtained a place to study for his first degree at Oxford. He then went to Cambridge, where he completed his PhD in 1977 on proton–deuteron interactions at CERN's 2 metre bubble chamber. Roger then took up a research post at Oxford, working on the TASSO experiment, and contributed to the discovery of the gluon in 1979.

In 1980, Roger was appointed to a lectureship at the University of Manchester and joined the JADE Collaboration, where his work on event reconstruction and Monte Carlo simulation led to one of the early measurements of the B-meson lifetime. During his early years at Manchester, Roger moved on to the OPAL experiment, becoming leader of the Manchester team in 1991. On OPAL, he helped design, build, commission and operate the muon chambers, which were crucial for many Standard Model physics studies, including precision measurements of the Z boson.

Roger became the overall leader of the Manchester particle-physics group in 2005, after the retirement of Robin Marshall. The group was then also involved in ATLAS, DO, several neutrino experiments and BaBar, which Roger had joined. Under his leadership, the particle-physics group grew to more than 100 members. As a collaborator on BaBar, he helped design the electromagnetic endcap, and he supervised the construction of half of the detector in Manchester. His data analyses included setting new limits on the existence of second-class weak currents in tau–lepton decays. As BaBar wound down, he took his group into LHCb.


University of Huddersfield

Roger Barlow contributed broadly to particle physics, accelerator science and the teaching of statistics.

In the early 2000s, Roger began researching accelerator science, forming an accelerators group in Manchester and becoming a founding member of the Cockcroft Institute of Accelerator Science and Technology. He was principal investigator for the CONFORM project that led to the successful operation of EMMA, the world's first non-scaling FFAG accelerator. This provided a proof of principle for a new type of accelerator with many potential applications. In 2011, he left Manchester for a post at the University of Huddersfield, where he formed another accelerator-science group.

In addition to his textbook, Roger produced several influential works on statistics, including a description of extended maximum likelihood, a highly cited paper on fitting using finite Monte Carlo samples, and a detailed paper on the treatment of systematic uncertainties.

Roger was a dedicated and skilled teacher, who cared deeply about educating the next generations. Among his many contributions to the public understanding of science, he introduced the Particle Physics Masterclasses for high-school students, which quickly expanded across the UK, before becoming truly international. In recognition of this, he was awarded the Institute of Physics' Lise Meitner Medal and Prize in 2022.

Roger retired from Huddersfield in 2017, but continued to work on BaBar and LHCb, and to publish papers and lecture on statistics, right up until his passing.

Outside of physics, Roger was active in UK national politics as a member of the Liberal Democrats. He was selected three times to stand as a candidate for the UK parliament. He will be greatly missed by his wife, Ann, his children Edward and Eleanor, his extended family, and his many friends and colleagues across the world.

George Lafferty *University of Manchester.*

Michael Wohlmuther 1975–2025

An expert on spallation physics

Michael Wohlmuther, an internationally recognised expert on spallation physics and technologies, tragically passed away on 30 October 2025 in Lund, Sweden, at the age of 50.

Michael was born on 26 January 1975 in Bruck an der Mur, Austria. In 2003, he received his PhD from the Graz University of Technology for his thesis "An Intranuclear Cascade Event Generator", written in collaboration with Forschungszentrum Jülich.

In his different roles, Michael contributed greatly to the development of targetry technologies, both from the physics and the engineering perspective. One of his major contributions was serving as project leader for the MEGAPIE project at PSI, the world's first high-power liquid-metal spallation neutron source. More recently, he actively participated in the effort to develop the ESS high-power tungsten target and related material analyses.

His involvement extended beyond PSI and ESS, and included collaborations with CERN, the Facility for Rare Isotope Beams (FRIB) and Oak Ridge National Laboratory (ORNL). He influenced the global landscape of spallation, high-energy physics and radioactive-ion-beam target technologies, in both operational practice and post-irradiation analysis.


M Calviani

Michael Wohlmuther contributed greatly to the development of targetry technologies.

Michael's work consistently achieved international recognition, and he served on important review panels and advisory committees, including the High-Power Targetry Workshop Scientific Program Committee and the FRIB Target Advisory Committee. He was also a founding member of CERN's HiRadMat Scientific Board.

Michael was an invaluable member of the spallation targetry community for many years. He contributed to our shared endeavours with his vast expertise, his attention to detail and his kindness towards the people around him. He will be remembered for his warm and welcoming spirit, his readiness to greet everyone with a smile, and his genuine humility.

Our thoughts and sincerest condolences are with Michael's family, his friends and all those who were fortunate enough to have known him. He will be deeply missed by everyone who had the privilege of working alongside him.

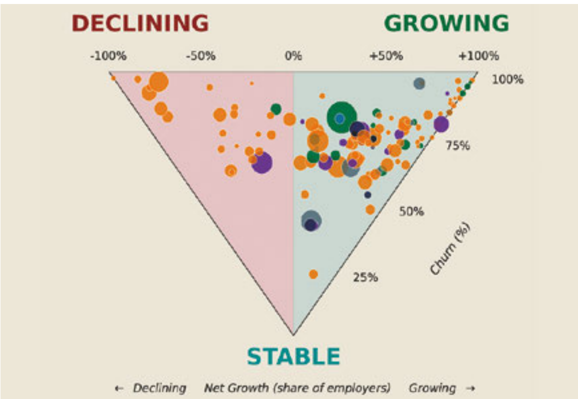
His friends and colleagues.

CERNCOURIER
Volume 66 Number 3 May/June 2026

BACKGROUND

Notes and observations from the high-energy physics community

Rayner plot



Before returning to the *Courier* as editor, Mark Rayner worked on the World Economic Forum's *Future of Jobs* report. Among his contributions is a plot that now bears his name. It shows where employers expect every occupation to head over the next five years, placing each one inside a triangle whose three corners represent unanimous expectations of growth, decline or stability. In its tribute, the WEF notes that Mark "brought the rigour of a particle physicist to an economics role".

92 Antiprotons moved across CERN's Meyrin site by the BASE collaboration on 24 March, in the first ever transport of antimatter

Media corner

"It's just a huge relief. This new measurement is a strong confirmation that we can trust the Standard Model."

Kenneth Long (MIT), a lead author of the new CMS measurement of the W-boson mass, which contradicts the 2022 CDF anomaly (*MIT News*, 8 April).

"I love the idea of CERN becoming the Deliveroo [a food-delivery company] of antimatter."

Tara Shears (University of Liverpool) on the BASE collaboration's transport of antiprotons across CERN's Meyrin site (*Nature*, 24 March).

"I think the most interesting times are the hard times. Why are you in this field, if you don't love hard?"

Janet Conrad (MIT) on the state of neutrino physics after recent experiments ruled out the electron-volt sterile neutrino (*Quanta Magazine*, 8 April).

"We believe this is the final nail in the coffin of the proton radius puzzle."

Lothar Maisenbacher (University of California, Berkeley) on a new ultra-precise measurement of the charge radius of a proton in a hydrogen atom, pointing away from new physics (*Ars Technica*, 14 April).

From the archive: May/June 1986

The two frontiers of physics

Even initial ideas about inflation had problems, as depicted by Andrei D Linde.

In March, at Garching, physicists took a hard look at the two major frontiers of physics – the very large and the infinitesimally small. Organised by CERN and the European Southern Observatory, the 'Symposium on Cosmology, Astronomy and Fundamental Physics' was the second in a series launched at CERN in November 1983.

The 1983 Symposium had come in the wake of the unification of the weak and electromagnetic forces, and with other interesting new ideas in the air – such as cosmological inflation and grand unification – the moment held out hope that the barriers around the problem of the origin of the Universe might be crumbling. Two years down the line, while inflation had once been a relatively straightforward idea, session chairman T. Kibble said that life had become more complicated, and symposium summarizer D. Sciama described inflation as 'baroque', but still full of possibilities.

● Text adapted from *CERN Courier* May 1986 pp29–33.

Around the Laboratories: Supertex

Despite the decision last year [1985] that the proposed US Superconducting Supercollider (SSC) should go for the high-field magnet design developed at Berkeley, Brookhaven and Fermilab, the Texas Accelerator Center has taken delivery and tested 'Supertex', its first full-scale 'superferric' magnet. The 28-m-long monster, the longest superconducting magnet ever built, was trucked from the General Dynamics factory in San Diego to Texas.

● Text adapted from *CERN Courier* May 1986 p23.

Compiler's note

The Texas Accelerator Center was set up in March 1984 to participate in the design of the SSC. It concentrated on an approach aiming for simplicity in construction and hence lower fabrication costs. The result was a low-field superferric magnet. However, the 3 T field implied a ring of about 160 km for a 20 TeV machine, as opposed to about 90 km for the chosen high-field type. (For a picture of the 28 m monster, see https://repository.cern/records/hbngb-5h664.) Construction of the SSC began in 1991, but stopped two years later when the project was cancelled. The ideas of cosmic inflation, by contrast, have survived various incarnations and are now generally accepted.

CERNCOURIER
VOLUME 66 NUMBER 3 MAY/JUNE 2026