WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the July/August 2026 issue of *CERN Courier*.

When the Large Electron–Positron collider (LEP) switched on, in 1989, the field had never worked at such a scale. Approved eight years earlier, it collided electrons and positrons until the turn of the century, marking two decades in which discovery truly turned global. Last November, some 200 physicists and historians gathered at CERN to take stock of those years (p22), while the Large Hadron Collider, built in LEP's tunnel, delivered its final collisions in June (p8).

For 10 years, NA64 has fired probes onto a target and watched for missing energy, seeking a dark sector too faint to catch otherwise. It will now undergo a full round of upgrades, to sustain much higher intensities and increase its dataset by up to two orders of magnitude (p28).

This edition of *CERN Courier* also explores Xsuite, the open-source framework that gathered the field's scattered beam-simulation tools. Today, it designs the colliders to come, tunes those already running and models synchrotrons to treat cancer (p33).

In May, the CERN Council updated the European Strategy for Particle Physics (p7). The preferred next flagship is once again an electron–positron collider, the FCC-ee. Council president Costas Fountas weighs what must fall into place before a decision, targeted for 2028 (p39).

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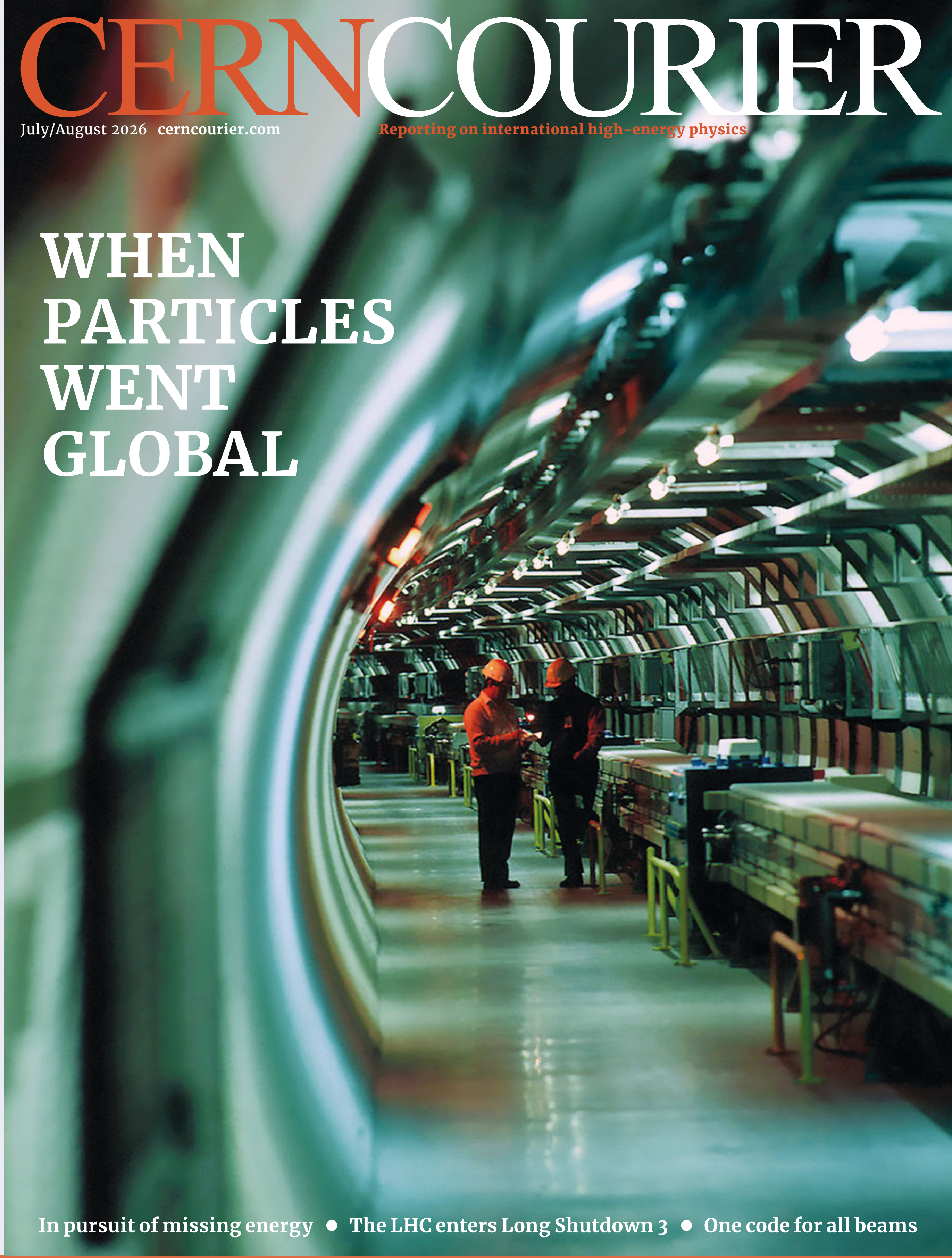
ASSOCIATE EDITOR: DAVIDE DE BIASIO



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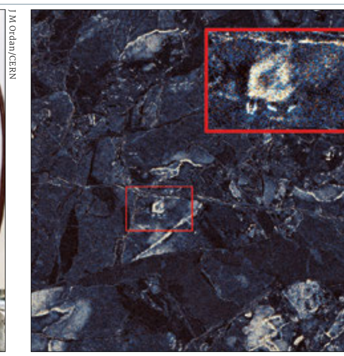

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FROM THE EDITOR

The long view

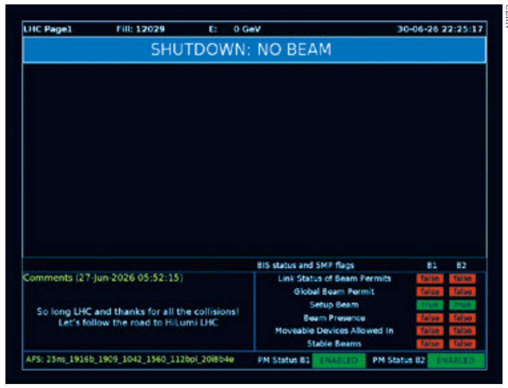
Davide De Biasio
Associate editor

When the Large Electron–Positron collider (LEP) switched on, in 1989, with its four vast experiments, the field had never worked at such a scale. Approved eight years earlier and pictured on this issue's cover, LEP collided electrons and positrons until the turn of the century – marking a period in which discovery truly turned global. The W and Z bosons came at CERN's Sp$\bar{p}$S in 1983, the top quark at Fermilab's Tevatron in 1995, neutrino oscillations at Super-Kamiokande in 1998. Other searches were less fortunate. Supersymmetry, long hoped to ease the problem of naturalness, never appeared, nor did leptoquarks or proton decay. Last November, some 200 physicists and historians gathered at CERN to take stock of those two decades (p22).

The hadron collider that took over LEP's tunnel, the LHC, delivered its final collisions in June (p8). After a four-year transformation, the machine will return as the High-Luminosity LHC, set to gather several times the data taken so far. Alongside it, CERN is already planning the next chapter of fundamental exploration. At a dedicated session in May, the CERN Council updated the European Strategy for Particle Physics (p7). The preferred next flagship is once again an electron–positron collider, the FCC-ee. More than three times the size of LEP, it would match its entire yield of Z bosons in minutes, to then climb through the WW threshold, the ZH production peak and the top-pair threshold over 15 years. At each step, it would subject the Standard Model to its most stringent tests yet, with a precision almost unthinkable in LEP's days. Council president Costas Fountas weighs what must fall into place before a decision, targeted for 2028 (p39).

The European Strategy also supports a diverse non-collider programme, and this issue explores one ingenious example. For 10 years, NA64 has fired probes onto a target in CERN's North Area and watched for missing energy (p28), seeking a dark sector too faint to catch otherwise. Among its results are bounds on the dark photon, once conjectured to contribute to the muon's anomalous magnetic moment. The experiment will now undergo a full round of upgrades, reaching much higher intensities and gathering up to a hundred times its current dataset.

The LHC delivered its final collisions in June



CERN

Beam off *The LHC's status screen after the end of its third run, with a message from the control room.*

This issue then turns to the codes that model, optimise and control accelerators, bringing their thousands of parts into accord. Written for LEP, the MAD program grew into the standard that served the LHC, while other tools proliferated and drifted apart. One open-source framework, Xsuite, set out to gather the scattered threads (p33). Today, it designs the colliders to come, tunes those already running, and models advanced synchrotrons to treat cancer.

Open-source principles also underpin a cheap and simple cosmic-ray detector built at CERN and driven across the planet to both poles (p41). With its near-continuous readout of muons, it offers another, more literal, take on how particle physics gets ever more global. Elsewhere in this issue, arXiv sets a one-strike rule against unchecked AI-written papers (p9), quantum observables gain pace at colliders (p17), a protocluster of galaxies appears ahead of schedule (p11), and much more.

Reporting on international high-energy physics

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bergoz INSTRUMENTATION

Bergoz Instrumentation goes digital

For more than 45 years, Bergoz Instrumentation is providing non-destructive current measurement solutions to particle accelerators worldwide.

To integrate the signals of our beam current transformers into accelerator control systems, particle accelerators require high-performance digitizers with optimized bandwidth, sampling rate, and dynamic range. These digitizers must be accurate, reliable, easy to deploy and simple to operate.

To meet these challenges, the Modular Digital Solution (MDS) suite has been designed to integrate with our existing products, providing a complete, end-to-end solution.

Their designs are guided by three main objectives:

- Preserving the integrity of the analog signal during digitization;
- Ensuring long-term sustainability through the use of high-performance and widely available components;
- Providing an easy-to-use and quick-to-set-up solution that can adapt to different beam types.

Beyond waveform acquisition, the MDS can provide extra features such as pulse charge, interlock on threshold, time stamping with further customization upon user request.

Each MDS variant is dedicated to specific Bergoz Instrumentation measurement system to best interface their analog signals with accelerator control systems.

Communication is implemented over Ethernet through a simple command protocol, and an EPICS soft IOC is provided.

The MDS-ACCT, based on a 16-bit analog-to-digital converter (ADC) operating at 160 MS/s, is already available. The MDS-NPCT and MDS-ICT are currently being developed and will soon be released.

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NEWS ANALYSIS

Policy

CERN Council updates the European Strategy

On 22 May, at a dedicated session in Budapest, the CERN Council updated the European Strategy for Particle Physics. The update confirms the full exploitation of the scientific potential of the LHC, through the completion of its high-luminosity upgrade (HiLumi), as the highest medium-term priority for European particle physics. For the longer term, it recommends the electron–positron Future Circular Collider (FCC-ee) as the preferred option for the next flagship project at CERN, thereby maintaining Europe's leadership in the field. A decision on the FCC-ee itself is targeted for 2028.

Strategy, updated *The CERN Council in Budapest for its dedicated session on the European Strategy for Particle Physics, on 22 May 2026.*

Critical importance

"The European Strategy reiterates the critical importance of the High-Luminosity LHC, which will use advanced accelerator and detector technologies to fully exploit the scientific potential of this incredible machine in the coming years," said Mark Thomson, CERN Director-General. "Beyond HiLumi LHC, the FCC-ee would be a visionary global research infrastructure for the next decades that will deepen our knowledge of the fundamental building blocks of the universe through ultra-precise measurements of the Higgs boson and other elementary particles. CERN's task now is to steer this unprecedented project towards a decision by the CERN Council."

According to the Strategy, the FCC-ee would offer the broadest exploratory programme in fundamental physics. The feasibility study, published in March 2025 (*CERN Courier* May/June 2025 p9), describes a baseline machine in a 90.7-kilometre ring, running at four centre-of-mass energies: the Z pole, the WW threshold, the ZH production peak and the top-quark pair threshold. Over a 15-year programme, it would be expected to yield some 6×10^{12} Z bosons, 2.4×10^{8} W-boson pairs, 2.7×10^{6} Higgs bosons and 2×10^{6} top-quark–antiquark pairs.

"The high-energy physics community and the CERN Council have been united for this critical update of the European Strategy for Particle Physics, and the FCC-ee has emerged as the preferred flagship project to maintain CERN's world-leading role in collider physics and technology in the decades to come," said Costas Fountas, Council president. "I wish the CERN management the greatest success in implementing the Council resolution between now and the 2028 target decision date."

The 2026 update follows more than two years of intense work by the European particle-physics community, under the auspices of the European Strategy Group. Initiated in March 2024, the process aimed to develop a concrete plan to advance fundamental physics by constructing a new flagship project at CERN, and drew on more than 260 written submissions. It builds on the 2020 update, which emphasised the importance of ensuring Europe's continued scientific and technological leadership, and recommended an electron–positron "Higgs factory" as the highest-priority next facility after the LHC reaches the end of its operational lifetime in 2041.

In addition to updating the Strategy, the Council has invited CERN management to initiate discussions with the relevant authorities and entities in the Member and Associate Member States, as well as non-Member States and the European Union, with a view to developing a financially feasible funding plan for the possible FCC-ee project. In the next two years, CERN management will provide annual reports on the implementation of the Strategy update and the necessary information to support national decision-making processes so that the Council will be in a position, by 2028, to take a decision on the FCC-ee, taking into account elements such as the scientific, technical and financial feasibility of the project, as well as results from the public consultation exercises in CERN's host states, France and Switzerland.

The FCC-ee would be a visionary global research infrastructure that will deepen our knowledge of the fundamental building blocks of the universe

Strong engagement

"The Strategy process has seen a very strong engagement of the particle-physics community and has led to a very clear conclusion: the FCC-ee, if approved, would deliver the world's broadest high-precision particle-physics programme, its technical feasibility has been demonstrated by the comprehensive FCC feasibility study, and its scope and cost are well defined," said Karl Jakobs, Strategy secretary. "It would also pave the way for a possible future hadron collider reusing the tunnel and much of the infrastructure, providing direct discovery reach well beyond the 10 TeV parton energy scale."

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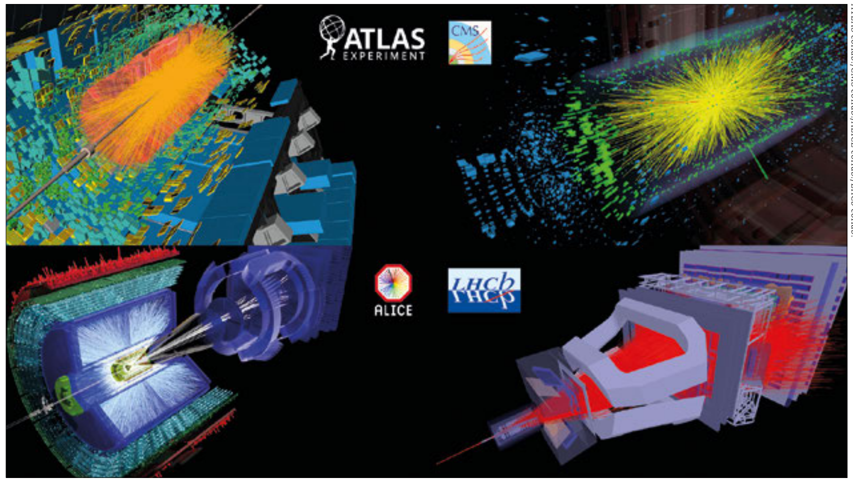
LHC

The LHC completes its third run

On 27 June 2026, proton beams circulated through the LHC for the final time before the machine entered its third Long Shutdown (LS3). After four years of operation, the world's highest-energy particle accelerator now begins an ambitious programme of upgrades that will transform it into the High-Luminosity LHC (HL-LHC).

"The performance of the LHC during Run 3 surpassed all expectations," says Oliver Brüning, director for accelerators and technology at CERN. "The LHC delivered nearly 550 fb^{-1} of integrated luminosity since its first collisions – almost twice the original target of 300 fb^{-1}. This amounts to 50 times the total combined dataset produced by all hadron colliders operating before the start of the LHC."

The LHC was approved by the CERN Council in December 1994 and built in the 27 km tunnel previously occupied by LEP, the electron–positron collider that operated at CERN until 2000 (p22). Collisions began in 2009, reaching the 7 TeV centre-of-mass energy milestone in 2010. The years since have brought the discovery of the Higgs boson, a wealth of new hadrons, detailed studies of the quark–gluon plasma and measurements of a wide range of Standard Model (SM) processes with steadily improving precision.



One last dance *Event displays from some of the final collisions recorded by the four large LHC experiments, ATLAS, CMS, ALICE and LHCb (left to right, top to bottom), before the machine's third Long Shutdown and its upgrade to the HL-LHC.*

Expanded searches

The recently completed third run exploited the accelerator and detector systems upgraded during the machine's second Long Shutdown (LS2), from 2019 to 2022 (*CERN Courier* May/June 2022 p29). "The LHC's Run 3 benefits from an increased proton–proton collision energy of 13.6 TeV and a data volume that is far greater than that of Run 2," says Gautier Hamel de Monchenault, director for research and computing at CERN. "This enabled detailed studies of the Higgs-boson's properties through high-precision measurements and explorations of its self-coupling and rarest decays. Searches for dark matter and new phenomena expanded considerably to include new topologies, such as exotic long-lived heavy particles, through improvements in trigger systems and advances in analysis techniques."

Run 3 also brought advances in flavour physics, with more precise measurements of rare decays and CP violation across the beauty and charm sectors, and in the heavy- and light-ion programmes. In summer 2025, the LHC successfully delivered its first oxygen–oxygen and neon–neon collisions (*CERN Courier* November/December 2025 p8). "The LHC provided the experiments with extensive samples of lead–lead collisions, as well as samples of events involving lighter nuclei of oxygen and neon, in order to map the properties of the primordial quark–gluon plasma with greater precision," remarks Hamel de Monchenault.

The upgrades to the experiments are the largest since the start of the LHC

During Run 3, the proton–proton collisions delivered to each of the general-purpose experiments ATLAS and CMS amounted to about 4×10^{16}, while the lead-ion programme delivered about 2×10^{11} collisions to the four experiments – ALICE being the one designed specifically for heavy-ion physics. LHCb, primarily a flavour experiment and the only one to also operate in fixed-target mode, collided the beams with several gas species injected through its SMOG2 system. Together, the experiments generated exabytes of data for processing, storage and analysis through the Worldwide LHC Computing Grid.

The final proton–proton collisions took place on 16 May, followed by the final lead–lead collisions on 14 June. The beams continued circulating for another two weeks for high-intensity machine tests before the accelerator was shut down. "The success of the LHC Run 3 is a testimony of the quality and ingenuity of the LHC design and hardware, and to the dedication and competence of the teams looking after the operation of the accelerator," says Brüning.

Although collisions have now ceased, analysis of the collected data will continue well into the 2030s. Meanwhile, the LHC and its experiments enter LS3, a four-year period during which extensive upgrades throughout the accelerator complex and the detectors will turn the machine into the HL-LHC.

Unprecedented efficiency

"The HL-LHC aims at increasing the data set produced by the LHC by an order of magnitude," says Brüning. "This implies not only an increase in the instantaneous performance but also an unprecedented availability and efficiency of the machine. To this end, new underground galleries and caverns were created next to the LHC tunnel, reducing radiation exposure to the electronics and thus the machine's downtime, and facilitating access for technical experts to intervene in case of problems. All these new underground structures have been completed during the LS2 and the Run 3 period. The production of the remaining components is in full swing, with more than half of them already available for installation in the tunnel and the new underground areas."

The upgrades to the experiments ▷

are the largest since the start of the LHC. Large sections of the detectors are being rebuilt from scratch, with new tracking systems, upgraded calorimeters and muon detectors, and next-generation trigger and data-acquisition systems built for the far higher event rates. These upgrades will let the experiments match and exceed their current performance under HL-LHC conditions, where around 200 proton–proton collisions are expected per bunch crossing, compared with about 60 during Run 3.

The HL-LHC's target of more than 3 ab^{-1}, around six times the data collected so far, will open several fronts at once. In the Higgs sector, the experiments expect to observe rare decays such as $H\to\mu^+\mu^-$ and $H\to Z\gamma$, and to pin down its couplings to fermions and vector bosons at the per cent level. More ambitious still are Higgs pair production, expected to be observed with the combined HL-LHC dataset, and the charm Yukawa coupling. The programme should establish longitudinally polarised vector-boson scattering and bring rare processes such as four-top-quark production into precision reach, while the sensitivity of direct and indirect searches will push well past that of Run 3.

The central prize remains the Higgs boson itself

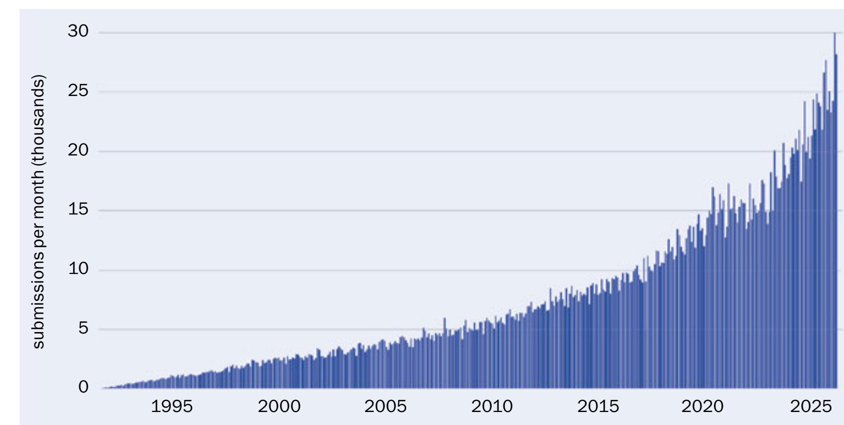
In flavour physics, precision measurements of rare decays and CP violation will test the SM and probe for deviations that would point to new physics. The study of quark–gluon plasma will enter a higher-precision phase of its own, with larger samples of lead–lead and proton–lead collisions mapping its properties in finer detail and tracing the collective behaviour of strongly interacting matter and the emergence of nuclear structure.

For John Ellis, theoretical physicist at King's College London and CERN, the central prize remains the Higgs boson itself: "Is the Higgs boson really what it seems? Experiments at the HL-LHC will measure accurately how it interacts with other particles and itself, searching for evidence of new physics that it may be hiding, and probing its role in the history of the universe."

POLICY

arXiv's one-strike rule on AI

Authors who submit a paper containing unchecked output from a large language model (LLM) will risk a year's suspension from arXiv. The preprint server, long the main channel for circulating papers in physics, mathematics, computer science and other quantitative fields before peer review, has clarified its content policy in response to a rising tide of AI-generated submissions.



Steep climb *Monthly submissions to arXiv since its launch in 1991, climbing past 30,000 for the first time in early 2026.*

The threshold for suspension is "incontrovertible evidence of hallucinatory AI generation", in the words of the arXiv scientific director Steinn Sigurðsson. Examples include hallucinated references, citations to non-existent papers, and meta-comments left by the model, such as an instruction to fill in the real numbers from an experiment. arXiv uses a detection algorithm to identify suspect papers, with readers also able to submit "Code of Conduct" complaints if papers have been released without being caught. "After the suspension period, the author can request reinstatement," Sigurðsson says, "but in a number of cases, depending on the reason for the suspension, the author will be asked to submit work that has passed peer review with a reputable journal or conference. Typically, after three such submissions, there is no further restraint."

The pressure behind the move is one of volume. Rejection rates have climbed, and the number of submissions held back for review, flagged by a quality-assurance tool or a moderator and often rejected in the end, has climbed faster still. "The increase in such cases puts a major strain on both the staff and the volunteer moderators," says Sigurðsson.

arXiv typically holds all co-authors jointly responsible for a paper's content. But that applies only when everyone listed has consented to it, a condition a fabricated paper may not satisfy. In such cases, arXiv relies on rules it already has. "Adding an author to a paper without their knowledge is a major academic misconduct," Sigurðsson says, "and would generally lead to referral to the relevant academic institutions."

For an offending submission from a large team of thousands, arXiv would not suspend the entire author list. It would defer instead to the collaboration, trusting it to identify the member who posted without clearance and to impose the primary sanction. That person would still be flagged for close inspection – and may be suspended by arXiv itself. "We have had several instances," says Sigurðsson, "both where a member of a collaboration has submitted a manuscript to arXiv without clearing it through the internal process, or even where completely unaffiliated submitting authors have added a collaboration without notifying it at all."

The one-strike rule on AI hallucinations is a matter of enforcement, rather than a new rule. arXiv has long held broad policies on content and scholarly standards, and recent internal discussions focused on how to apply them consistently to AI-generated content.

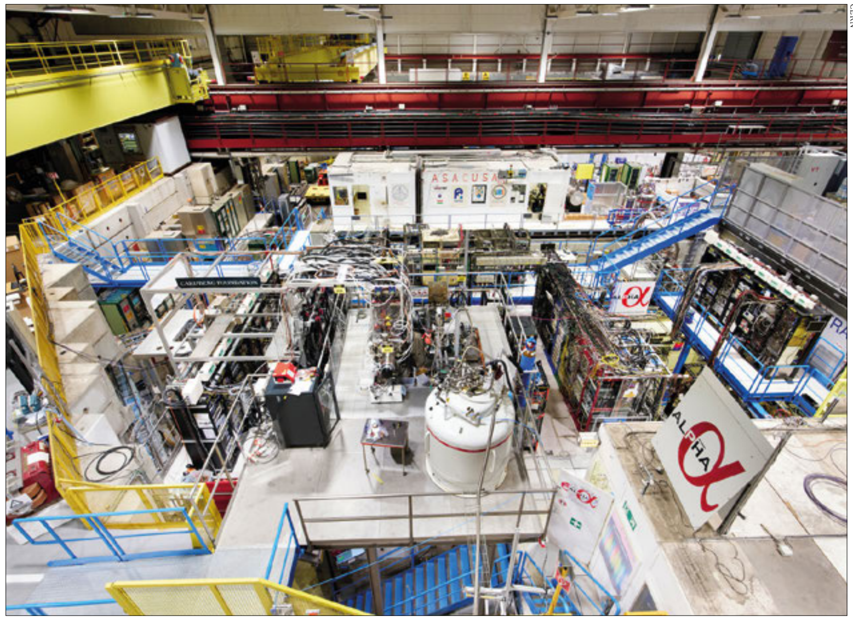
As LLMs develop, however, quality-control mechanisms are liable to date quickly. The difficulty, Sigurðsson says, is "not the lack of possible tools and counters, but the work involved in testing the tools and implementing them in a production system. This is due especially to their short useful lifetime, as AI tools evolve and users react to arXiv measures."

Antimatter

Antihydrogen toes the line

Hydrogen's ground state is split into two closely spaced energy levels, the tiny gap set by the magnetic tug between its proton and electron. Antihydrogen should split by exactly the same amount. The ALPHA experiment at CERN's Antimatter Factory has now found that it does, a hundred times more precisely than before. The new result, with an uncertainty of four parts per million, delivers one of the most stringent comparisons between matter and antimatter, and a potential probe of the antiproton's internal structure.

ALPHA is designed to measure the spectrum of antihydrogen, compare it with hydrogen, and test the limits of CPT symmetry. This principle holds that physics is unchanged when charge, parity and time are reversed together. Matter and antimatter must then have the same masses and spectra – hydrogen and antihydrogen included. "The current measurement represents the culmination of many years of effort," says Jeffrey Hangst, spokesperson of the ALPHA Collaboration. "We have been pursuing the precise determination of the hyperfine splitting of antihydrogen since we demonstrated how to trap antimatter atoms in 2010."



CERN

Ground state, split *An aerial view of the ALPHA experiment in CERN's Antimatter Factory, where antihydrogen is trapped and its ground-state hyperfine splitting measured to four parts per million.*

Early evidence

Precision measurements of atomic hyperfine structures in the late 1940s provided early evidence for the electron's anomalous magnetic moment, and, together with the discovery of the Lamb shift, contributed to the development of quantum electrodynamics. Today, the ground-state hyperfine splitting of hydrogen is known to better than one part in a trillion.

Measuring antihydrogen, however, is much more challenging. To do it, the ALPHA collaboration uses microwaves to drive spin-flip transitions in trapped antihydrogen atoms. Within the magnetic field of the trap, the ground-state hyperfine structure resolves into four sublevels, separated in energy by the Zeeman effect. Antihydrogen atoms in the two high-field-seeking states are ejected from the trap and annihilate, while those in the two low-field-seeking ones stay confined. Researchers determine the two transition frequencies by scanning the microwave frequency and observing when trapped atoms flip, leave the trap and annihilate. The splitting then follows from the difference between the two, through the Breit–Rabi formula.

We have made strong progress in the control, stabilisation and characterisation of the magnetic fields in the antihydrogen trap

The first demonstration of this approach came in 2012, and in 2017 the collaboration made the first quantitative measurement of the ground-state hyperfine splitting with a precision of 400 parts per million, in agreement with hydrogen. The precision was limited by the amount of antihydrogen available. "We have made strong progress in the control, stabilisation and characterisation of the magnetic fields in the antihydrogen trap," explains Hangst. "Our new accumulation technique has also been a real game changer."

The technique uses laser-cooled beryllium ions to cool positrons before mixing them with antiprotons, raising the trapping rate eightfold. The data behind the 2017 result came from 22 runs of 11 to 14 trapped atoms. The new measurement comprised instead 16 runs, eight at each of two magnetic-field settings, each accumulating roughly 1500 antihydrogen atoms. This improved the precision on the ground-state hyperfine splitting by two orders of magnitude, finding it consistent with the hydrogen value.

ALPHA now plans to study the nuclear magnetic resonance transition between the two trapped levels. This measurement is far less prone to systematics from the magnetic trap, and is expected to improve on the present result by a further two orders of magnitude. In the same Antimatter Factory, the ASACUSA collaboration is developing a complementary approach to measure the hyperfine splitting with a beam of antihydrogen in a field-free region.

Further reading

ALPHA Collab. 2017 *Nature* **548** 66.

ALPHA Collab. 2025 *Nat. Commun.* **16** 10106.

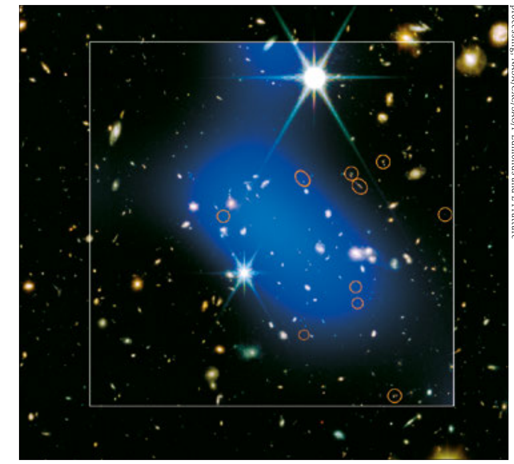
ALPHA Collab. 2026 *Nature* **653** 1022.

Astrowatch

A hot start for cluster formation

Galaxy clusters are the largest bound objects in the universe, and among the most spectacular astrophysical systems. Their gravity lenses the light of background sources and heats the intracluster gas to X-ray-emitting temperatures. Within them – or in their smaller counterparts, galaxy groups – resides a large fraction of today's galaxies. Their dense environments also drive galaxy evolution, with the densest clusters hosting the most evolved systems in the local universe.

By studying clusters at different epochs, we can track how galaxies and their environments changed over time. They are also signposts of large-scale structure, and their number counts constrain cosmological models, including the nature and amount of dark matter, and the behaviour of dark energy. The South Pole Telescope, for example, searches for massive high-redshift clusters via the Sunyaev–Zel'dovich effect, in which hot electrons in the intracluster medium scatter cosmic microwave background (CMB) photons to higher energies, distorting their spectrum.



X-ray, NASA/CXC/CfA/Á Bogdán; infrared, NASA/ESA/CSA/STScI; processing, NASA/CXC/SAO/P Edmonds and L Frattare

Ahead of schedule *The protocluster JADES-ID1, seen about one billion years after the Big Bang. The Chandra X-rays (blue), overlaid on a JWST image, trace hot gas that marks it as the earliest bound system of its kind yet found. The circles locate JADES-ID1's known galaxies.*

When deep optical and infrared imaging surveys began in the 1990s, it became clear that massive galaxy clusters are rare in the early universe – if they exist at all. In the first few billion years after the Big Bang, we find galaxies associated with one another spatially, but generally not in bound systems approaching the 10^{15} solar masses of the largest present-day clusters. This reflects the growth of structure predicted by the cold dark matter (CDM) model, which reproduces the density fluctuations seen in the CMB and the clustering of galaxies on large scales, but is harder to test against the properties of galaxies themselves.

When and how?

And yet, a major question remains open: when and how did the first galaxy clusters and groups form? An answer could potentially come from the James Webb Space Telescope (JWST), which measures the three-dimensional positions of astrophysical objects back to when the universe was less than a billion years old. Galaxies in the same region of sky that share similar radial velocities, and thus distances, are likely physically associated, and may evolve over time into a massive present-day cluster.

Such a system was recently identified in the GOODS-S field, as part of the JWST Advanced Deep Extragalactic Survey (JADES), a guaranteed-time programme of two of JWST's instrument teams. A recent analysis of galaxy positions and distances in this field by our group revealed significant overdensities as far back as when the universe was about a gigayear old. But proximity in the sky alone does not guarantee a bound structure: such systems could still be assembling, rather than already being mature and gravitationally bound. One way to tell is to look for X-ray emission from intracluster gas shocked to high temperatures as the system collapses. At these early times, however, such emission is expected to be extremely faint.

JADES-ID1 is an exceptionally rare but plausible example of early structure formation

Our team discovered an X-ray-emitting protocluster, JADES-ID1, at redshift $z \approx 5.68$. Found just one billion years after the Big Bang, it is the earliest protocluster known to host a hot intracluster medium, a stage of cluster formation not previously seen before the universe was three billion years old. Measured in the deepest X-ray observations ever taken by the Chandra observatory, it has a total gravitational mass of about 20 trillion solar masses – far too large for a single galaxy. Instead, it must comprise many galaxies within a shared gravitational potential that has existed long enough to heat the intracluster gas, allowing it to emit X-rays.

This discovery may have important implications for both galaxy evolution and cosmology. The presence of an X-ray-emitting intracluster medium indicates that substantial gravitational collapse, shock heating and mass assembly have already occurred, whereas most cosmological models predict that protoclusters should have been at much earlier stages. JADES-ID1 appears as a mature, bound group significantly earlier than when models predict such systems should be abundant.

Early efficiency

The patch of sky in which JADES-ID1 was discovered is exceptional, with the deepest multiwavelength coverage available, X-rays included. Finding such an object in a small patch of sky suggests that it may not be a statistical fluke: standard predictions would expect the most massive bound systems in the surveyed volume to be roughly an order of magnitude lighter than JADES-ID1. If comparable systems are discovered in other regions, it may imply that current models of early universe structure and galaxy formation underestimate the efficiency of early structure growth. Caution is in order, however, as a single detection is not enough to demonstrate a failure of Lambda–CDM cosmology.

Still, JADES-ID1 adds to a growing set of JWST observations pointing to faster early structure formation (*CERN Courier* November/December 2025 p11). For now, the conservative reading is that JADES-ID1 is an exceptionally rare but plausible example of early structure formation. If upcoming JWST, X-ray and Sunyaev–Zel'dovich surveys reveal a substantial population of similarly massive systems, this may eventually warrant a revision of galaxy and cluster-formation models.

We have now been awarded JWST spectroscopy time to study the system in more detail, which may give us more clues to its origin as well as how an early structure overdensity drives the formation of its host galaxies.

Guest Astrowatch correspondent

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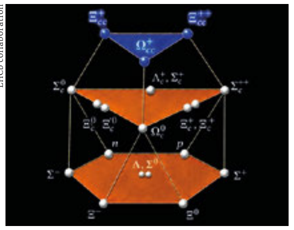
Christopher Conselice *University of Manchester.*

NEWS DIGEST

LHCb collaboration



The spin-½ baryons built from the four lightest quarks, a multiplet now completed by the Ω_{cc}^{+}.

Doubly charmed, complete

At the Beauty 2026 conference in Maastricht, the LHCb collaboration reported the first observation of the doubly charmed baryon Ω_{cc}^{+}, made of two charm and one strange quark. Its detection completes the ground-state family of light spin-½ doubly charmed baryons, alongside the Ξ_{cc}^{++} (ccu) discovered in 2017 and its isospin partner, the Ξ_{cc}^{+} (*CERN Courier* May/June 2026 p12). LHCb found the Ω_{cc}^{+} as a peak in the $\Omega_c^0\pi^+$ mass spectrum, at a mass near 3727 MeV, using data recorded in 2024 with the upgraded LHCb detector. Unlike the Ω^-, the eightfold way's missing baryon found within two years of its 1962 prediction, the Ω_{cc}^{+} had eluded experiments for more than 50 years.

FCC consultation opens

On 18 May 2026, public consultations on the proposed Future Circular Collider (FCC) started in the two CERN host states. If approved, the FCC would occupy a 91 km ring at an average depth of 200 m beneath the canton of Geneva and the French departments of Haute-Savoie and Ain, colliding electrons and positrons as a precision Higgs, flavour and electroweak factory. The Swiss process, overseen by independent guarantors, will run until 2 October 2026. In France, a formal public debate under the Commission Nationale du Débat Public (CNDP) opened on 2 June, with a kick-off meeting on 4 June, and will run until 1 October 2026.

A new value for Big G

On 16 April 2026, a team at the US National Institute of Standards and Technology (NIST) reported a new precision measurement of Newton's gravitational constant, obtaining $G = (6.67387 \pm 0.00038) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$ (Schlamminger *et al.* 2026 *Metrologia* **63** 025012). The experiment repeated an earlier determination by the International Bureau of Weights and Measures (BIPM) on the same torsion balance, with new personnel and under different environmental conditions. The value lies below the BIPM result and on the opposite side of the 2022 CODATA recommendation – though statistically compatible with it. The authors identified no single cause for the disagreement.

First physics from ICARUS

The ICARUS collaboration has reported its first oscillation result in Fermilab's Short-Baseline Neutrino (SBN) Programme (ICARUS Collab. 2026 arXiv:2603.22557). Analysing data taken in 2022 and 2023, the experiment found no sign of

Al Johnson, Fermilab

The ICARUS liquid-argon neutrino detector.

muon-neutrino disappearance, the signature that a hypothetical fourth, sterile neutrino would imprint on the beam. ICARUS, the first large-scale liquid-argon neutrino detector, ran at Italy's Gran Sasso laboratory before being refurbished at CERN and shipped to Fermilab in 2017. It is a technological forerunner of the Deep Underground Neutrino Experiment (DUNE), now under construction, which will deploy the same detection principle on a far larger scale.

Steel beams for DUNE

On 7 May 2026, Fermilab and the Sanford Underground Research Facility (SURF) began lowering steel beams 1.5 km underground in South Dakota, opening the detector-installation phase of DUNE. Around

M Kapust, SURF

About 4500 tonnes of steel beams will be lowered to frame DUNE's detector modules.

4500 tonnes of steel, an in-kind contribution from CERN and its first investment in infrastructure for an experiment outside Europe, will form the structural framework for DUNE's giant liquid-argon detector modules. The experiment will send the world's most intense neutrino beam 1300 km from Fermilab to SURF, to study neutrino oscillations, determine their mass ordering and search for leptonic CP violation – a possible source of the matter–antimatter asymmetry of the universe. Fermilab aims to deliver the first beam by 2031.

A new g–2 prediction

On 22 April 2026, the Budapest–Marseille–Wuppertal (BMW) lattice collaboration and the data-driven group of Davier, Malaescu and Zhang published a hybrid calculation of the hadronic vacuum polarisation (HVP), the dominant uncertainty in the Standard Model prediction of the muon's anomalous magnetic moment, g–2 (Boccaletti *et al.* 2026 *Nature* **653** 373). The method draws most of the HVP from lattice QCD and derives its small low-energy tail from experimental data in the region where all measurements agree, reaching 0.48% precision. The resulting prediction lies within 0.5σ of the final Fermilab measurement, in step with the lattice-based 2025 white paper of the Muon g–2 Theory Initiative, and almost twice as precise.

CMS finds 5.2 TeV lepton pair

The CMS collaboration has carried out one of its most sensitive direct searches to date for heavy particles beyond the Standard Model (BSM) using almost the full Run 3 dataset of proton–proton collisions taken between 2022 and 2025 at 13.6 TeV (CMS Collab. 2026 CMS-PAS-EXO-25-021). The analysis searched the high-mass dilepton spectrum for a resonant peak, the clean signature a new state such as a Z′ boson or extra-dimensional graviton would leave upon decaying to a pair of electrons or muons. No significant excess appeared, but CMS recorded the most energetic dilepton event it has ever seen, a pair of electrons with a combined mass of 5.2 TeV. The search sets the world's strongest limits so far on several BSM scenarios.

Enter the Muoniverse

On 1 May 2026, the Swiss National Centre of Competence in Research (NCCR) Muoniverse began operations, led by the Paul Scherrer Institute (PSI) and the University of Zurich, and funded by the Swiss National Science Foundation. Built on PSI's muon source, among the most intense in the world, the programme gathers work ranging from high-precision tests of the Standard Model to muon spin rotation (μSR) studies of quantum materials and non-destructive elemental analysis of batteries, semiconductors and

PSI

The 590 MeV ring cyclotron, the source of the proton beam that makes PSI's muons.

museum artefacts. Directed by Klaus Kirch and Marc Janoschek, with partners including CERN and the Swiss National Museum, Muoniverse has a budget of about 34 million Swiss francs for its first four years, and may run for up to 12 years.

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

A light on partons at the nuclear edge

When nucleons are bound within nuclei, their parton distribution functions (PDFs) differ from when they are free. The origin of these modifications, first discovered by the European Muon Collaboration in 1982 (*CERN Courier* November 1982 p362), remains one of the central open questions in nuclear physics, since the MeV-scale energies that bind nucleons together should have little bearing on the GeV-scale processes that probe their quarks and gluons. Results presented by the ATLAS collaboration at the Deep Inelastic Scattering (DIS) conference now provide the first observation that nucleons near the edge of a nucleus exhibit different PDFs from those near its centre.

The measurement relies on ultra-peripheral collisions (UPCs) of lead ions at the LHC, where – unlike a typical head-on collision – the ions glance past each other without their nucleons overlapping. They still interact, however, through the intense electromagnetic fields that surround each ion. Photo-nuclear UPCs occur when one nucleus emits a high-energy photon that strikes the other. One possible outcome is the production of jets through hard scattering between the photon and the nucleus, whose cross-section is sensitive to the parton distribution.

Such hard scatterings usually break the nucleus up, producing forward neutrons that are detected in the ATLAS zero-degree calorimeters located 140 metres from the interaction point. The key insight of this measurement is that, in about 4% of photonuclear scatterings, the photon strikes a single nucleon and leaves the rest of the nucleus whole. These events can be tagged by the absence of neutrons in the direction of the struck nucleus. Since nucleon densities are lower near the edge of the nucleus, collisions that leave it intact are also typically the more peripheral ones.

To study these collisions, the collaboration analysed lead–lead collision data collected in 2018 during Run 2 of the LHC, corresponding to an integrated luminosity of 1.72 nb^{-1}. Events were selected by requiring at least two jets in the calorimeter with large rapidity gaps – regions of the detector devoid of particle production, characteristic of these photon-initiated processes. These were then categorised as "inclusive" or "peripheral" according to the presence or absence of forward neutrons, respectively.

To interpret the results, proxy variables for the parton kinematics were defined using the properties of the measured jets. One such variable is x_+, which provides an estimate for the Bjorken-x of the struck parton, the fraction of the nucleon's momentum that it carries. The measured ratio of the x_+ distributions between inclusive and peripheral collisions has a clear slope (see figure 1), indicating a significant difference in the nuclear modification of the parton distributions between the two classes. The size of this effect is quantified through a statistical test of the difference between them, which reaches a significance of 6σ.

These results provide the first observation that nucleons near the edge of a nucleus have different PDFs from those near the centre, and mark a significant step forward in understanding the structure of nuclei. The analysis also has important implications for the interpretation of relativistic heavy-ion collisions, which are sensitive to the PDFs of the colliding ions, and demonstrates a novel methodology that could be applied at the future Electron-Ion Collider (EIC). While this analysis uses Run 2 data, the larger Run 3 lead–lead dataset and the HL-LHC programme will offer substantial opportunities to improve both the precision and scope of these measurements.

ATLAS Collab 2026

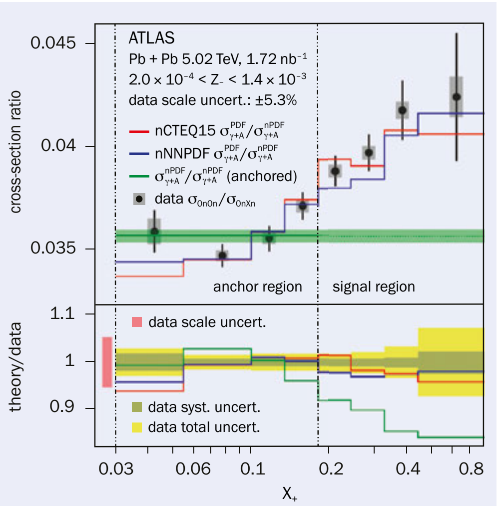


Fig. 1. *The ratio of peripheral to inclusive photonuclear jet production cross-sections as a function of x_+, a proxy for the Bjorken-x. Theoretical predictions corresponding to two models in which PDF modifications are limited to inclusive collisions (red, blue) are shown, as well as the case of identical PDF modifications in both classes of collisions (green).*

Further reading

ATLAS Collab. arXiv:2604.20559.
ATLAS Collab. arXiv:2604.24435.

CMS

W boson decays to three charged hadrons

Since its discovery at CERN in 1983 (*CERN Courier* November 1983 p355), the W boson has been one of the most thoroughly studied particles in high-energy physics – yet some of its rarest decay modes remain unobserved. The CMS experiment has recently carried out a search for its decay into three light charged hadrons, using 420 fb^{-1} of proton–proton collision data recorded between 2016 and 2025. The result sets an upper limit on the branching fraction that excludes a large range within the theoretical expectation, constraining certain models of these rare decays.

The study focused on a much cleaner and rarer signature

While decays of the W boson into hadrons are the most common, they are also exceptionally complex. The process of ▷

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hadronisation, in which quarks transform into detectable particles like pions and kaons, typically produces around 30 final-state particles in a single W-boson decay. Consequently, reconstructing the parent W boson and studying its properties with high precision is significantly more difficult than for leptonic decay modes.

In its recent study, the CMS experiment focused on a much cleaner and rarer signature: W-boson decays into three light charged hadrons. This decay offers the highest potential of observation among low-multiplicity exclusive modes, as it combines a clean, fully charged final state with a relatively high rate, well above that of competing processes such as decay into a photon and a pion. Observing it would provide valuable new insights into quantum chromodynamics, particularly the behaviour of factorisation and form factors at high energies.

To identify these events, charged hadrons are reconstructed either from isolated particle tracks in the detector or as hadronically-decaying tau leptons, since a common decay mode of the tau lepton produces a charged pion together with a neutrino.

The analysis requires events with at least three hadron candidates. The two candidates with the highest transverse momentum are reconstructed as hadronically-decaying tau leptons, whilst the third may also be reconstructed as an isolated charged-particle track. This strategy both expands the accessible phase space – by taking advantage of the lower transverse momentum threshold for isolated tracks – and suppresses background contributions through stricter momentum requirements for hadronically-decaying tau leptons. The sensitivity is further improved using a dedicated DeepTau machine-learning classifier, which helps distinguish hadronically-decaying tau leptons from jets.

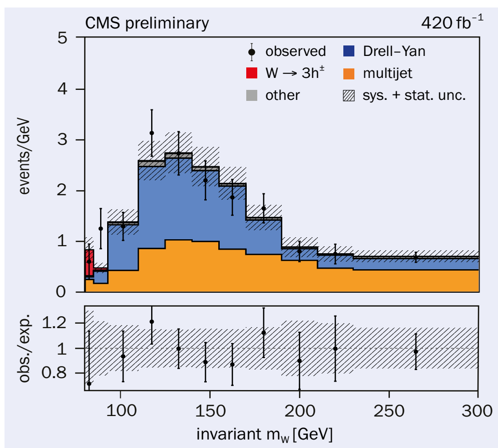

Fig. 1. *Data, fitted signal and background distributions over the invariant mass of three selected light charged hadrons, reconstructed as hadronic tau candidates. The signal corresponds to a branching fraction of about 1.0×10^{-7}. The first bin is an underflow bin, including events below 80 GeV. All data recorded from 2016 to 2025 are combined, totalling $420\,fb^{-1}$.*

The search is performed by examining the invariant mass of the hadrons (see figure 1). No significant excess of events with W bosons decaying into three charged hadrons is observed. The most stringent 95% CL upper limit on the branching fraction of the W boson to three light charged hadrons is set at 3.0×10^{-7}, while theory estimates a branching fraction in the vicinity of 10^{-5}–10^{-7}.

The decay of the W boson into a low-multiplicity exclusive state probes an interesting dynamical domain at the boundary of perturbative and non-perturbative QCD physics, where theorists strongly need experimental input. Although the signal has not yet been observed, the result already constrains certain models of this rare W-boson decay. As larger datasets become available, these rare decay modes offer a new window on the dynamics of the strong interaction.

Further reading

CMS Collab 2026 CMS-PAS-SMP-25-011.

LHCb

A new doubly charmed baryon

The LHCb collaboration has reported the observation of the doubly charmed baryon Ξ_{cc}^{+}, the first new particle found with the upgraded LHCb detector. The result completes the isospin doublet of the doubly charmed baryons, allowing the two states to be compared directly in mass, lifetime and decay channel. The Ξ_{cc}^{+} contains two charm quarks and a down quark, and is the isospin partner to the Ξ_{cc}^{++} baryon, much as the neutron is to the proton. Yet unlike the neutron, which is more massive than the proton, the Ξ_{cc}^{+} is expected to be lighter than the Ξ_{cc}^{++}, because electromagnetic effects outweigh the down–up quark mass difference.

The two states also differ in their lifetimes. The Ξ_{cc}^{+} is predicted to decay about six times faster than the Ξ_{cc}^{++}, owing to an additional W-exchange contribution and to interference between decay amplitudes. Precise measurements of their masses and lifetimes, therefore, test the heavy-quark dynamics at work inside baryons.

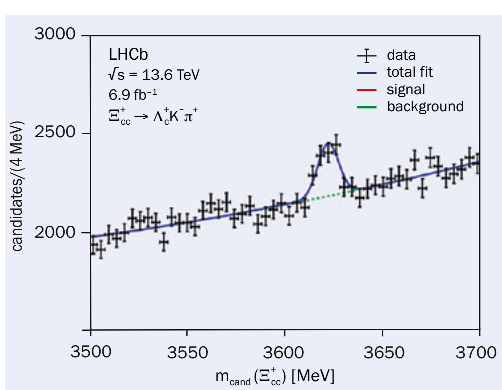

Fig. 1. *Mass distribution of the selected Ξ_{cc}^{+} candidates in 2024 data, along with the fit results.*

The experimental search for the Ξ_{cc}^{+} baryon has a long history. In 2002, the SELEX collaboration at Fermilab claimed to have observed it, a result that has not been confirmed by subsequent searches at FOCUS, BaBar, Belle and LHCb. Meanwhile, the LHCb collaboration observed the Ξ_{cc}^{++} baryon using proton–proton collisions recorded at a centre-of-mass energy of 13 TeV in 2016. The LHCb detector was then upgraded during the second long shutdown of the LHC (2019–2021), to maintain its performance while operating at around five times the instantaneous luminosity of Runs 1 and 2. The online trigger system, in which the interesting signals are selected from a huge number of proton–proton collisions at the LHC in real time, was also upgraded, increasing the efficiency for selecting hadronic decays by more than a factor of two.

The new LHCb search used proton–proton collision data recorded at a centre-of-mass energy of 13.6 TeV in 2024. The Ξ_{cc}^{+} baryon was reconstructed through its decay to the $\Lambda_c^+ K^- \pi^+$ final state in a blind analysis, designed to avoid any experimenter bias. A topologically similar decay of the Ξ_{cc}^{++} baryon, $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, was used as a control mode for developing the event-selection strategy and calibrating the mass measurement. More than 8000 Ξ_{cc}^{++} candidates were reconstructed in the 2024 dataset, corresponding to an efficiency increase of about a factor of four relative to Run 2. The measured Ξ_{cc}^{++} mass was found to be consistent with the average of previous measurements.

Once the analysis was finalised, the Ξ_{cc}^{+} signal region was unblinded and examined. A structure with a statistical significance exceeding seven standard deviations was observed (see figure 1), corresponding to more than 900 Ξ_{cc}^{+} candidates. The corresponding efficiency is about two and a half times higher than that achieved during Run 2, with the smaller improvement relative to Ξ_{cc}^{++} reflecting the shorter lifetime of the Ξ_{cc}^{+} baryon.

The observation demonstrates the enhanced capabilities of the upgraded LHCb experiment

The collaboration also performed a precision measurement of the Ξ_{cc}^{+} mass and the difference between the masses of the two doubly charmed baryons. The Ξ_{cc}^{+} mass was measured to be $3619.97 \pm 0.83\,(\text{stat}) \pm 0.26\,(\text{syst})^{+1.90}_{-1.30}$ (lifetime) MeV, with a difference of $-1.77 \pm 0.84\,(\text{stat}) \pm 0.15\,(\text{syst})^{+1.90}_{-1.30}$ (lifetime) MeV from that of the Ξ_{cc}^{++}, compatible with theoretical predictions. It was also about 100 MeV higher than the one reported by the SELEX collaboration, disfavouring the interpretation of that state as the Ξ_{cc}^{+} baryon.

The observation of the Ξ_{cc}^{+} baryon completes the isospin doublet of the doubly charmed baryons. It also demonstrates the enhanced capabilities of the upgraded LHCb detector and its trigger system, laying the groundwork for hadron spectroscopy studies with data taken in Run 3.

Further reading

LHCb Collab. 2026 arXiv:2603.28456.

ALICE

Collective flow in hypernuclei

When lead nuclei collide at the LHC, they create tiny droplets of quark–gluon plasma, an extremely hot and dense state of matter in which quarks and gluons are no longer confined within protons and neutrons. Although these droplets exist for only a tiny fraction of a second, they expand collectively before cooling into the particles detected by the ALICE experiment. One of the clearest signatures of this collective motion is the elliptic flow, which quantifies how particles preferentially emerge along certain directions in the plane transverse to the collision axis.

ALICE has now measured, for the first time, the elliptic flow of the hypertriton ($^{3}_{\Lambda}$H) in lead–lead collisions at $\sqrt{s_{NN}} = 5.36$ TeV, and compared the results with those of anti-^{3}He, a more compact nucleus of similar mass (about 3 GeV). A bound state of a proton, a neutron and a Λ hyperon, the hypertriton is among the most weakly bound nuclei known. As a result, it is significantly larger than ordinary nuclei – while the radius of ^{3}He is about 1.96 fm, the distance between the deuteron core and the Λ hyperon in the hypertriton is of the order of 10 fm. Measurements of the hypertriton flow thus provide a unique opportunity to test whether such a large and loosely bound nucleus follows the collective motion of the medium in the same way as more compact ones.

The analysis is based on approximately five billion lead–lead collisions recorded in 2023. ^{3}He candidates are identified by measuring their specific energy loss in the ALICE Time-Projection Chamber, complemented by information from the Inner Tracking System. Hypertriton candidates are reconstructed through their decay into ^{3}He and a charged pion. To distinguish the tiny signal from the much more abundant particles produced at the collision vertex, the analysis identifies a secondary vertex, displaced from the point of collision, where the hypertriton decay happened. Despite their very different sizes and binding energies, the measured elliptic flow of the hypertriton is found to be consistent with that of the ^{3}He (see figure 1).

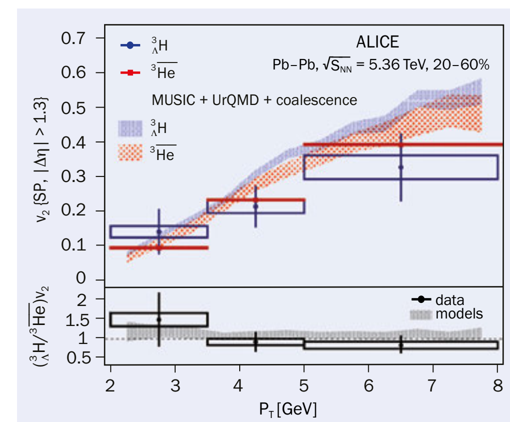

Fig. 1. *Measured elliptic flow (v_2) of ^{3}He (in red) and hypertriton (in blue) as a function of transverse momentum in lead–lead collisions at $\sqrt{s_{NN}} = 5.36$ TeV, in the 20–60% centrality interval, compared with coalescence-model calculations.*

The ^{3}He measurement reaches unprecedented precision and shows an increase in elliptic flow with transverse momentum, exceeding 0.5 at intermediate and high transverse momenta in the 40–60% centrality interval. Such large values suggest that larger azimuthal modulations contribute to the full angular pattern of ^{3}He production. This behaviour arises naturally in coalescence models, in which light nuclei are formed near kinetic freeze-out by the coalescence of already formed nucleons. In this picture, their collective motion reflects the combined motion of their constituents. The combination of several flowing nucleons can then reshape the nucleus's final azimuthal distribution, producing the large observed modulation.

Theoretical models reproduce the ^{3}He flow only when a coalescence stage is included, providing strong evidence that light nuclei are not simply born as complete objects at hadronisation, but are assembled from nucleons at a later stage of the collision. Together, the new measurements provide a coherent picture of how composite objects emerge from the hot and dense medium created in high-energy nuclear collisions. Light nuclei appear to carry the collective motion of their constituents, and their elliptic flow is largely governed by the dynamics of the expanding medium. Even for the loosely bound hypertriton, the acquired flow remains insensitive to the large spatial size of the final nucleus. These results establish light nuclei as powerful probes of how and when composite matter forms in heavy-ion collisions.

Further reading

ALICE Collab 2026 arXiv:2603.19398.

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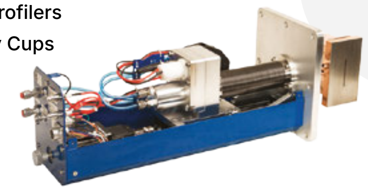

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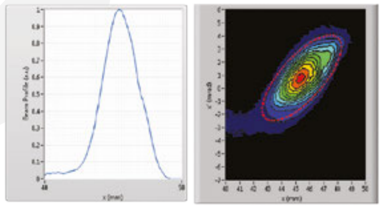

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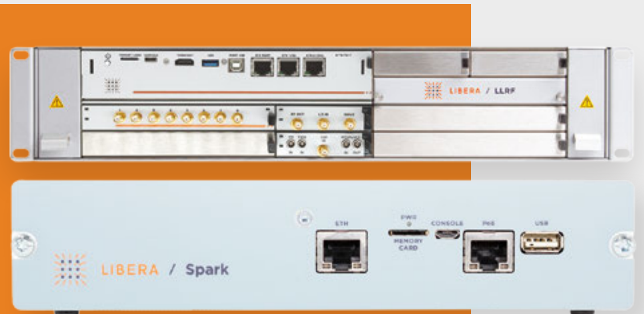

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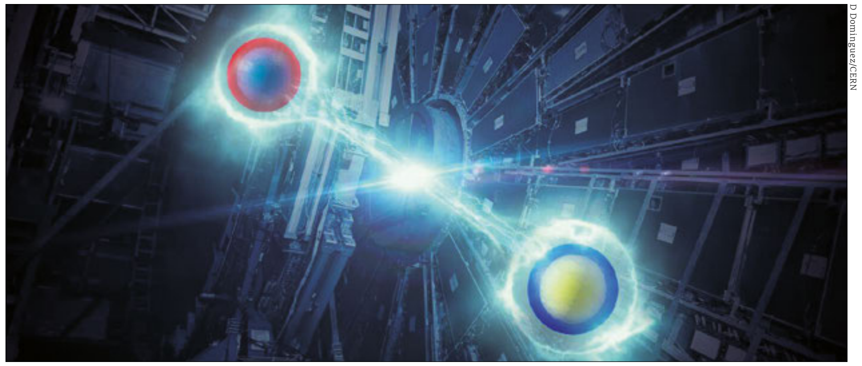
QUANTUM OBSERVABLES FOR COLLIDER PHYSICS 2026

All entangled around the collider

The Quantum Observables for Collider Physics 2026 workshop, held at CERN from 20 to 24 April, was the third edition of a series that began at the Galileo Galilei Institute in Florence in 2023 – now brought to the heartland of high-energy physics. Around 100 invited specialists from across the world gathered to take stock of a programme that has grown, with surprising speed, from a mere theoretical curiosity into a substantial body of experimental results.

The study of quantum observables with colliders is not starting from scratch. Phenomena such as oscillations and CP violation in neutral meson systems, or quantum interference in decay amplitudes and entanglement between B mesons at the $\Upsilon(4S)$ resonance, have been under scrutiny for decades. The novelty lies in the systematic application of the conceptual vocabulary of quantum information science – entanglement witnesses, Bell inequalities, quantum state tomography, and magic and decoherence as observables – to the highest-energy collisions accessible today.



D Dominguez/CERN

Inseparable *An artistic visualisation of a top quark–antiquark pair in front of the ATLAS detector. The line between the particles symbolises their entanglement, the kind of quantum behaviour discussed at the Quantum Observables for Collider Physics workshop.*

Catalogue of entanglement

The most sharply focused experimental news came from the Higgs sector, where both ATLAS and CMS reported evidence that the two Z bosons produced in Higgs decays are entangled. Tairan Xu (University of Michigan) presented the ATLAS result, with an observed significance of 4.7σ. Jeffrey Davis (Johns Hopkins University) reported the CMS analysis, which measured spin correlations and extracted helicity fractions within an effective-field-theory framework. Together, the two results mark the Higgs boson's entry into the catalogue of entanglement sources at the LHC.

In the top sector, CMS presented a full tomographic characterisation of the top quark–antiquark quantum state, with Otto Hindrichs (University of Rochester) showing the reconstructed spin-density-matrix elements across the full kinematic range of Run 2. Fiona Jolly (DESY) presented complementary ATLAS measurements, probing quantum-information observables in top-quark pairs. What has changed since the first edition of the workshop is the ambition, with early proof-of-principle measurements giving way to precise reconstructions of the full quantum state.

One of the most striking results came from the STAR experiment at RHIC, presented by Zhoudunming Tu (BNL). The measurement reports spin correlations of Λ–$\bar{\Lambda}$ hyperon pairs in proton–proton collisions at a centre-of-mass energy of 200 GeV, with a clear angular dependence that existing predictions do not fully describe. Elsewhere, Dmitri Kharzeev (Stony Brook University) argued that partons within a proton approach maximal entanglement at high energies. Their entanglement entropy then becomes directly observable in final-state multiplicities, making structure functions themselves carriers of quantum information. Beatrix Hiesmayr (University of Vienna), whose earlier work on entanglement and Bell-inequality violations in neutral kaon systems helped lay the foundations of the field, provided perspectives from the meson sector that grounded the newer collider-based results.

What has changed since the first edition of the workshop is the ambition

Marcel Vos (IFIC Valencia) showed that, at a future lepton collider, the entanglement of the top spins in $e^+e^- \to t\bar{t}g$ events is expected to fall with the gluon's energy, vanishing near the kinematic endpoint. This would be a computable, measurable signature of decoherence from real gluon emission. Lian-Tao Wang (University of Chicago) offered a striking reinterpretation, according to which decoherence due to soft, collinear radiation in high-energy collisions can be understood as a renormalisation-group flow.

Two-faced

Several talks explored whether entanglement suppression and enhanced symmetry are two faces of the same phenomenon. Ian Low (Northwestern University) showed, in an abstract spin-system setting, that entanglement reaches a minimum precisely where the Hamiltonian acquires an enlarged symmetry. Carlos Wagner (University of Chicago), Kamila Kowalska (NCBJ Warsaw), and Spencer Chang (University of Oregon) pressed the question from the collider side, asking whether the causal arrow runs from symmetry to entanglement or vice versa. The discussion remained productively unresolved.

A dedicated session on Bell tests reflected a field that has matured in its self-understanding. After a period of a rapid proliferation of proposals, there is now broad agreement on what is and is not achievable at a collider: entanglement can be established, Bell-violating quantum states can be witnessed, but a loophole-free Bell test – of the kind ▷

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achieved with photons in a standard laboratory setting – is structurally out of reach with existing techniques. The community has, by and large, made peace with this distinction, and is now focusing on what can actually be done.

Many contributions pushed the programme's conceptual boundaries outward. Vlatko Vedral (University of Oxford) argued that laboratory interference experiments could test quantum effects in the gravitational field, while Nikos Mavromatos (King's College London) explored entangled squeezed states of gravitons – associated with black-hole environments – as a potential probe of quantum gravity. David Kaiser (MIT) recounted how foundational debates about Bell inequalities, pursued by an unlikely group of physicists in 1970s California, eventually catalysed the cosmic Bell experiments. The account served as a reminder that questions dismissed as purely philosophical have a habit of becoming precision science.

On a longer timescale, the next generation of colliders promises a significant step forward. Tao Han (University of Pittsburgh) made the case that FCC-ee and CEPC would deliver large statistical samples in cleaner conditions than the LHC, and that beam polarisation in lepton colliders would open access to quantum process tomography of fermion pairs. Paweł Horodecki (Gdańsk University of Technology) emphasised that, by controlling the initial quantum state, this technique could enable tests of subtle deformations of quantum mechanics – possible extensions of the theory that state tomography alone cannot reach. Yoshitaka Hatta (BNL) and Kun Cheng (University of Pittsburgh) pointed to a further frontier at Brookhaven's Electron–Ion Collider, where polarised beams will allow the partonic structure of the proton to be probed through its entanglement content.

The next generation of colliders promises a significant step forward

Phrases overheard in the corridors, in the panel sessions and at the well-attended poster session captured the mood: "That's fascinating," "I disagree with you," and "Let's talk over coffee." As Yoav Afik (University of Chicago) observed, the field has grown from a handful of proposals into a genuine international programme. The questions being asked are real ones, and the answers, when they come, will sharpen our understanding of quantum mechanics at the highest accessible energies. The next edition of the workshop will be in Chicago.

Alan Barr *University of Oxford and* **Sokratis Trifinopoulos** *CERN.*

PLANCK2026

Theorists ponder across scales

From 18 to 22 May 2026, the 28th annual PLANCK conference – held in conjunction with the 6th EuCAPT Symposium – brought more than 250 theoretical physicists to CERN to confront a set of dilemmas that are, at root, about scale. Where should the hunt for dark matter focus, when its mass might span 90 orders of magnitude? Why is the Higgs mass so tiny compared to the Planck scale, with no signs of a mechanism to stabilise the gap? Can one learn about particle production in the early universe, when evidence is spread thinly over the farthest sky?


Ml Escudero Abenza

Unified field *PLANCK 2026, held alongside the 6th EuCAPT Symposium, brought more than 250 physicists to CERN.*

Microscopic to galactic

Faced with these puzzles, theorists are seeking answers from systems ranging from the microscopic to the galactic. Jordy de Vries (NIKHEF) discussed novel methods to look for subtle differences in how the strong force affects matter and antimatter using tiny molecular dipole moments. At the opposite end, Kai Schmitz (Münster University) reported on work using the rhythms of pulsars spread across the Milky Way to detect gravitational waves produced in the first moments after the Big Bang.

The framework of effective field theory (EFT) threaded through the conference. By capturing the physics at a given scale and folding higher-scale effects into a handful of parameters, it proves ubiquitously powerful for advancing complex calculations. Giulia Isabella (UCLA) presented new results applying scattering methods – originally developed for particle physics – to calculate gravitational-wave signals from black hole mergers. Mikael Chala (University of Granada) discussed the use of EFTs in calculations of thermal phase transitions, such as those that occurred in the early universe. Anders Eller Thomsen (University of Bern) presented precision calculations of the Standard Model EFT used to predict subtle effects of undiscovered particles with masses beyond the energy range of the LHC.

The electroweak scale, at which electroweak symmetry breaks and particles acquire mass through the Brout–Englert–Higgs mechanism, continues to play a unique role across a variety of fundamental puzzles. The possibility that a strong electroweak phase transition led to a universe filled with matter was discussed in talks by Jorinde van de Vis (CERN), Dave Sutherland (University of Glasgow) and Maria Cristina Fiore (University of Granada), anticipating future tests of this scenario with gravitational waves, Higgs measurements and resonance searches.

The idea of a "WIMP miracle", in which the observed abundance of dark matter is due to a weakly interacting particle with mass around the electroweak scale, is one of the most compelling and long-standing dark-matter explanations. Weishuang Linda Xu (Stanford University) presented work interpreting gamma-ray observations of the galactic centre, arguing that this dark-matter framework can be fully tested once the next generation of telescopes comes online.

Many talks presented novel model-building ideas, including some related to the recent burst of activity around models explaining the observed hierarchies in fermion masses, many of which answer other theoretical puzzles. Marta Zamoro (Autonomous University of Madrid) showed how both the mass hierarchies and the strong CP problem could be explained through a model with extra copies of the Standard Model QCD group. Javier Lizana (University of Castilla–La Mancha) and Simone Marciano (University of Valencia) presented different models in which a dark-matter candidate ▷ arises within theories predicting hierarchical fermion masses. Each of these predicts novel phenomena, particularly in flavour-changing processes that could be measured at LHCb.

PLANCK 2026 presented a picture of a highly varied field, united around big questions and emerging techniques. Speakers and participants looked towards the new opportunities offered by upcoming measurements, colliders and telescopes, building a theoretical toolkit to interpret their insights across all scales.

A highly varied field, united around big questions

Sophie Renner *Glasgow University.*

IPAC'26

Accelerator experts meet in Normandy

The 17th International Particle Accelerator Conference (IPAC'26) took place from 17 to 22 May 2026 in Deauville, a charming small town in Normandy, France. The event drew 1520 registered participants, including 264 students, from more than 40 countries. The programme ranged across flagship high-energy accelerator projects, synchrotron light sources, novel acceleration techniques, and the underlying technologies and beam dynamics.


Photographe BabXIII

Interactions *IPAC'26, organised by GANIL, drew more than 1500 participants from over 40 countries to Deauville, Normandy.*

Present facilities and beyond

In his opening talk, Robin Ferdinand (GANIL) reviewed the installations, activities and plans at the host institute GANIL, which provides a large variety of ion beams. Next, CERN Director-General Mark Thomson outlined CERN's priorities and future vision, from the implementation and exploitation of the HL-LHC to the FCC-ee, the proposed next high-energy physics flagship project (p7). He set out the aim of bringing FCC-ee to a state where it can be proposed for approval in 2028.

With facilities transitioning from third- to fourth-generation, synchrotron light sources stood out as a particularly active field – as reflected in a plenary talk by Laurent Chapon (Argonne National Laboratory), director of the Advanced Photon Source. Later contributions returned to topics such as the preparation for the fourth-generation SOLEIL II, the rapid and successful commissioning and first operation of SLS 2.0 at PSI, and the plans for MAX 4U, an upgrade even beyond the fourth generation.

The opening plenary sessions also included a talk by Masashi Otani (KEK) on a proof-of-principle demonstration of a method to produce and accelerate low-emittance positive muon beams (see *CERN Courier* July/August 2018 p8). A status report by Natalia Milas (ESS) on the commissioning of the ESS highlighted key milestones and steady progress towards first beam on target in 2027.

Presentations on proposed and operational high-energy flagship facilities included a review of linear colliders by Steinar Stapnes (University of Oslo), a report by Jörg Wenninger (CERN) on the luminosity records achieved by the LHC, a progress report by Paul Jurj (Imperial College London) on ongoing muon collider studies and a final review by Michiko Minty (BNL) on a quarter of a century of RHIC (see *CERN Courier* May/June 2026 p10), whose infrastructure will be largely reused for the Electron–Ion Collider.

Robert Apsimon's (Lancaster University) presentation on the innovative "ghost collider" drew wide interest among participants. By superimposing electron and positron bunches, it mitigates the strong non-linear forces of conventional collisions at the interaction point (IP) and suppresses beam loading along the energy-recovery linacs. A second feature is the energy transfer between the electron and positron bunches, so that their energy in the return arcs is slightly more than half that at the IP, strongly reducing synchrotron radiation losses.

This edition also saw a significant increase in contributions on machine learning and artificial intelligence (AI), indicating a shift in the development of next-generation accelerators. Several presentations reported substantial progress, particularly through the use of simulated datasets, and potential improvements in commissioning workflows and strategies, as demonstrated at the HIAF complex in China. Thorsten Hellert (LBNL) discussed the growing role of generative AI in accelerator operations, showcasing agentic frameworks enabling natural-language interaction with machines. In the closing plenary, a broader perspective further emphasised that machine learning is increasingly being integrated into accelerator design, optimisation and control, moving toward more autonomous, data-driven facilities.

Advanced acceleration techniques were widely covered, with multiple sessions dedicated to plasma-based acceleration. Medical applications were also discussed, including tests with a mixed helium-carbon beam at MedAustron to develop monitoring techniques in hadron therapy (p33), presented by Elisabeth Renner (TU Wien). Also featured were noteworthy contributions on nonlinear beam dynamics, ranging from higher-dimensional resonances and phase-space topology to novel methods for analysing complex beam motion in modern accelerators.

Science and society

The theme of sustainability, as a societal and political necessity to be taken into account when designing future projects, ran through the programme, including the "engagement with industry" session. It also motivated the presentation by Igor Syratchev (CERN) on the development of the TRISTRON, an RF source proposed to increase efficiency.

The conference reached a record 35% of female speakers, and a well-attended equal-opportunities session drew about 380 participants to discuss the main factors limiting gender parity in accelerator science and beyond. In addition to multiple plenary and parallel sessions, scientific results were presented in more than 1500 posters throughout the conference, encouraging in-depth one-to-one discussions. The event also featured a large industrial exhibition, with 113 exhibitors, two media partners and six institutional exhibitors.

The discussions, new collaborations and inspiring contributions shared at IPAC'26 demonstrate the continued strong interest in the particle accelerator field and provide solid foundations for future advances in accelerator science and its applications. The next three IPACs will be held in May 2027 in Detroit, June 2028 in Tokyo and May 2029 in Liverpool.

Christian Carli *and* **Marion Vanwelde** *CERN.*

CERNCOURIER

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CPOD26

QCD cartographers gather at CERN


CERN

Phase portrait *Participants at CPOD26 discussed the phase structure of strongly interacting matter and the search for the QCD critical point.*

The 16th Workshop on Critical Point and Onset of Deconfinement (CPOD26), held at CERN from 13 to 17 April 2026, brought together more than 100 researchers focused on the phase structure of strongly-interacting matter. The workshop continued the long-running CPOD series, which centres on understanding how and when ordinary hadronic matter transforms into quark–gluon plasma (QGP), and whether a critical point exists in the QCD phase diagram.

The series adopts a plenary-only format, to encourage unified discussion across theory and experiment and bridge gaps between different approaches to the same underlying questions. In this same spirit, the programme emphasised clarity and synthesis rather than specialised talks for a narrow audience. Many of the review talks were devoted to emerging subfields, making it easier to connect developments across traditionally separate areas.

Critical point

The central scientific theme was the search for the hypothetical QCD critical point, where the smooth crossover between hadronic matter and the QGP gives way to a genuine first-order transition, deconfining and chiral-restoring at once. Identifying it remains one of the most important open problems in high-energy nuclear physics.

Speakers examined how matter behaves under extreme temperature and density – conditions recreated in relativistic heavy-ion collisions. While lattice QCD provides invaluable results at vanishing net-baryon density, extending these calculations to high net-baryon density remains difficult due to the infamous "sign problem". Still, new exclusion limits were presented, ruling out parts of the phase diagram as possible locations for the critical point.

On the experimental side, several contributions highlighted results from ongoing heavy-ion programmes, probing a wide range of observables with beam-energy and system-size scans. These efforts are designed to uncover non-trivial structures in the excitation functions of observables that might signal critical behaviour – or the onset of deconfinement. Particular attention was given to event-by-event fluctuations and correlations, as well as to methodology, since signals can be distorted by the dynamical evolution of the collision system.

A key takeaway from CPOD26 was the importance of integrating multiple approaches

Central were, of course, the properties of the QGP. Presentations addressed transport coefficients, collective flow, dileptons and the role of fluctuations in the QGP, aiming to understand how such properties vary across different regions of the phase diagram. The connection between early-time dynamics and final-state observables was a recurring theme, with hydrodynamic and transport models playing an important role.

Understanding hadronisation – the transition from QGP back to hadrons – is essential for linking theoretical descriptions of deconfined matter to experimental measurements. Various models of particle production and freeze-out were compared, with emphasis on how they affect fluctuation observables and potential signatures of critical phenomena. Subtler effects, such as possible indications of isospin-symmetry breaking, were also noted.

The workshop's scope extended to dense QCD matter in astrophysical environments, particularly in neutron stars, with observations from modern astrophysics providing complementary constraints on the QCD equation of state at high density. This interdisciplinary perspective highlighted how insights from astrophysics and heavy-ion collisions can inform each other, contributing to a more complete picture of the phase diagram.

Looking to the future, several talks focused on new experimental facilities and detector upgrades. Speakers discussed developments at the FAIR complex at GSI – home to the CBM and HADES experiments – and at CERN, including the proposed new fixed-target experiment NA60+/DICE, the upgrade of NA61/SHINE and the next-generation ALICE 3 detector for the HL-LHC. The possibility of a fixed-target experiment at the Electron–Ion Collider (EIC) was also discussed. These efforts aim to improve sensitivity to rare signals and extend coverage into previously unexplored regions of the phase diagram.

Intriguing hints

A key takeaway from CPOD26 was the importance of integrating multiple approaches, especially given the uncertainty about the existence and location of the critical point. Experimental hints are intriguing but not yet conclusive, and theoretical predictions still face challenges in achieving quantitative agreement with data. The need for new, precise measurements at collision energies between 3 and 10 GeV was stressed throughout the workshop.

By bringing together diverse perspectives in a focused and collaborative setting, CPOD26 highlighted both how far the community has progressed in refining its tools and how much remains to be understood about the fundamental behaviour of strongly interacting matter. The next workshop is planned in Lanzhou (China), on 16–20 August 2027.

Roberta Arnaldi *INFN Sezione di Torino*, **Tetyana Galatyuk** *Technische Universität Darmstadt and GSI, and* **Maja Maćkowiak-Pawłowska** *Warsaw University of Technology.*

LOOPFEST XXIV

Precision loops back to Brookhaven

K Coughlin/Brookhaven National Laboratory

Homecoming *This year's edition of the LoopFest conference series returned to Brookhaven National Laboratory, where it began in 2002.*

From 27 to 29 May 2026, LoopFest returned to Brookhaven National Laboratory, where the conference series started in 2002. Since then, LoopFest has been held each year across universities and national laboratories in the US and, more recently, Canada. With around 60 participants, this year's edition provided a forum for discussing the latest results in precision quantum field theory (QFT), along with their applications to interpreting current experimental results and anticipating the precision reach of future experiments, primarily in collider physics. Its cousin event, the Loops and Legs symposium, was hosted last April in Bayreuth, Germany.

Talks highlighted impressive developments in multi-loop and multi-leg calculations, in matching fixed-order higher-order calculations with multi-purpose parton-shower event generators, and in the evaluation of parton distribution functions for precision measurements. Areas central to the precision-physics programme of the LHC, such as differential measurements of Higgs-boson and top-quark processes, received particular attention, while dedicated talks turned to future e^+e^- machines. There, the main challenge will be for theory to equal the extreme experimental accuracy expected for electroweak precision observables.

Exquisite control

Matching the precision of the High-Luminosity LHC and future e^+e^- colliders is vital for future discoveries. This endeavour will require exquisite control of theoretical predictions, at the (sub) percent and permille level, respectively, and already poses issues that are both technical and conceptual. Most importantly, aiming for extreme precision could not only enable the indirect discovery of new physics, but also lead to new insights into the fundamental structures of quantum field theory. Several talks stressed this point, some reviewing cutting-edge studies of amplitudes in N = 4 super Yang–Mills theories, others the impact of recent advances in quantum amplitudes for gravitational waves from black-hole scattering.

If anomalies emerge from precision studies, their interpretation will be equally challenging. Multiple contributions traced the state of the art of Standard Model effective field theory (SMEFT) calculations. SMEFT extends the Standard Model with a series of higher-dimensional operators built from its own fields, so that the imprint of unknown heavy particles is captured by small shifts in couplings. It is a common way to explore physics beyond the Standard Model under very general assumptions.

A dedicated effort to provide the dimension-6 SMEFT Lagrangian at the first non-trivial order of quantum corrections is reaching completion and will become a fundamental building block for future studies. Results from a global fit of the SMEFT Lagrangian – including, for the first time, a broad spectrum of electroweak, Higgs-boson, top-quark, Drell-Yan, di-boson and flavour observables – were presented as a proof of concept of how the SMEFT could help explore models of new physics.

Finally, the focus shifted to how the groundbreaking ideas that have transformed the theoretical calculation of scattering amplitudes have also opened new ways to apply artificial intelligence/machine learning (AI/ML) and quantum information (QI) science. This is creating new opportunities to rethink how loop calculations are performed, potentially overcoming longstanding computational bottlenecks and enabling qualitatively new approaches and conceptual frameworks. For instance, recent work has explored the application of reinforcement learning, supervised regression and self-supervised learning to some of these problems.

New ways to apply artificial intelligence/ machine learning and quantum information science have opened up

At the same time, generative models – including normalising flows and diffusion-inspired methods – have already demonstrated impressive gains in Monte Carlo integration and importance sampling, the random-sampling methods used to evaluate the high-dimensional integrals underlying cross-section predictions. Since precision QFT calculations are quantum-mechanical at heart, a genuinely quantum computation of precision scattering opens the door to synergies with QI studies of collider processes. Some talks asked how far a future quantum computer could help study QFT processes from a QI perspective, to best exploit the precision data produced by colliders like the LHC.

Extended reach

Overall, LoopFest conveyed the impressive theoretical progress achieved in recent years, enabling the exploration of new physics through precision measurements at current and future experiments. Ground-breaking methods developed during the last two decades have progressed rapidly and are now entering a mature phase, providing a robust framework within which future technical and conceptual challenges can be identified and addressed. Combined with new emerging technologies such as AI/ML and QI, this could extend the reach of current precision-physics programmes far beyond expectations.

Laura Reina *Florida State University.*

CERNCOURIER

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WHEN PARTICLES WENT GLOBAL

Former CERN Council President Eliezer Rabinovici reflects on the 4th International Symposium on the History of Particle Physics, and on the two decades in which discovery owed its successes to competition and cooperation alike.

CERN

Balance of power *A prototype storage cavity for LEP's copper radio-frequency system, photographed in 1980. The largest electron–positron collider ever built, LEP came of age at a time when particle physics had grown to a planetary scale.*

Once in a while, the particle-physics community takes stock of its own history. The latest such occasion was the 4th International Symposium on the History of Particle Physics, held at CERN from 10 to 13 November 2025.

The series began at Fermilab, with meetings in 1980 and 1985 that traced the field from its origins to the particle zoo of the 1950s. A third, at SLAC in 1992, took the story through the 1960s and 1970s, when much of the Standard Model (SM) fell into place. The 2025 edition brought together about 200 physicists and historians, with many more following online, to pick up where its predecessor left off, turning to the period from 1980 to 2000. With some 40 contributions across four days, the programme was far richer than any single report can convey. The symposium's Indico page (indico.cern.ch/event/1480892) carries it in full, along with recordings of most of the talks.

Strong foundations

By the end of the 1970s, the foundations were laid. Quarks had been accepted as physical constituents of matter, neutral currents had validated the electroweak theory in its SU(2)×U(1) form – ruling out an alternative that contained no Z – and the proof that gauge theories yield finite predictions had given the SM its mathematical backbone. The talks painted a shiny and coherent image of what came next: fundamental discoveries of new particles, the stabilisation of the SM, outstanding – and sometimes revolutionary – progress in the construction of accelerators and detectors. These achievements were spread across laboratories worldwide, and made possible by two seemingly contradictory forces: fierce international, national and "intramural" competition, and close cooperation among thousands of dedicated scientists and engineers, on a scale unheard of in civilian industry. A unique and precious ecosystem, that of the high-energy physics community, had established this "coopetition" as its own modus operandi.

Starting from the early 1980s, discovery truly became a global endeavour, against a steady shift in experimental activity from the US to Europe. The W and Z bosons, massive carriers of the weak force, were found at CERN's SPS (Super Proton Synchrotron) collider by the pioneering UA1 and UA2 experiments between 1982 and 1983 (see "The opening act" and "Sharing the ring" images). The top quark eluded a long search before being found at Fermilab in 1995, at the mass scale of the weak interaction. Its existence, required by anomaly cancellation, completed the third generation of quarks (see "Top, at last" image). Three years later, Super-Kamiokande caught neutrinos

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CERN

The opening act *The final stages of the construction of CERN's Antiproton Accumulator in 1980. The machine accumulated and stochastically cooled the antiprotons that fed the SPS collider for the discovery of the W and Z bosons.*

oscillating between flavours, building on a tradition of neutrino physics to which Soviet groups had made decisive contributions.

At both LEP (Large Electron-Positron collider) and the SLC (Stanford Linear Collider) at SLAC, the number of light neutrino species coupling to the Z was measured to be three, implying no more were left to find. Cornell's CESR/CLEO explored the upsilon family and the physics of the b-quark, while ARGUS, at DESY's DORIS storage ring, made the first observation of B-meson mixing in 1987. The B-factory programmes at KEK and SLAC then opened the door to the observation of charge-parity (CP) violation in B-meson decays. Not all searches bore fruit: no leptoquarks appeared at HERA and no supersymmetric particles at LEP. These null results, too, shaped the direction of the field.

Still, participants could revel in how one prediction of the SM after another found experimental confirmation, be it the nature of the particles discovered or the detailed structure of hadronic jets, the most direct way quarks and gluons can manifest themselves as constituents of hadrons in a detector far from the interaction region. The same holds for the deep-inelastic structure functions measured at HERA, which mapped the proton's internal structure with unprecedented precision.

On the theoretical side, several talks described the laborious process of assembling the many pieces of the SM jigsaw, a striking example of a concise and predictive compendium of human knowledge. The Brout–Englert–Higgs mechanism received particular attention, along with the emergence of the concrete Higgs-hunting strategies that would ultimately lead to the 2012 discovery at the LHC (Large Hadron Collider). The solar neutrino problem, a persistent and puzzling shortfall in the detected flux of electron neutrinos from the Sun, found its resolution in the conjecture that neutrinos are massive and can oscillate between flavours, later confirmed experimentally. More broadly, the talks exposed the characteristic dissatisfaction of theorists with any present state of understanding, paired with a restless curiosity for finding in it clues to the next frontier.

Participants could revel in how one prediction of the SM after another found experimental confirmation

The hunt for new physics

The Peccei–Quinn solution to the strong CP problem, proposed in 1977, was soon shown to imply a new pseudoscalar boson: the axion (*CERN Courier* January/February 2026 p21). By the 1980s, the idea was mature enough to start searching for it. Grand unified theories (GUTs) sought to merge the electroweak and strong forces at energies not far below the Planck scale, corresponding to the shortest distance our current physics allows us to contemplate, and at which quantum gravitational effects become unavoidable, but the early predictions for proton decay were soon contradicted at the Irvine–Michigan–Brookhaven (IMB) detector and Kamiokande (see "The proton stays" image). Supersymmetry offered a potential resolution of the naturalness problem, the puzzle of why the Higgs-boson mass is so much lighter than the Planck scale, and predicted a host of new particles. Its presence would soothe the nagging concern that a long energy desert might separate the electroweak scale from any new physics. Spoiler alert: at the time this article goes to press, no sign of supersymmetry has yet emerged.

The 1980s also witnessed the resuscitation of string theory, following a rather technical proof that specific string theories could be made free of quantum anomalies – a problem most theoretical physicists were unaware

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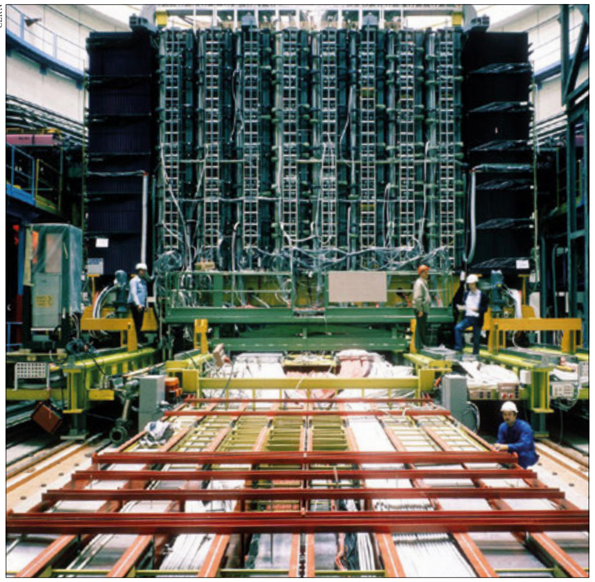
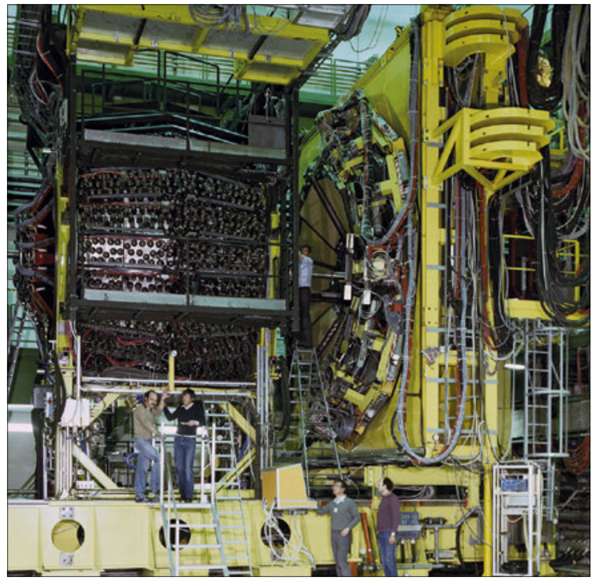




Sharing the ring *The multipurpose magnetic detector UA1 (left), integrating tracking, calorimetry and muon chambers for the widest possible coverage of the collision, and the calorimetric experiment UA2 (right), with high-granularity calorimetry optimised to detect electrons and hadronic jets. Together, they discovered the W and Z bosons at the SPS collider.*

R Hahn, Fermilab

Top, at last *The audience in Fermilab's Ramsey Auditorium on 2 March 1995, gathered to hear the joint CDF and D0 announcement of the discovery of the top quark.*

Institute for Cosmic Ray Research, University of Tokyo

The proton stays *The Kamiokande detector during construction in spring 1983, a kilometre beneath Mount Ikeno in Japan. Designed to detect proton decay, it found none, ruling out the simplest grand unified theories. Its successor, Super-Kamiokande, observed neutrino oscillations in 1998.*

of anyway. The mid 1990s brought matrix models, the non-local objects called D-branes and the unifying vision of M-theory, drawing much of the theoretical community into the programme. Unexpected connections between gauge theory and gravitational physics followed, culminating in the AdS/CFT correspondence at the decade's end. String theory, when combined with supersymmetry, provided a first candidate for a finite quantum theory of gravity, turning questions such as the number of flavour generations, their mass structure and even the number of spacetime dimensions from speculations suitable only for after-dinner talks into scientific ones. Finally, the period saw astrophysicists, cosmologists and particle physicists joining forces, giving rise to the new field of particle cosmology. The absence of the abundant monopoles predicted by GUTs was among the puzzles that led to inflation, the conjecture that the very early universe underwent a brief phase of exponential expansion.

Technology was celebrated in its own right. Talks traced the development of the superconducting magnets and cooling methods that made the great colliders possible. One could hear of the Rutherford cables wound into the superconducting coils of the Tevatron, HERA, RHIC and the LHC, with precision collars and yoke structures containing the enormous magnetic forces. Impressive advances in detector technology, data management, computing and analysis were also reviewed. It was made clear that without tight international collaboration and knowledge flow extending from KEK and Novosibirsk through Europe to the USA and down to Antarctica, among many competing groups, such progress would have been extremely unlikely. The lesson for those now planning future colliders like the FCC (Future Circular Collider) was explicit: even more than for the LHC, pull together the centres of excellence well in advance and concretely prepare what is needed for the construction of both the accelerators and the detectors.

Successes and setbacks

The 1980s and 1990s were good years for opening champagne bottles in accelerator labs. Insightful talks stressed the pioneering role of the ISR (Intersecting Storage Rings) and described how the SPS and the Tevatron were built. The challenges and successes of HERA, the first and only electron–proton collider so far, were described, as were the birth pains and rewarding growth of the SLC, which demonstrated that linear colliders could do precision physics. The triumphs all involved facing and overcoming substantial scientific, engineering and financial challenges. Side by side with the exhilarating successes were the setbacks. Perhaps it was less pleasant to dwell on failures, but studying them while planning future projects is as important as basking in the description of successes.

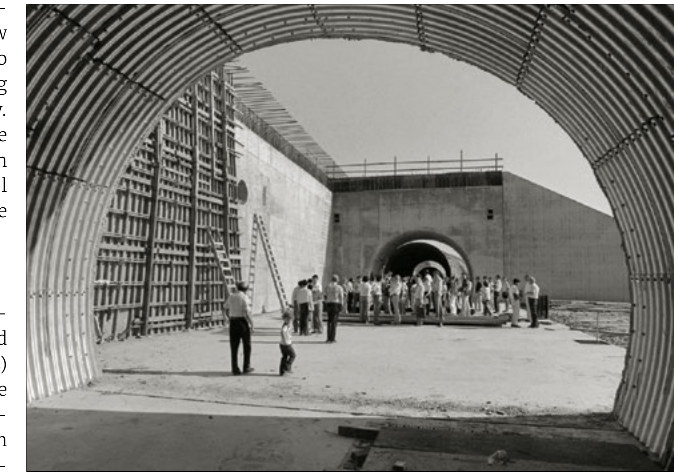
A very telling story was that of ISABELLE, a high-energy proton collider planned at Brookhaven National Laboratory that ran into magnet trouble in the early 1980s. A proposal to double the energy fared no better, especially after the discoveries of the W and Z at CERN made the original physics case less compelling. Yet its rebirth as RHIC, the Relativistic Heavy Ion Collider, opened a whole new field of research for the community (see "Second life" image), allowing physicists to recreate and study the quark–gluon plasma that filled the universe microseconds after the Big Bang. A case of snatching victory from the jaws of defeat, and an important trajectory to keep in mind for the future.

A different story was that of the Superconducting Super Collider (SSC), cancelled by the US Congress in 1993 after construction began in Texas. Understanding all the causes of this failure and appreciating its full impact on both the US and the CERN programmes is still fertile ground for historians, and should be required reading for those planning new frontier colliders.

The dissolution of the Soviet Union terminated the UNK programme, which envisaged a 3 + 3 TeV proton collider at IHEP Protvino. The impact on high-energy research in Russia was profound, yet the community showed remarkable resilience, sustaining the heavy-ion programme at JINR in Dubna and continuing neutrino experiments in politically challenging times. A silver lining was the international call for scientific solidarity that crossed geopolitical lines, helping keep Soviet colleagues part of the high-energy physics community.

The protagonists of the 1980s and 1990s fulfilled, with honour, their duty – passed down from generation to generation – to lay the groundwork for their successors. Many of them were in the room, recounting their own experience. All endeavours were extremely challenging. Some

Brookhaven National Laboratory



Second life *The construction of BNL's Relativistic Heavy Ion Collider began in 1991, in the tunnel left by the cancellation of the ISABELLE proton collider eight years earlier. The machine would come into operation in 2000 and establish the quark–gluon plasma as a near-perfect liquid.*

overcame the obstacles and reaped success, some had to reconcile themselves with descoping, and some failed. All left lessons for the future.

Free energy

As Winston Churchill himself put it in the House of Commons, it is "much better by all parties to leave the past to history, especially as I propose to write that history myself." Inevitably, those who lived through the events are not always best placed to write the conclusive story. Future editions would benefit from a larger contribution by historians of science, offering independent analysis of the processes, credits and timelines to which the physicists themselves may be too close. Still, many words of wisdom emerged from the combined experience of the speakers. Among them, a remark redefined "free energy" as the small reserve of discretionary funds that a visionary director-general can deploy to test major breakthrough ideas, free from the scrutiny of funding agencies.

Various flavours of human behaviour in competition and in collaboration found expression throughout the talks: the intramural rivalry between UA1 and UA2 at CERN, the national competition between SLAC and Cornell, the international contests between LEP and the SLC, and between KEK and SLAC at the B-factories. All these stories contain lessons for the future. For me, none matters more than coopetition.

The symposium was dedicated to the memory of Herwig Schopper, who passed away in August 2025 at the age of 101 (*CERN Courier* November/December 2025 p32). He was CERN Director-General from 1981 to 1988, in the years of the SPS collider, of LEP's approval and of the early conception of the LHC. ●

The 1980s and 1990s were good years for opening champagne bottles in accelerator labs

Further reading

https://indico.cern.ch/event/1480892/.

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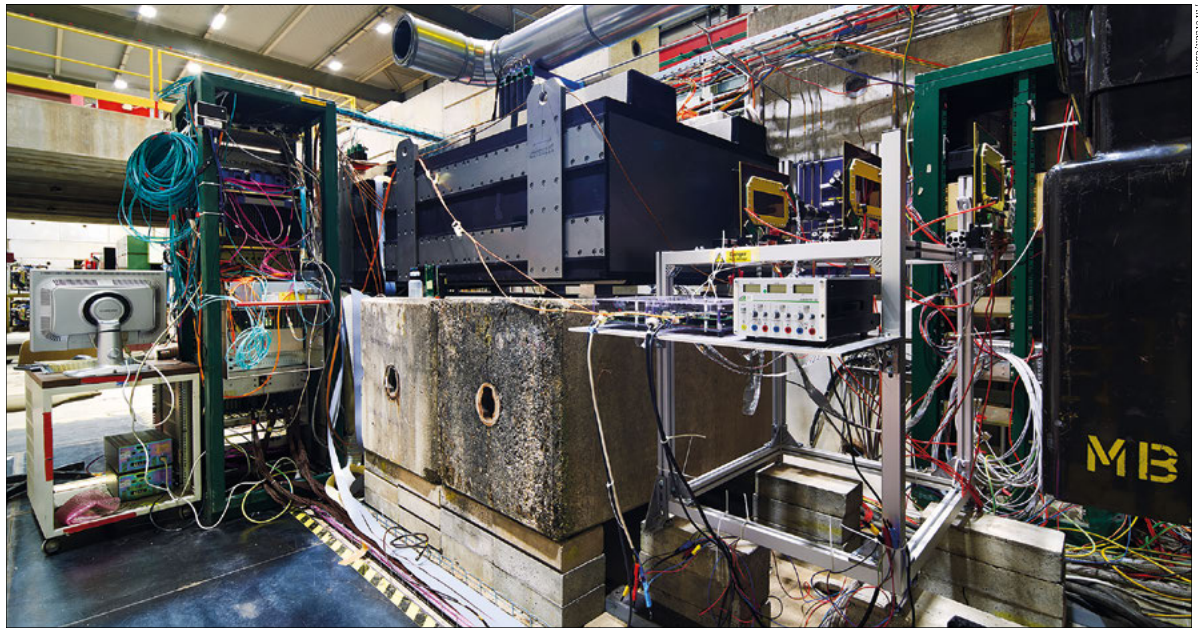


Energy gap *The NA64 experiment in CERN's North Area. Designed to search for sub-GeV dark matter, it looks for events in which a high-energy particle strikes a lead target and part of its energy fails to reappear.*

TEN YEARS AT THE MISSING-ENERGY FRONTIER

If dark matter couples feebly enough to evade direct detection, it may still betray itself by stealing energy from a beam. Paolo Crivelli, Laura Molina-Bueno and Sergei Gninenko look back on 10 years of NA64, the CERN experiment that puts this principle to work.

Missing energy has long served as a clue to unseen physics. In December 1930, Wolfgang Pauli suggested a "desperate remedy" to explain the continuous spectrum of beta-decay electrons: an undetected, neutral state that accompanied the electron, carrying off the rest of the energy and saving its conservation (see "A desperate remedy" image). The particle, named the neutrino by Enrico Fermi, interacted so weakly that Frederick Reines and Clyde Cowan observed it only a quarter of a century later.

Missing transverse energy and momentum were also essential to the 1983 discovery of the W boson at the SPS proton–antiproton collider (see p22). At LEP, the same principle was applied to events whose only visible trace was a single photon, with a neutrino pair recoiling against it and escaping with the rest of the energy. The rate of such events agreed with the existence of three light neutrino species, a count fixed far more precisely by the shape of the Z resonance.

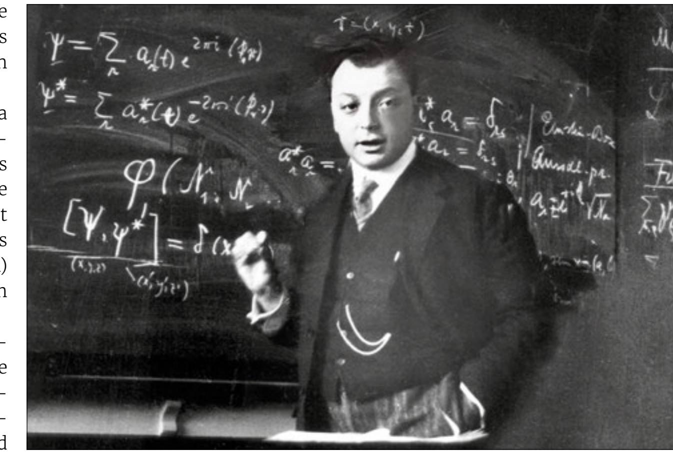
The same observables have driven searches for supersymmetric particles and invisible Higgs decays at the LHC. Their application to fixed-target experiments is more recent, and at its forefront is CERN's NA64 search for feebly interacting, dark-sector particles.

THE AUTHORS

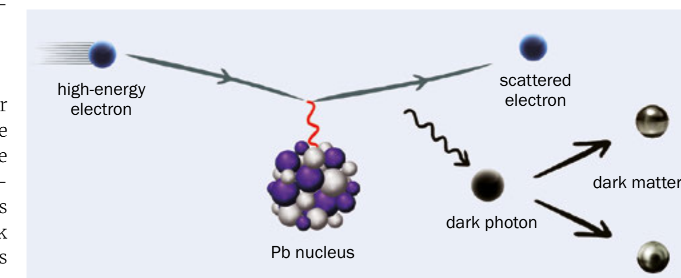
Paolo Crivelli *ETH Zurich*, **Laura Molina-Bueno** *IFIC (CSIC/UV) and* **Sergei Gninenko** *SAPHIR Chile.*

The case for such states has been building for half a century. Several astrophysical and cosmological observations point to a "dark" form of matter, whose presence is inferred only through gravity. Together with a pervasive and no-less-mysterious dark energy, it accounts for about 95% of the energy content of the universe. Despite its extraordinary precision, then, the Standard Model (SM) of particle physics does not provide a complete description of matter.

For many years, the dominant dark-matter candidate has been the weakly interacting massive particle (WIMP), a thermal relic in equilibrium in the early universe, whose present-day abundance is set by its annihilation rate. Remarkably, models with masses and interaction strengths characteristic of the electroweak scale, around 100 GeV, naturally reproduce the observed dark-matter density – a coincidence often referred to as the WIMP miracle. This expectation motivated searches at high-energy colliders such as the LHC, as well as direct- and indirect-detection experiments.



A desperate remedy *Wolfgang Pauli lecturing in Copenhagen in April 1929. Twenty months later, in an open letter to a meeting in Tübingen, he postulated the neutrino to account for the missing energy in beta decays, doubting it would ever be detected directly.*



Portal, ajar *A high-energy electron scatters off a nucleus in the active target and radiates a dark photon, which decays into two dark-matter particles. The dark photon's decay products escape unseen, and the electron emerges with reduced energy.*

The dark sector

With these efforts yielding no clear signal, the case for looking elsewhere has grown. In particular, it has become clear that the thermal mechanism behind the WIMP can be realised for much lighter particles, provided their interactions with ordinary matter are sufficiently weak. This is most naturally achieved if new physics resides in a "dark sector", comprising additional particles and interactions beyond those of the SM, with only a tenuous coupling between the two. Much like ordinary matter, the dark sector could possess its own intricate, internal dynamics, beyond the reach of direct observation.

In addition to gravity, communication between the dark sector and ordinary matter may occur through a faint "portal" interaction, distinct from the known SM forces. The forms such a portal can take are tightly constrained, since the symmetries of the SM allow only a handful of ways for a hidden sector to couple to ordinary matter: a dark photon can mix with the ordinary one, a new scalar particle can couple to the Higgs boson and a hidden fermion can couple to neutrinos. In most scenarios, the dark sector lies at mass scales comparable to those of electrons and protons, with couplings tuned to set the relic abundance at the observed value. The portal coupling is typically so weak that dark-sector particles would be produced only rarely, so high-intensity beams are needed to reach detectable rates. Once made, they would traverse large volumes of ordinary matter almost unattenuated, making signatures hard to detect.

This feebleness limits the reach of traditional beam-dump experiments, such as CHARM at CERN and E137 at SLAC, which rely on producing a new particle in a target and observing its decay or interaction in a far, downstream detector. The signal rate is therefore suppressed twice by the small portal coupling: once in production and once in the subsequent decay or scattering. In the missing-energy approach, by contrast, a well-characterised particle is sent into a target, and the energy emerging from the interaction is measured with hermetic calorimetry (see "Portal, ajar" figure). Any deficit would point to a particle that escaped without interacting, with sensitivity suppressed only by the production probability. For a representative mixing parameter of order 10^{-5} between the photon and its hypothetical dark counterpart, the number of beam particles required to reach a given sensitivity can be reduced by up to 10 orders of magnitude. This brings well-motivated regions of parameter space associated with light thermal dark matter within reach of existing accelerator facilities.

This perspective has motivated a new generation of high-intensity experiments, designed to probe rare processes associated with extremely weakly interacting particles. Among these, NA64 has played a pioneering role.

NA64 was proposed in 2013 to employ the missing-energy technique at the CERN SPS, using the H4 high-energy electron beam impinging on an instrumented target. Early test measurements carried out in 2014 demonstrated the

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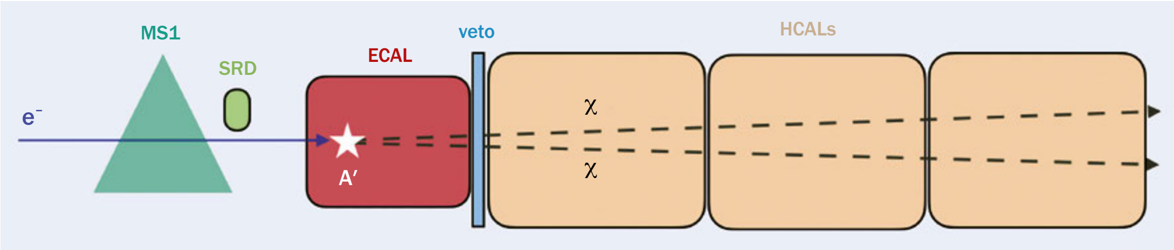
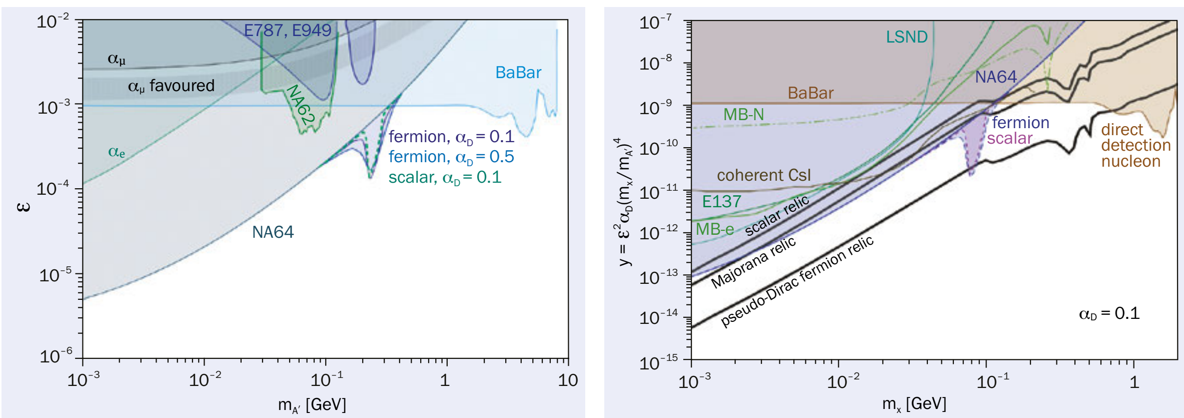


Hermetic chain *The NA64 experimental setup. A 100 GeV electron is tagged by the magnetic spectrometer (MS1) and synchrotron radiation detector (SRD). It then enters the electromagnetic calorimeter (ECAL), a lead/scintillator active target, where it may radiate a dark photon (A′) that decays into two dark-matter particles (χ). The scintillator veto and the downstream hadronic calorimeters (HCALs) help control for missing-energy effects from Standard Model processes.*



A dark corner *Experimental bounds on the dark photon, plotted as the mixing parameter ε against the dark-photon mass $m_{A'}$ (left), and as the dimensionless variable y – which sets the relic abundance in the standard thermal scenario – against the dark-matter mass m_χ (right). On the left, NA64 sets the leading bounds at sub-GeV masses and excludes the region once favoured as an explanation of the muon g–2 anomaly. On the right, three black lines show where the scalar, Majorana and pseudo-Dirac fermion relics reproduce the observed dark-matter abundance. The parameter α_D denotes the dark fine-structure constant.*

feasibility of the approach and helped validate the detector concept. Building on these results, the experiment was approved in 2016 as the 64th experiment in the North Area, from which it takes its name. It is part of CERN's broader Physics Beyond Colliders (PBC) initiative, which coordinates efforts to explore new physics using high-intensity and precision experiments. The success of NA64 has also relied on the continuous support of the CERN accelerator and beams department, in particular in optimising the beamline and preparing a dedicated experimental area following Long Shutdown 2.

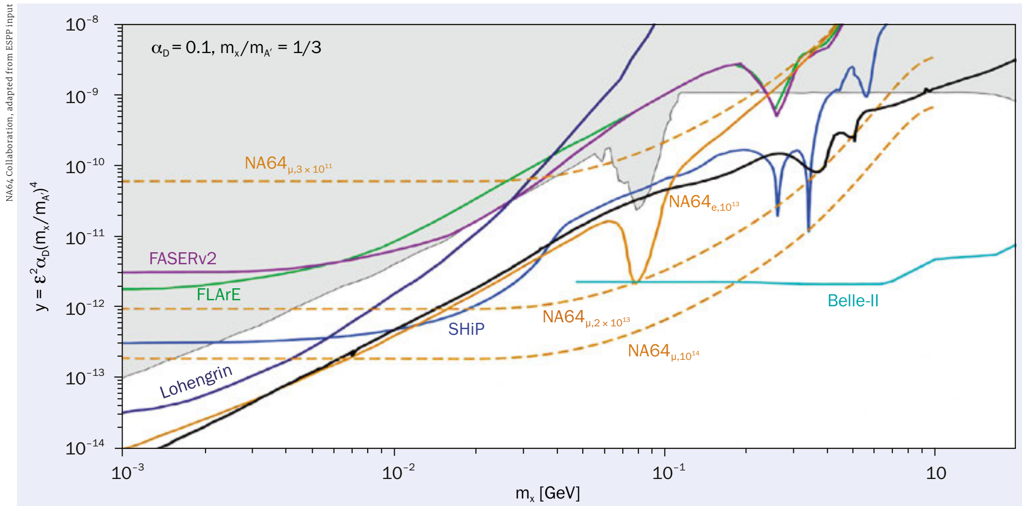
The success of NA64 has relied on the continuous support of the CERN accelerator and beams department

Pure heart

At the heart of the experiment, an electromagnetic calorimeter serves as an active target (see "Hermetic chain" figure). Incoming electrons are individually tagged and their energy precisely measured before entering the calorimeter, where they initiate an electromagnetic shower. The tagging system, based on the detection of synchrotron radiation emitted by beam particles in the dipole magnets of the spectrometer, provides a highly pure electron beam. Additional tracking and identification detectors upstream of the target reject contaminating particles, further improving the purity of the selected events, while hadronic calorimeters downstream provide a veto against escaping particles and ensure a hermetic measurement of the event.

A candidate signal is an event in which the measured energy falls below a predefined threshold. SM processes can also give rise to missing energy, most notably through neutrinos produced in hadronic interactions in the target. These backgrounds are strongly suppressed and can be efficiently discriminated, as they are typically accompanied by significant energy deposition in either the electromagnetic or hadronic calorimeters. Detector effects such as energy leakage are likewise carefully controlled.

Over the past decade, NA64 has carried out a series of measurements using high-intensity electron beams, progressively improving its sensitivity to light, feebly coupled particles. The initial focus has been the search for dark photons that decay invisibly, a well-motivated benchmark scenario for dark-sector models. A dark photon was also considered a possible explanation for the muon g–2 anomaly (*CERN Courier* March/April 2025 p21), since it would contribute to the muon magnetic moment at one



Reaching the relic *Projected NA64 reach for light dark matter, plotted as the dimensionless variable y against the dark-matter mass m_χ. The black line (relic curve) marks where a pseudo-Dirac fermion relic reproduces the observed dark-matter abundance. Dashed orange lines show NA64 projections in electron and muon modes with increasing data samples, while solid lines show other proposed experiments. With 10^{14} muons on target, NA64 reaches well below the relic curve across a wide range of masses. The grey region is already excluded by current experiments.*

Long Shutdown 3 provides the opportunity to further extend the sensitivity of NA64 to increasingly rare processes

loop through kinetic mixing with the ordinary photon. In these searches, no significant excess of events with missing energy has been observed, allowing stringent constraints to be placed on the interaction strength between the dark sector and ordinary matter.

The NA64 programme has since expanded to a wider class of dark-sector mediators. The results are typically presented as exclusion regions in the plane defined by the mediator mass and its coupling to the SM. The collaboration has explored a broad range of masses in the MeV–GeV region, probing parameter space previously inaccessible to both collider searches and traditional beam-dump experiments.

Beyond electrons

Over time, the experimental programme has also expanded beyond the original electron-beam configuration. The use of positron beams enables the resonant production of dark photons through the annihilation of beam positrons with atomic electrons of the active target. In an electron beam, the same process is suppressed because it relies on secondary positrons produced in the electromagnetic shower. Complementary approaches using hadronic beams extend the reach to dark-sector particles coupled to quarks, while measurements with muon beams at the M2 beamline, based on the missing energy–momentum technique, probe portals that couple to second-generation leptons and reach higher mediator masses. Each beam targets a different region of the dark-sector model space, and the combined programme covers a far wider range than the original electron-beam design.

These constraints have important implications for models of light dark matter. In a number of well-defined scenarios, the parameter-space region consistent with the observed relic abundance can be directly tested, and NA64 has already excluded significant portions of it (see "A dark corner" figure).

Thanks to its high-energy beam and compact detector, NA64 is also sensitive to particles with much shorter lifetimes than those targeted by traditional beam-dump experiments, which would typically decay inside the dump or shielding and so escape detection. By looking for visible decay products close to the production point, NA64 reaches a regime intermediate between prompt collider signatures and long-lived beam-dump ones. This has enabled, for example, searches for axions and axion-like particles decaying into two photons.

The exploration of dark sectors at high intensities is still in its early stages, and the recently started CERN Long Shutdown 3 (LS3) provides the opportunity to further extend the sensitivity of NA64 to increasingly rare processes (p8). Planned detector upgrades aim to improve hermeticity and background rejection, ensuring that the missing-energy signature remains robust even at higher beam intensities. The integrated statistics will then grow by up to two orders of magnitude beyond present datasets (see "Reaching the relic" figure).

The combined electron, positron, muon and hadronic beam programmes, together with the post-LS3 increase in statistics, are projected to probe a large portion of the parameter space of leading thermal-relic models of sub-GeV dark matter. Inelastic, semi-visible and muon-philic mediators will be tested in parallel, alongside searches for axion-like particles and other weakly coupled states. Together with complementary searches at colliders, in other fixed-target experiments and in direct detection, NA64 will help test a broad range of dark-sector scenarios. ●

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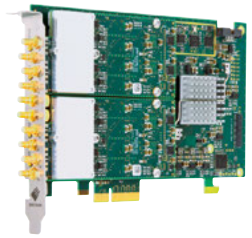

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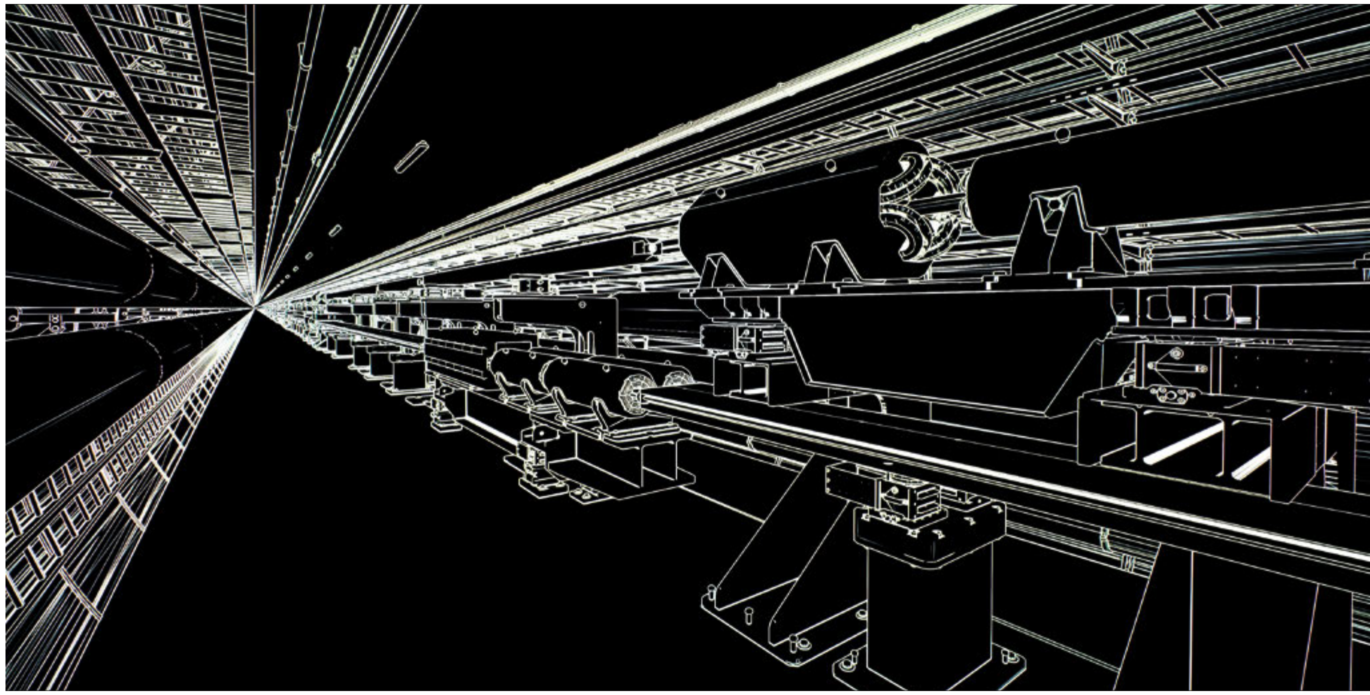
THE SWISS ARMY KNIFE OF BEAM SIMULATION

Szymon Łopaciuk, Giacomo Broggi, Frederik Van der Veken and John Salvesen explain how Xsuite drew CERN's fragmented beam-simulation tools into a single framework used to operate and optimise existing colliders, design future ones and model medical accelerators.



Beams in bits *An artistic view of the proposed FCC-ee collider. Xsuite, the open-source framework that brought together the capabilities of several beam-simulation tools, now helps design such future machines and optimise those already running. (Credit: CERN/M Brice/I Snozzi)*

Particle accelerators are complex engineering marvels, with thousands of components working in concert. Magnets bend, focus and shape particle beams, while radio-frequency cavities accelerate them and keep the bunches dense. Feedback systems stabilise their motion, collimators intercept stray particles to protect the machine and the detectors, and injection and extraction devices guide them into and out of the accelerator. In addition to these external fields, beams are shaped by their own collective effects, in which particles influence one another directly or through the electromagnetic fields they generate in the surrounding beam pipe and accelerator structures.

Faced with these intricate effects, physicists have long relied on computer simulations to design, study and operate particle accelerators. At CERN, the development of computer programs to calculate the orbit and optics of synchrotrons, transfer lines and experimental lines dates back to the late 1960s (see "Hello, world" image). The Methodical Accelerator Design program, better known as MAD, was developed in the 1980s as part of the design effort for the Large Electron–Positron Collider (LEP). It later evolved into MAD-X, which became the de facto standard for optics calculations and accelerator operation at CERN throughout the LHC era.

THE AUTHORS

Szymon Łopaciuk, Giacomo Broggi, Frederik Van der Veken *and* **John Salvesen** *CERN.*

Hello, world *CERN's IBM 709 arrives at Geneva's Cointrin airport in 1960. Successor to the vacuum-tube Ferranti Mercury of 1958, it was the first CERN machine that could be programmed in FORTRAN.*

With the growth of computing power, it became possible to follow individual particle trajectories over thousands, and later millions, of revolutions. This opened the door to more detailed studies of beam-quality preservation in the presence of non-linear forces and magnet imperfections. At CERN, much of this work was carried out with SixTrack, inspired by an earlier tool created for DESY's HERA collider. Like MAD-X, SixTrack became one of the standard simulation tools of the LHC era. Further programs were tailored over the years to specific phenomena. For example, HEADTAIL and the later PyHEADTAIL became workhorses for studying transverse collective instabilities, in which the electromagnetic fields induced by a bunch in its surroundings act back on the bunch itself. Together, these programs distilled decades of accumulated expertise in accelerator physics, from which the community still benefits on a day-to-day basis.

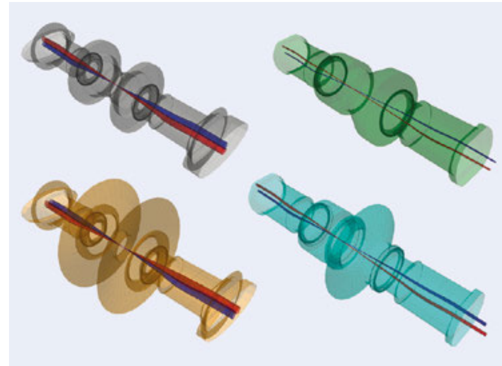
As studies became more sophisticated, however, legacy tools began to show their limitations. Developed by separate teams to analyse different physical phenomena, they were not easy to combine when studying their interplay, often requiring slow, ad hoc interfaces. Many had not been designed with long-term extensibility in mind, and some of the experts familiar with the original technologies had since moved on. At the same time, the promise of workflows accelerated by GPUs was becoming increasingly attractive for accelerator physics, but difficult to retrofit into software architectures designed for a different computing era. The Xsuite framework was developed to pull all these threads together (see "Enter Xsuite" panel).

Machines such as the Future Circular Collider push accelerator modelling to its limits

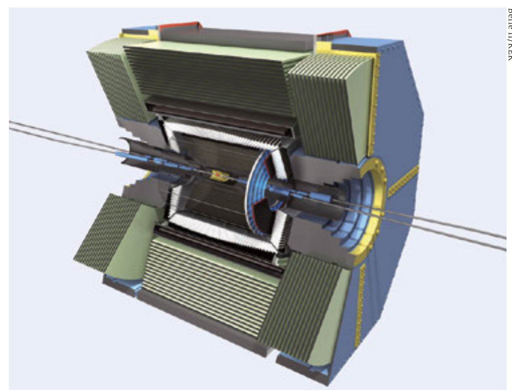
Launched in 2021, within the Accelerators and Beam Physics group at CERN, Xsuite brings accelerator-specific tools for design and simulation into a modern, integrated computing environment, connected to the wider scientific Python ecosystem for data analysis, visualisation, optimisation and machine learning. This transition is particularly important for future accelerator projects. Machines such as the Future Circular Collider (FCC) push accelerator modelling to its limits: the underlying physics calls for detailed simulations, while their scale and complexity demand the full exploitation of modern computing hardware.

Xsuite now serves as a core tool for beam-dynamics simulations in all synchrotrons operating at CERN (see "Four crossings" figure), as well as in upgrade projects and future design studies. Beyond CERN, it is used by teams at GSI, the Heidelberg Ion-Beam Therapy Center (HIT), MedAustron and DESY in Europe, Fermilab and Brookhaven in the US, the Canadian Light Source, and J-PARC and KEK in Japan. A clear sign of Xsuite's growing adoption is the steady rise in mentions in recent proceedings of the International Particle Accelerator Conference (IPAC), which now exceed those of MAD-X, for many years one of the most widely used accelerator codes.

Xsuite's open-source model has been central to this success. Free availability invites scrutiny, builds trust by allowing users to inspect the source code, and lowers the barrier to contribution. The teams that use Xsuite increasingly help to shape it, returning improvements and new features to the shared codebase. Xsuite is used for student training in schools such as the CERN Accelerator School, the Joint Universities Accelerator School and the US Particle Accelerator School, where it gives students hands-on experience with tools directly applicable to the machines they will go on to build and operate.



Four crossings *Xsuite-generated views of the beam pipes and 3σ beam envelopes at the four LHC experiments: ATLAS, ALICE, CMS and LHCb (left to right, top to bottom). To make the envelopes visible, the transverse and longitudinal scales are rendered in a 300:1 ratio.*



At the luminosity frontier *A cutaway of the Belle II detector at SuperKEKB. The colliding beams pass through the experiment solenoid, while accelerator magnets inside the detector steer and focus them close to the interaction point. Xsuite can model these nested magnetic fields, supporting studies to optimise SuperKEKB as it advances toward design parameters.*

Enter Xsuite

Xsuite aims to bring together the functionality of MAD-X, SixTrack and PyHEADTAIL in a modern, extensible, Python-based toolkit, with GPU acceleration and collective effects included by design. Its architecture is modular, with clean, well-defined interfaces between components. The main building blocks include Xtrack, Xpart, Xfields, Xcoll and Xwakes, supported by the lower-level packages Xdeps and Xobjects (see "Division of labour" figure).

This modular structure helps keep the individual components manageable as the framework grows, while making the code easier to understand, extend and contribute to. Development has been user-centric from the start, with features implemented in response to concrete needs and tested on real-use cases. A major investment in automated testing supports a fast release cycle, with new versions appearing several times a month. Comprehensive tests run every night on all supported platforms, helping to catch errors from developers and third-party dependencies early.

Much of Xsuite's value lies in how readily it connects to other codes, allowing a single study to combine effects that would otherwise sit in separate programs. Integration with FLUKA and BDSIM-Geant4, for example, enables precise modelling of particle-matter interactions across the accelerator environment, while interfaces with RF-Track and BLonD extend simulations to include complex electromagnetic fields and RF feedback systems. An interface to MAD-NG adds methods to perform high-order non-linear optimisation.

Physics modules

Xtrack
tracking and optics engine

Xpart
generation of particle distributions

Xfields
computation of EM fields from particle ensembles

Xcoll
particle-matter interaction and collimation

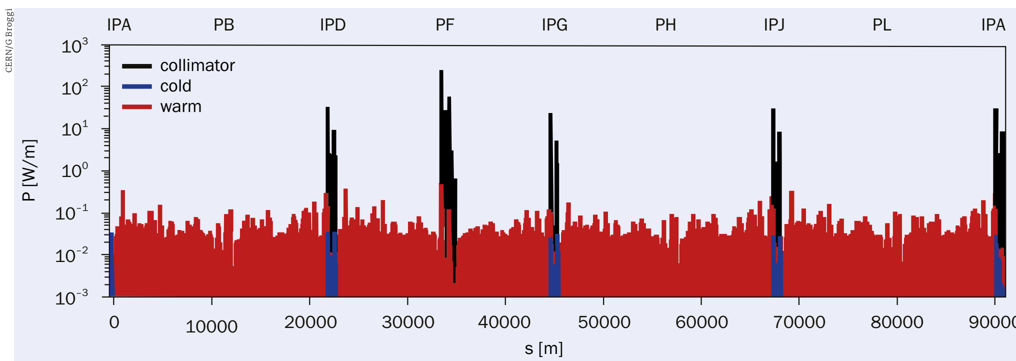
Xwakes
wakefields and impedances

Lower-level packages

Xobjects
interface to different computing platforms (CPUs and GPUs of different vendors)

Xdeps
data-flow manager, deferred expressions

Division of labour *The modular architecture of Xsuite, with each physics module handling a specific aspect of beam dynamics. All build on the Xobjects and Xdeps lower-level modules.*



On the safe side *Xsuite is used in the design of the proposed FCC-ee collider to predict beam losses and protect sensitive cold components. The resulting loss map shows the power lost per metre around the ring. The black peaks mark the collimators that catch the losses, so that little reaches the cold elements (blue), while the top labels name the eight access points.*

Xsuite's open-source model invites scrutiny, builds trust and lowers the barrier to contribution

Testing future limits

Proposed future colliders present daunting but exciting challenges for accelerator physicists, making simulation tools more important than ever. Following the success of the integrated LEP and LHC programme, the leading proposals for the next high-energy facility are once again electron-positron colliders, potentially followed by larger hadron machines. Among them are the FCC study at CERN (p7) and the CEPC study at IHEP in China (*CERN Courier* November/December 2025 p7).

The most luminous lepton collider currently operating is SuperKEKB at the KEK laboratory in Tsukuba, Japan. Its three-kilometre electron-positron rings hold the world record for the highest collider luminosity, and set the benchmark the next generation aims to pass (see "At the luminosity frontier" figure). As SuperKEKB works towards its design parameters, simulation has been central

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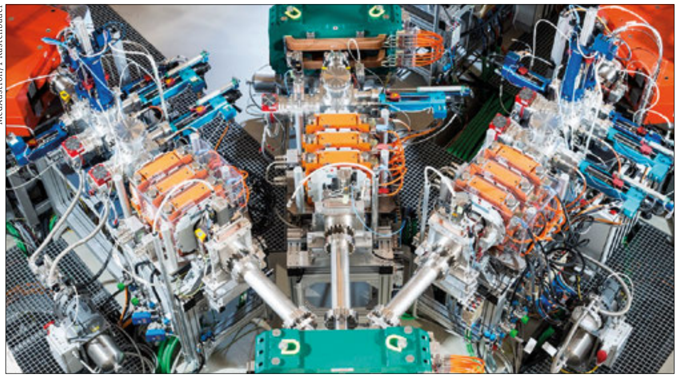

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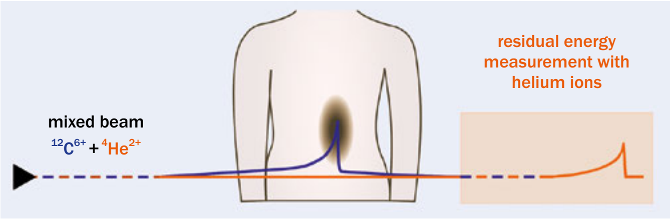

Tag team *The ion-beam injectors (top) of the MedAustron synchrotron in Wiener Neustadt, Austria, where a mixed carbon–helium beam is produced. The two ions share almost the same charge-to-mass ratio, so they can be accelerated together to the same energy per nucleon. A schematic (bottom) shows the beam in a patient: the carbon stops in the target to deliver the dose, while the lighter helium, with about three times the range, passes through. The energy the helium still carries when leaving the body can be used for online monitoring of the treatment.*

to understanding observations and optimising the machine configuration. This work has, in turn, driven the development of Xsuite and strengthened collaboration between CERN and KEK, supported by exchange schemes such as the European Union's Europe–America–Japan Accelerator Development Exchange Programme (EAJADE).

The clean way Xsuite's components fit together enables integrated studies of several beam-dynamics effects at once – a capability that is increasingly important for the FCC-ee design. A faithful model must include thousands of magnetic and radio-frequency elements, together with synchrotron-radiation emission, the tapering of magnet strengths to follow the local beam energy, beam–beam interactions, beamstrahlung and scattering in collimators. Xsuite can treat these effects together, in a self-consistent and flexible way, making it possible to study how they influence one another in realistic machine configurations. The loss distribution around the FCC-ee ring, for example, was obtained from such integrated simulations (see "On the safe side" figure). These studies test whether the machine can operate safely while delivering its target luminosity, and help guide key design decisions early in the project's life cycle.

Built for multi-tracking

Particle accelerators usually accelerate one kind of particle at a time. Nevertheless, secondary particle species are produced whenever beam particles hit the surface of beam pipes or collimators, and following them matters for the protection of sensitive components such as superconducting magnets and cavities, as well as detectors. Xsuite was therefore built to track more than one particle species at once. This feature is regularly used for collimation studies for the LHC complex and for the FCC design, and it is also proving valuable for advanced studies in hadron therapy, where carbon and helium ions are a case in point.

The charge-to-mass ratios of the two species are close enough that the two species can be accelerated together in one ring. At MedAustron, in Austria, researchers are studying mixed carbon–helium beams for "online range verification" during patient irradiation (see "Tag team" figure). In practice, while the carbon ions deposit their energy in the area to be treated, the helium ones pass through the patient and can be used to precisely localise the beam. Xsuite is used to simulate and optimise how the two ion species are injected, accelerated and extracted together in the synchrotron (*CERN Courier* November/December 2025 p45).

Shared expertise

Xsuite has by now become the working tool of hundreds of accelerator physicists. The advantages of having a large and diverse community working with the same toolkit are tangible, including synergies across projects, shared expertise, community support for new users, and collective validation of results. The current effort is to bring it into the control room. Connecting Xsuite to the CERN layout database and to the accelerator control system would let operators use the same simulation models to read, build and adjust machine configurations directly. Early control-room tests have been very positive – including a machine-development session where a full proof-of-concept LHC cycle was designed entirely with Xsuite and tested in the machine.

These steps towards operational readiness coincide with a broader shift in how accelerators are studied and controlled. Machine-learning methods and AI are becoming increasingly present in accelerator workflows, from beam tuning and injection optimisation to anomaly detection and correction of slow drifts across CERN's complex (*CERN Courier* May/June 2025 p35). Their development benefits from simulation tools that can generate realistic scenarios, explore many configurations efficiently and connect naturally to modern data-analysis environments. By combining fast-tracking, GPU capabilities and Python integration, Xsuite is well placed to support this growing convergence of beam-dynamics modelling, machine learning and accelerator operation.

Built to bring established accelerator modelling capabilities into a modern, integrated framework, Xsuite now spans applications from future-collider design and accelerator operation to the synchrotrons used in cancer therapy. If Xsuite is relevant for your work, give it a try – the team is eager to hear your feedback! ●

Further reading

http://xsuite.web.cern.ch.
G Iadarola, R De Maria *et al.* 2024 *JACoW HB2023*, TUA2I1.
F Van der Veken *et al.* 2024 *JACoW HB2023*, THBP13.

Advertisement

SenSiC: advanced SiC diagnostics for next-generation synchrotron beamlines

As synchrotrons evolve towards fourth-generation light sources, beamline diagnostics must keep pace with increasingly demanding beam conditions. Higher brilliance, smaller beam sizes and increased photon flux require compact, fast, reliable and radiation-hard devices capable of high-resolution measurements without compromising beam quality. SenSiC addresses these challenges by developing advanced silicon-carbide-based devices specifically designed for modern X-ray beamlines.

Our portfolio covers the main diagnostic needs of a synchrotron beamline: from white-beam to monochromatic diagnostics, from soft to hard X-rays, and from in-line monitoring to after-sample detection.

For white-beam applications close to insertion devices, SenSiC provides non-fully intercepting diagnostics designed to collect only the non-relevant portions of the beam. This enables reconstruction of key information on the incoming radiation while leaving the useful central beam available for the experiment, ensuring reliable monitoring under high-power-density conditions with minimal interference.

For monochromatic beams, SenSiC develops I0 and position monitoring (XBPM) for incident photon-flux measurements over a broad energy range, with dedicated solutions from soft to hard X-rays. Based on free-standing SiC membrane technology, these devices combine high homogeneity, high sensitivity and extremely low beam absorption, enabling accurate photon-flux reconstruction even at low intensities. The SiC devices are optimised for experiments requiring reliable normalisation, dose evaluation and quantitative comparison between measurements.

SenSiC also develops XBPM sensors for both white and monochromatic

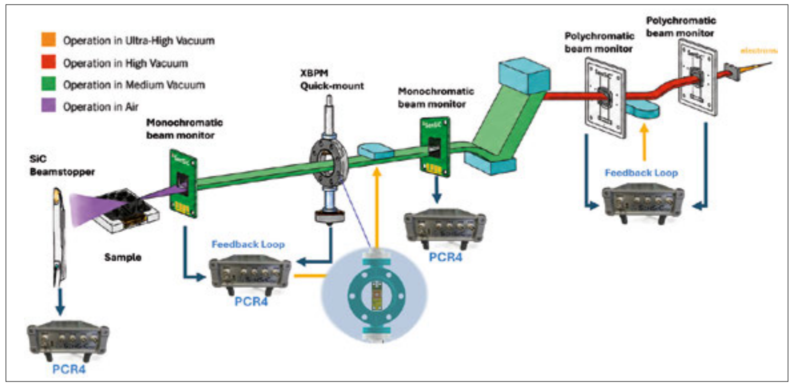

Figure 1. Integration of SenSiC SiC sensors across the full synchrotron beamline, covering white-beam monitoring, monochromatic I0 and XBPM diagnostics, active feedback-loop control and after-sample beamstopper detection.

Figure 2. SenSiC resistive XBPM technology for advanced beam-position diagnostics.

beams. Thanks to optimised geometries and SiC-based sensing elements, position resolutions below 100 nm are achievable, depending on beamline design and operating conditions. Combined with the proprietary PCR4 readout electronics, these XBPM devices can be easily integrated into active feedback-loop control systems for real-time beam stabilisation, drift correction and reproducible beam delivery.

After the sample, SenSiC devices can operate as beamstopper-integrated SiC detectors. In scattering, coherent imaging and related techniques, information from the direct or transmitted beam can provide insight into beam stability, sample interaction and experimental reproducibility.

To fully exploit the potentiality of the SiC sensors, the SenSiC PCR4 picoammeter covers the full range, from pA to several mA currents, allowing for versatile integration in the beamline enviroment.

SenSiC supports beamline scientists from device selection to customised detector design, offering tailored geometries, custom PCBs, readout and beam-stabilisation solutions. This detector-electronics co-design approach enables compact, reliable and optimised diagnostics with reduced integration complexity.

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www.sensic.ch

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OPINION VIEWPOINT

Regrouping for success

The CERN Council has updated the European Strategy for Particle Physics, naming the FCC-ee as the preferred next flagship collider for CERN. Council president Costas Fountas reflects on the process that led here, and on what it will take to carry the project to approval in 2028.

Preferred path *An artistic representation of the electron–positron Future Circular Collider.*

M Brice, CERN

Costas Fountas *is president of the CERN Council.*

As president of the CERN Council, I have followed the updating of the European Strategy for Particle Physics (ESPP) first hand. The proposals for CERN's future flagship project – the central goal of the ESPP 2026 update – were set out in the open, and physicists fought for their ideas with passion, as they should when the stakes are this high. Such conviction is the sign of a healthy field, and I am grateful to all who took part. Eventually, the community reached an overwhelming consensus on the electron-positron Future Circular Collider (FCC-ee), distilled in the recommendation of the European Strategy Group (ESG). When the Council met in Budapest this May, I was delighted to see it vote unanimously to update the ESPP accordingly.

The road ahead

The path to that vote is well known. The Council launched this bottom-up process in 2024, instituting the ESG, and the particle-physics community took it up with enthusiasm. Hundreds gathered to air and debate the proposals at the open symposium in Venice in June 2025 (*CERN Courier* September/October 2025 p24), before the recommendations were drawn together at the December drafting session in Ascona (*CERN Courier* January/February 2026 p7).

The ESPP's medium-term recommendation is to complete the high-luminosity LHC upgrade and fully exploit the scientific potential of the HL-LHC. Looking further ahead, it recommends the FCC-ee as the preferred choice for CERN's next flagship collider, aiming to maintain Europe's leading role in particle physics. Given the clear scientific and strategic superiority of the FCC-ee relative to all other potential options, a descoped FCC-ee is recommended as the preferred option if the full machine is not considered to be feasible.

> **The time has come for us to unite behind the choice that has been made**

The Council invited the CERN management to use the ESPP update as input for its medium-term plan and for the ongoing studies of the FCC-ee as the possible next flagship at CERN. As a sign of its strong support, the Council further asked management to initiate discussions with the relevant authorities and entities in the Member and Associate Member States, as well as non-Member States and the European Union. The goal is to obtain pledges of additional cash and/or in-kind contributions to the cost of constructing and operating the FCC-ee, and, on this basis, to develop a financially feasible funding plan.

Securing those funds is now central, and the current CERN management continues an effort begun under its predecessor. The draft Multiannual Financial Framework (MFF) released by the European Commission in July 2025 foresees €3 billion towards the FCC, and pledges amounting to €860 million have already been secured by private donors in 2025 (*CERN Courier* January/February 2026 p9).

Certain Member States requested specific information to approve the FCC project through their finance agency system, and management has been instructed to provide it. It then promised to do an exercise on paper, which will result in an option analysis to assist these Member States in their approval procedures for the FCC. A large part of this information exists already in the ESPP documents. However, the Council did not support the development of alternative options in parallel with the FCC reference design.

In June, the Council approved the management's plans and the milestones leading to a reference design for the FCC. The strategic question is now answered. From here, the task is one of carrying the project to approval, and the Council stands fully behind that effort.

The debate leading here was substantial, but it was conducted on the merits of the scientific case, and that is the common ground from which the community can now move forward. The time has come for us to unite behind the choice that has been made, see it through to success in 2028, support the management and contribute to CERN's standing as the leading laboratory in particle physics.

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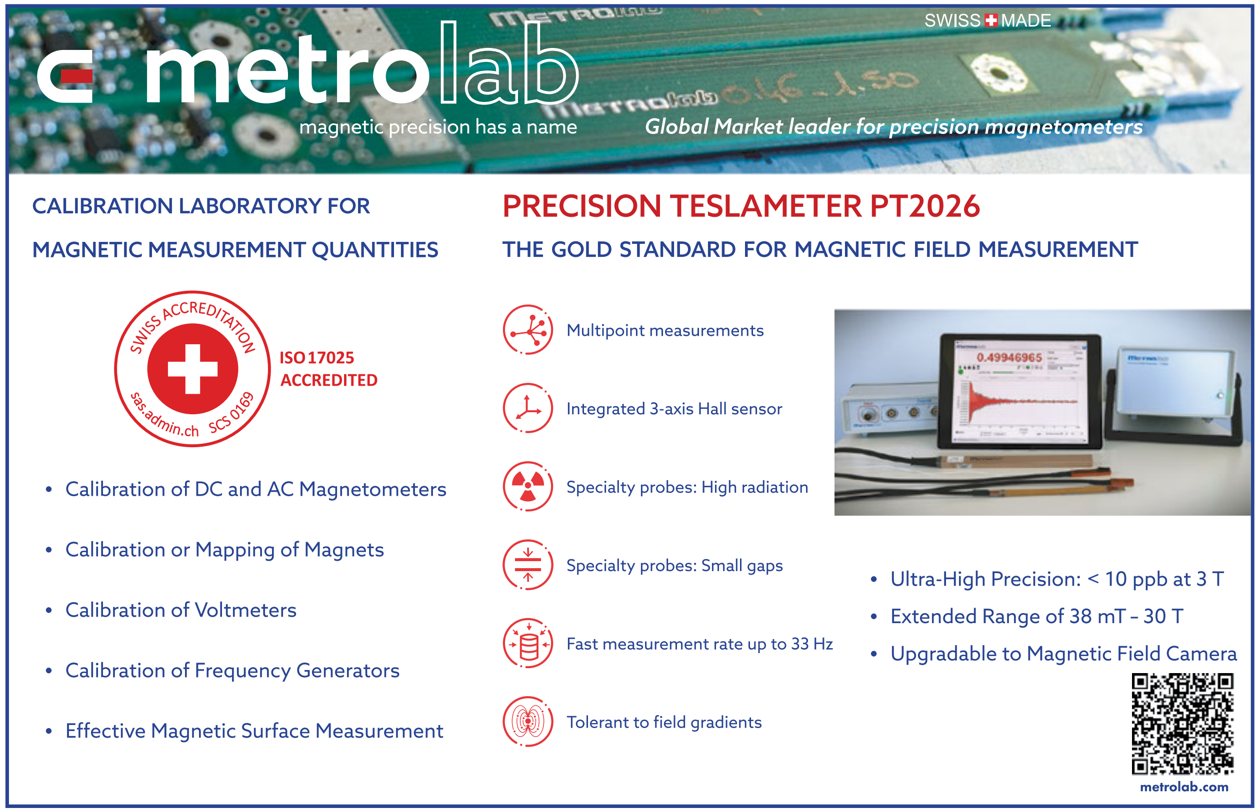

OPINION
INTERVIEW

Cosmic rays from pole to pole

A cosmic-ray detector built at CERN has measured muons from one pole to the other. The *Courier* spoke to James Devine and Etam Noah, who built and ran the project, about the open hardware behind it, the data it brought back, and the car expedition that carried it across the world.

Etam, Victor Hess discovered cosmic rays on a historic balloon flight in 1912. More than a century later, why is measuring them at the poles interesting?


E Noah

The physicist *Etam Noah, lead Cosmic Pi physicist.*

Etam Noah Near the equator, the Earth's magnetic field deflects the lower-energy cosmic rays arriving from space, while at the poles those same particles stream almost freely down the field lines. Although this latitude dependence has been known since the 1930s, ground-level measurements from the polar caps themselves are remarkably scarce, which is exactly the gap we wanted to close. After all, the origin of cosmic rays – at energies many orders of magnitude beyond those of the LHC – is still debated, and their secondary products continue to provide an accessible, free-of-charge source for both fundamental and applied research. CERN's CLOUD experiment, for example, has shown that cosmic-ray-induced ionisation can influence aerosol nucleation, with implications for climate modelling.

How far north had anyone measured muons before?

Etam In 2018, the Polarquest2018 expedition (*CERN Courier* December 2018 p30) sailed the 18 m aluminium yacht *Nanuq* into the Svalbard archipelago, carrying a scintillator detector built at CERN by high-school students from Italy, Switzerland and Norway as part of the Extreme Energy Events (EEE) network proposed by Antonino Zichichi in 2004. Polarquest2018 reached 82°07′ N, setting what was then the northernmost published ground-level muon record. Around the same time, the Dutch Clean2Antarctica expedition wheeled a solar-powered cart instrumented with a HiSPARC scintillator panel from Nikhef to the South Pole, across 1200 km of Antarctic ice. Both projects were as much about education and environmental advocacy as they were about physics, which is also the spirit behind Cosmic Pi.


M Rabilin

Onto the ice *Vehicles from the Transglobal Car Expedition on the frozen Arctic sea. The cosmic-ray detector Cosmic Pi rode aboard them across more than 92,000 km.*

Could a detector designed for the classroom survive being driven onto the sea ice?

James, how did the Cosmic Pi project come about?


J Devine

The engineer *James Devine, CERN.*

James Devine The story goes back to a weekend project at the 2012 CERN Webfest. There, we wired together an Arduino microcontroller, an Android phone and a single Geiger–Müller tube borrowed from the ERGO project, to demonstrate a low-cost approach to distributed cosmic-ray timing over the public internet. Our prototype was crude. Android's USB accessory ecosystem was barely usable at the time, but it convinced us that the idea was sound. The project resumed in 2014 under the code name X1 at THE Port, a hackathon hosted at CERN's IdeaSquare. The explicit target was to switch from Android to the new Raspberry Pi single-board computer – and to release all designed components as open hardware and open source.

And how does the detector actually work?

James The principle is simple. Each unit has two plastic scintillator slabs, one above the other, each read out by a silicon photomultiplier. A particle passing straight through both, lights them up together, and that coincidence is what picks out muons and rejects the stray background, which usually triggers only one of them. A microcontroller timestamps each event with help from a satellite navigation receiver down to 65 ns, while the Raspberry Pi handles the internet connection and logs all the data.

From the start, you wanted the detector to be cheap and widely accessible. How has that worked out?

James Not in the way we planned. We had initially hoped to crowd-fund production for less than $500 a unit, but six years of supply problems put that out of reach. The first major hiccup in the global semiconductor supply chain occurred in 2020, when COVID-19-related shutdowns at chip fabrication plants massively restricted the flow of much-needed components. This worsened in 2022, with Russia's invasion of Ukraine. Unrestrained enthusiasm for AI has driven further chip shortages, making

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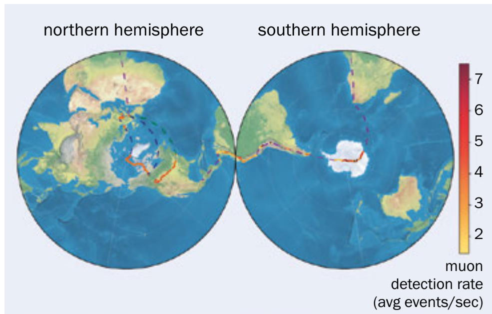
it almost impossible – and very expensive – to obtain a Raspberry Pi. DRAM prices have increased by more than five times in just one year. So we changed strategy, and focused on building small batches of detectors to ship as prizes to runners-up in CERN's Beamline for Schools (BL4S) competition. More than a hundred units have now been distributed to schools and individual experimenters around the world.

So how did one of them end up on a polar expedition?

James Almost by accident. In the autumn of 2023, I got a call from Paola Catapano (CERN), leader of Polarquest2018. She had been contacted by the Transglobal Car Expedition (TGCE), which was attempting to cross both the north and south poles by car. The idea was to take the EEE detectors from the *Nanuq* expedition along, but they were too big to fit in the polar vehicles. Her question was straightforward: could a detector designed for the classroom survive being driven onto the sea ice, and would it be ready for the start of the expedition, in January 2024?

And, of course, the answer was yes. How did you prepare?

James The expedition was, by any measure, an incredible logistical challenge. It covered more than 92,000 km across 42 countries, including a 6000 km Arctic crossing and a 7200 km Antarctic crossing, with ambient temperatures swinging from –50 °C to +50 °C. No previous wheeled expedition had reached the geographic North Pole – and we had a very short time to get ready. So we improvised. First, I called around some other educational cosmic-ray projects to see if anyone had suitable hardware. We soon concluded that the spare parts left over from BL4S would be the best option. We knew our detectors should behave acceptably down to at least –20 °C, and we did the only test available: we put them in a domestic chest freezer overnight, and any that were still working in the morning were sent on the expedition. They were repackaged into rugged Pelican-style cases to protect against water ingress and vibration, and each was named after a polar explorer or vessel: Nansen, Amundsen, Scott, Nobile and Erebus. The last honours the *HMS Erebus*, which sailed to both polar regions.



G Basile

Pole to pole *The expedition route, as reconstructed from Cosmic Pi data. Blue, purple and green dashed segments indicate where the different detectors – shipped from CERN to various locations and brought together before crossing the Arctic – were switched off.*

We set out to make a cutting-edge cosmic-ray detector available to the whole world

Etam, how did the detectors hold up out there?

Etam As James said, we carefully packed and tested every unit before sending it out – along with as many spare parts as we could think of. The constant vibration during long overland transits can affect solder joints and the points where the each scintillator's light reaches its sensor. And then there was the extreme environment. We didn't expect all the detectors to make it, so we were very pleased to see that three of them successfully recorded data for almost the entire North Pole leg. Power, a modest 5 W per detector, came from the expedition vehicles, and the data was relayed back to Geneva over our Starlink satellite link, a piece of infrastructure unavailable to our 2018 polar predecessors. The most surreal moment of the journey was perhaps a live call with the team at the North Pole, including expedition leader Vasily Shakhnovsky, while detector data was streaming in real time to our servers.

And what did all that data add up to?

Etam The dataset covers 10 January to 12 May 2024, along a route from North America through the Arctic, to the North Pole and onward to Greenland. It includes per-second muon event counts, along with associated GPS coordinates, temperature, humidity, pressure, accelerometer and magnetometer readings. The key result is a continuous, geo-tagged record of secondary muon flux extending to 90° N, surpassing Polarquest's 82°07′ N by nearly eight degrees of latitude.

The expedition then turned to Antarctica. What does the second pole bring?

Etam Of the units that worked in the Arctic, only one returned usable data from the Antarctic, a reminder of how tough a multi-year, multi-vehicle expedition is, even for ruggedised hardware. Yet that one unit covered Cape Town to the South Pole and back to the equator through South America. Taken together, the two datasets total 6.7 GB – a comprehensive latitude scan of secondary muon flux from approximately 90° N, crossing the equator, to approximately 90° S (see "Pole to pole" figure), all collected with the same instrumentation. Thanks to it, we can compare measurements without cross-calibration uncertainties dominating the result. The muon rate changes most clearly with latitude, but the scan also sets it against altitude, pressure, magnetic field and temperature. We hosted a workshop for high school students analysing the North Pole data at the CERN Science Gateway. We haven't discovered anything new, but we are nonetheless very proud of what we achieved, and grateful to the expedition team for taking our detectors along.

James, how much of Cosmic Pi is open for others to build on?

James Cosmic Pi is a volunteer project, with contributors donating their own time alongside their regular work. In keeping with its origins, everything is open. The board designs are published under CERN OHL v1.2, an open-hardware licence that lets anyone reproduce and modify them. The firmware, dashboards and analysis notebooks are under GPL-3.0, the standard free-software licence, and the raw and sanitised datasets are openly available on Zenodo. We also ran outreach events along the route and kept close links with the CREDO citizen-science consortium.

Looking back over more than a decade, what did you set out to do, and where did you end up?

James We set out to make a cutting-edge cosmic-ray detector available to the whole world, and we ended up going on a fantastic journey and measuring around the whole world instead. It's been a challenge, and an exciting one at that.

Further reading

Full transglobal dataset, doi:10.5281/zenodo.19470071.
http://cosmicpi.org.

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

Advertisement

Vortex DVZ series flow meters – at low prices

The new Kobold DVZ series flow meters are compact and affordable, and can be optimally incorporated into any applications that use low-viscosity fluids. Because the units operate without any moving mechanical parts, they are virtually maintenance-free and have distinct advantages compared with units that are based on the float or rotor principle. In contrast to calorimetric flow measurement, this measurement principle operates without time delays and can therefore also be used in time-critical applications.

Flow measurement without moving parts

The vortex flow meter does not require any moving parts to take measurements. A Karman vortex path is built into the flow meter. For this, a sharp-edged object is integrated into the flow channel as a baffle. Vortices are then formed at the generator and displaced from the baffle by the medium flowing past. The displacement frequency of the vortices is directly proportional to the speed of the flow and the flow rate. This measurement process is suitable for practically all liquids with a viscosity similar to that of water, and is independent of the pressure, temperature, specific gravity and electrical conductivity of the medium.

The right system for each area

Due to the special measuring process, the flow meters are excellent for the measurement of aggressive, corrosive or salty solutions, and they can also be used effortlessly for extremely pure media. Different variants of the DVZ series cover measuring ranges up to 100 L/min, and the unit can be equipped, by choice, with a fixed or swivel connection. Depending on the version, switched output (1 A/30 VDC), frequency output (open collector, PNP or NPN) or analogue output (4–20 mA) options are available. Also offered are programmable compact electronics that contain a digital display and a switched and analogue output.

This inexpensive flow meter is also excellently suited to OEM applications, as virtually any customer requirement can be met thanks to its modular construction.

Typical areas of application for the new flow meters are monitoring the coolant for lasers, welding robots or induction heating.

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OPINION REVIEWS

From the golden age to the Hubble wars

Discordance: The Troubled History of the Hubble Constant

By Jim Baggott

Oxford University Press


Harvard College Observatory, public domain

Reckoning the stars *The Harvard Women Astronomical Computers at work around 1890. Henrietta Swan Leavitt (third from left) found the Cepheid period–luminosity relation, now central to measuring the Hubble constant.*

Jim Peebles won the Nobel Prize in Physics in 2019 for his work on the foundations of cosmology. Looking back at the state of his field in the early 1960s, he did not paint a pretty picture. Cosmology was, he recalled, "a limited subject … with two or three numbers." He added, "A science with two or three numbers always seemed to me to be pretty dismal." It was even worse than Peebles made it out to be. One of those numbers – the main number for many people – was the Hubble constant, named after Edwin Hubble, which quantified the expansion rate of the universe. Since the late 1920s, there had been a systematic campaign to measure the Hubble constant with ever-increasing precision. Yet, as the astronomer Allan Sandage showed in a 1962 review of the topic, there was no real agreement. Some astronomers found that the Hubble constant was 113 (in units of kilometres per second per megaparsec), with an uncertainty of about five. Others were getting 75, with an uncertainty of 25. Given the uncertainties, the results were remarkably discrepant – or "discordant".

By the mid-1990s, the situation wasn't much different. I remember attending the Critical Dialogues in Cosmology conference in Princeton in 1996, at which Wendy Freedman advocated a "high" value of the Hubble constant (above 70), while Gustav Tammann pushed for a low value (around 50). In a heated debate, they were at each other's throats, and it became clear that the different camps weren't going to agree, nor were they going to concede. By the early 2000s, the "Hubble battles" seemed to have ended, and a consensus was emerging that the Hubble constant was around 70. That is, until measurements became so precise that "discordance" re-emerged. This is the situation we find ourselves in now. Measurements that probe the early universe by looking at the cosmic microwave background yield a "low" value of the Hubble constant of 67, while methods that examine the late universe by measuring the properties of variable stars and supernovae give us a "high" value of 74. These numbers seem close, but the uncertainties have come down so dramatically that the difference matters.

It is a mesmerising story that has been in the background of my career as a cosmologist. On the one hand, we want the tension to go away, to see it resolved, given how successful the cosmological model is. On the other, for the more theoretically minded, there is hope that this is tantalising evidence for new physics, an undiscovered fundamental property of the universe yet to be uncovered. There is yet another possibility, which sounds much less scientific, namely that the protagonists throughout the ages have become wedded to their own favourite values, preventing convergence. Having met many of them, I can vouch that they are strong and fascinating characters.


Oxford University Press

Jim Baggott's *Discordance* is an attempt to describe the history of cosmology throughout the past century or more. It covers a lot of ground and delves into some of the less explored aspects of the story. For example, he describes the "Harvard computers", a cohort of women working at the Harvard College Observatory who played an instrumental role in establishing the foundations for the distance indicators crucial in measuring the Hubble constant. Henrietta Leavitt stands out as the person who unearthed the period–luminosity relation for Cepheid variables, which are at the heart of the current Hubble debates.

He also rightly describes what I call the "golden age of cosmology", from when Peebles and others first began building accurate mathematical models of the large-scale structure of the universe to the modern measurements of the cosmic microwave background. I grew up during this era and have been lucky enough to witness firsthand this remarkable success story, a beautiful example of theory and observation coming together. This is physics and astronomy at their best. It is not all about discordance.

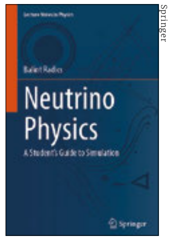
What I missed was a more in-depth analysis of what is going on, of how the different camps work and interact with each other. The characters are interesting, and it would have been good to get to know them better and understand what drives them. As it stands, they are mostly two-dimensional protagonists in a whistle-stop tour through the history of cosmology. Often, I found myself reading the book as if it were a layperson's review article, a simplified version of what one might find in the *Reviews of Modern Physics* or *Physics Reports*. The result is a useful and easy way to get up to date on what is going on in cosmology, but no more than that.

Pedro G Ferreira *University of Oxford.*

Neutrino Physics: A Student's Guide to Simulation

By Balint Radics

Springer



An effective manual to simulate the lives of neutrinos from their birth until they touch a detector

Established around the turn of the century, neutrino-flavour oscillation is among the clearest signs of physics beyond the Standard Model (BSM), as it requires neutrinos to be massive. Over the past decades, neutrino-oscillation experiments have grown in physical size, collaborative scale and scientific success.

The missing solar neutrinos identified by the Davis chlorine experiment in the 1960s brought the first hints of oscillation, while atmospheric-neutrino oscillation was established by the Super-Kamiokande experiment in 1998. This was followed by the Sudbury Neutrino Observatory's confirmation that solar neutrinos do indeed change flavour. Since then, measurements of neutrinos from long-baseline beams and nuclear reactors have confirmed the oscillations seen in natural sources and refined the parameters of the three-flavour neutrino picture.

The current-generation long-baseline experiments are now approaching the limits of their reach, and the community are awaiting results from the next-generation large-scale experiments – the Jiangmen Underground Neutrino Observatory in China, Hyper-Kamiokande in Japan and the Deep Underground Neutrino Experiment in the US. These, along with many smaller neutrino experiments employing various technologies, are chasing down the remaining known parameters of the three-flavour paradigm, testing with precision measurements and pursuing broad searches for BSM physics.

While the primary title of this book, *Neutrino Physics*, suggests a broad subject matter, the subtitle *A Student's Guide to Simulation* immediately indicates the much more constrained scope. The material presented strongly emphasises simulation techniques of interest for neutrino-oscillation data analysis, and is of most direct relevance to long-baseline-beam oscillation experiments. Furthermore, the treatment is confined to simulating the production, oscillation and interaction of neutrinos. It stops before addressing the simulation of neutrino interactions' final-state products in detectors. While typical expertise sought by students in the field includes detector simulation, event reconstruction from low-level data and parameter inference, these topics are mostly absent, as are many non-oscillation-related neutrino topics. Nevertheless, the topics covered are essential for any student of neutrino physics, and the material provides a clear, concise, step-by-step tutorial that develops both physical insight and practical skills. A student working through this book will gain a substantial understanding of the concepts behind neutrino-event generation and the computation of flavour-transformation effects.

The book is aimed at graduate students who already possess some knowledge of particle physics and basic familiarity with special relativity. For this audience, the level is exactly right. The reader is gently introduced to standard terminology as well as common tools and computational techniques. A review of relativistic kinematics follows, and then a deeper dive into applications to the specific cases most likely to arise in experimental neutrino-oscillation physics. Weak decays and neutrino scattering in the GeV regime are also covered in some detail. The text concludes with a discussion of the computation of flavour transformation in vacuum and matter.

The numerous and well-chosen code examples are a strength of this book. Some might complain that the provided examples make exclusive use of the ROOT software framework. While ROOT remains widely used in high-energy physics and is available in Python via PyROOT, many students now prefer more modern, Python-native tools. Also missing is a discussion of modern AI tools, which have by now become integrated into many code-development workflows.

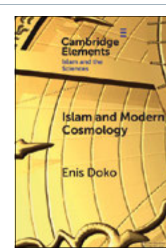
Nevertheless, the core content of the examples can be easily converted to any software environment. Although it delivers a rather narrower scope than suggested by its primary title, this book is an effective manual for anyone who wishes to simulate the lives of neutrinos from their birth until they touch a detector. It will be of value to all students embarking on research in neutrino-oscillation experiments, and it contains clear pedagogical examples that are likely to be of use to others as well. I will recommend this book to my students and keep a copy on my own virtual shelf.

Kate Scholberg *Duke University.*

Islam and Modern Cosmology

By Enis Doko

Cambridge University Press



Enis Doko's *Islam and Modern Cosmology* is an ambitious and intellectually serious contribution to a genre too often dominated by superficial concordism. Doko explores whether modern cosmology and Islamic intellectual traditions can enter into meaningful philosophical dialogue. In an age when "science and religion" literature often oscillates between naive scientism and mystical vagueness, this alone is noteworthy.

The work's strongest feature is methodological. In its early chapters, Doko repeatedly emphasises that the Qur'an is not a scientific textbook and that cosmological theories remain provisional. This is a refreshing departure from the "scientific miracle" literature that continues to dominate much popular Islamic discourse. Doko is familiar with both contemporary cosmology and analytic philosophy of religion, and he treats scientific theories with seriousness and nuance. Discussions of singularities, inflation, fine-tuning, quantum cosmology and multiverse scenarios are generally informed and competently presented.

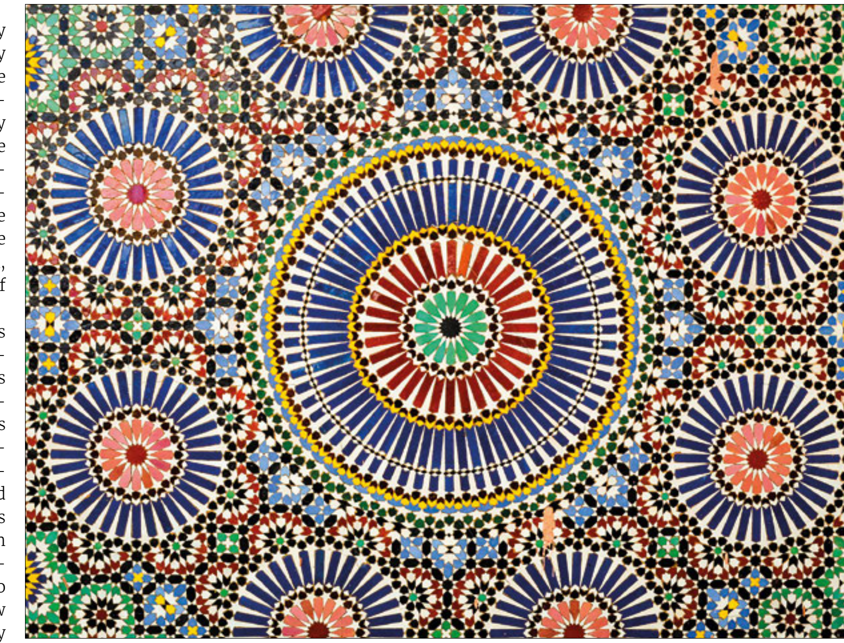
Yet the project's very ambition also reveals some delicate tensions. The central epistemic issue, which Doko himself recognises in the earlier chapters, is that modern cosmology and "Qur'anic cosmology" do not operate within the same conceptual framework. Scientific cosmology is empirical, mathematical and inherently revisable, whereas Qur'anic cosmology is symbolic, existential and theological in orientation. The former seeks predictive explanatory models constrained by observation, while the latter addresses meaning, creation, transcendence and humanity's place in the cosmos.

Doko is aware of this distinction, and this awareness gives the early sections of the book much of their intellectual strength. As the argument develops, however, symbolic "resonance" occasionally edges toward implied cosmological correspondence. At times, modern cosmological ideas seem to be read back into Islamic theological frameworks in ways that some readers may find historically ambitious or ▷

philosophically debatable.

This tendency becomes particularly visible in the treatment of inflationary cosmology and multiverse theories. The book often presents inflation as the dominant explanatory paradigm for the early universe – a position that reflected the optimism surrounding inflationary cosmology and landscape multiverses during the late 1990s and early 2000s. Since then, however, the intellectual landscape has become more nuanced and contested, and alternatives have shown up, even if not necessarily more credible.

Inflation was introduced to address important puzzles in Big Bang cosmology, including the horizon and flatness problems. It achieved considerable phenomenological success and remains influential, but several conceptual difficulties remain unresolved. The inflaton field itself is still hypothetical, and some critics argue that inflation shifts fine-tuning questions rather than resolving them entirely. The proliferation of inflationary models has also led some cosmologists to question how predictive the framework ultimately remains. Doko acknowledges some of these debates, though he occasionally presents inflation as closer to a stable consensus than many cosmologists today might consider warranted.



Ordered to infinity *A detail of Islamic geometric tilework from the Marrakech Museum, Morocco.*

A related issue arises with string theory and landscape cosmology. Much of the speculative architecture of the later chapters draws upon ideas such as extra dimensions, branes and multiverse landscapes. Yet string theory remains experimentally unconfirmed despite decades of theoretical development, and some of the motivations that once strongly supported supersymmetric extensions of the Standard Model have weakened. This does not delegitimise such theories, but it does suggest that the broader theoretical context remains less settled than it once appeared.

In this changing scientific context, attempts to draw theological significance from speculative cosmological frameworks inevitably become more delicate. Doko sometimes moves rather quickly from mathematical possibility to metaphysical interpretation, particularly when discussing the multiverse as a possible expression of divine creativity or cosmological plurality within Islamic thought.

One of the most thoughtful and sophisticated attempts to place Islamic thought into dialogue with contemporary cosmology

This does not make the project illegitimate, but it does make it historically and philosophically fragile. The effort to connect modern cosmology with the four major classical Islamic creation frameworks – emanation, temporal origination, manifestation and perpetual creation – is imaginative and stimulating, yet it also raises difficult historical questions. These classical doctrines emerged within intellectual worlds very different from those of inflationary cosmology or string landscapes, and the bridge between them is necessarily interpretive rather than direct.

Attempting to put the Sufi doctrine, with its spectrum of rather vague and ethereal views, in resonance with some cosmological concepts – the multiverse in particular – may provide existential depth and protect cosmology from reductive scientism by allowing it to become spiritually meaningful rather than merely mechanistic.

However, a symbolic framework capable of accommodating Aristotelian cosmology, Newtonian mechanics, relativistic spacetime, inflationary multiverses and string landscapes with equal ease risks losing any explanatory claim. The issue is not that Sufi metaphysics is "wrong", but that its interpretive openness can make it difficult to distinguish enduring metaphysical insight from retrospective symbolic accommodation.

In this respect, the later chapters increasingly read less as a study of historical Islamic cosmology and more as a contemporary philosophical synthesis shaped by Doko's intellectual and spiritual vision. This is not necessarily a flaw, as many important philosophical works are constructive rather than purely historical, but some readers might benefit from a clearer distinction between inherited doctrine and modern reinterpretation.

Despite these reservations, *Islam and Modern Cosmology* remains one of the most thoughtful and sophisticated attempts in recent years to place Islamic thought into dialogue with contemporary cosmology. It is serious, learned and often genuinely illuminating. It is also a good introduction to Islamic philosophy during the formative centuries, as well as an elaborate review of modern cosmology written with as much depth and accuracy as a short monograph permits. If the book occasionally stretches the connection between speculative cosmology and theology further than some readers may find fully persuasive, this reflects less a lack of rigour than the immense difficulty of the enterprise itself. The result is a stimulating and intellectually ambitious synthesis. Its long-term significance may depend as much on where cosmology itself evolves scientifically as on how successfully the author's work and others of the same strand engages with the theological questions it raises.

Jamal Mimouni *University of Constantine 1 and CERIST.*

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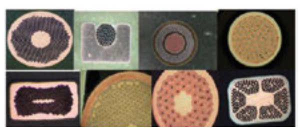

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PEOPLE CAREERS

Field theory at CERN and UEFA

A particle physicist at CERN for 12 years, Barbara Storaci now coordinates UEFA's competition draws. She recounts the move from academia to industry, and how her physics skills proved transferable.

S E Bennett, CERN

Barbara Storaci *is a senior project manager at UEFA.*

Some 30 kilometres from CERN, on the northern shore of Lac Léman, sits the home of European football. The Union of European Football Associations (UEFA) brings together 55 national associations from across the continent and organises its most prestigious tournaments, including the European Championship and the Champions League. It sets the rules for those competitions and allocates most of the revenue they generate back into the game.

"When I saw the job description, I remember thinking: oh my God, they are looking for a physicist," recalls Barbara Storaci. "It didn't make any sense, but the profile they wanted was exactly mine."

Although the role did not explicitly mention physics, it demanded someone who could coordinate, code, analyse large volumes of information and thrive in an international environment. "Who in the world has all this in one person?" she asked. "Well, physicists do."

From physics to football

Today, nine years on, Storaci is a senior project manager, responsible for the more than 50 draws UEFA conducts each year, as well as for coordinating projects across the organisation. Football, though, was not the original plan.

Storaci wanted to be a particle physicist from the age of 12. "I planned my studies to reach this goal. I started to collaborate with the LHCb experiment from my bachelor's and master's studies at the University of Milano-Bicocca, coming to CERN for the summer before my last year, and never going back." Based at CERN throughout, she completed a PhD with Nikhef and a postdoc at the University of Zurich. Storaci spent 12 years at LHCb, rotating through nearly every role, from data analysis to data-acquisition coordination.

But the suspense of discovery came with the anxiety of instability. "At a certain point, I didn't have fun anymore because it was more a matter of always looking for the next contract instead of actually doing research," she says. "When I reached an age where I wanted more stability for family life, the short-term contracts made things extremely difficult."

Curiosity is the key. If I had to select just one trait, that's the one I'd choose

Getting a permanent academic position felt like a lottery. Storaci often found herself up against competent colleagues who made for tough competition, and the constant race for short-term contracts made her question whether it was wise – or healthy – to continue. She grappled with many doubts, and was hesitant to seek roles outside of academia. "For many years I wondered: am I giving up on my dream?" she recalls. "Is it a failure? Should I try a little longer?"

Her curiosity, and her willingness to take risks, led her to leave the lab. "All my life I have been outside my comfort zone," she reflects. "That's what I love about my present job: I know what I'm doing today, but I have no clue what I will be doing in two years. And that fits me extremely well."

One of the biggest adjustments was learning to present herself as a strong candidate to people outside academia. "Physicists often believe we can do any job, but when you actually look for a job, you start wondering: is that really true?" Her advice to other researchers is to translate their skills into a language recruiters understand.

"Nobody outside of particle physics will care about your decay channel," she says bluntly. "Forget about the jargon. What matters is what you developed to make that research happen: coding, managing projects, analysing huge datasets, coordinating teams. That's what you have to explain."

Practical preparation helped. Before her first UEFA interview, a friend outside academia offered to role-play as a recruiter. Storaci was sceptical. She had done plenty of academic interviews, and surely this would be no different. But when they met for coffee, some of her friend's questions left her stumped.

"She asked me questions I had never thought about, like who my worst boss was," she recalls. "How could anyone expect that question? It turns out I wasn't ready at all! But it helped me approach the real interview much more calmly."

Every job application is apt preparation for the next, she argues, even if it results in a rejection or seems out of your depth. What sets a candidate apart is the ability to demonstrate transferable skills, sustained work on long-term projects, time management and teamwork.

Same skills, new context

Storaci now applies the analytical mindset she honed at CERN to a very different environment. She insists the transition was less about leaving physics behind, and more about carrying those skills into new contexts. "It's normal to be scared, but you have so many skills you don't even realise you've developed. Once you learn how to show them, you'll see you can succeed in very different worlds," she says. "The ability to absorb and connect information, to see inconsistencies, to debug problems, these are skills physicists have, and they're incredibly valuable outside academia too."

Above all, she believes success comes down to two things: curiosity and courage. "Curiosity is the key. If I had to select just one trait, that's the one I'd choose," says Storaci. "If you're curious, everything else will come. And you must be willing to step out of your comfort zone. It's scary, of course, but that's where growth happens."

Interview by **Alex Epshtein** *CERN.*

CERNCOURIER

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Appointments and awards

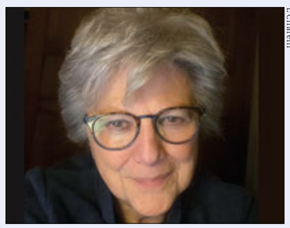

D Rahner/Brookhaven National Laboratory

John Hill to lead Brookhaven
Brookhaven Science Associates, the Stony Brook University and Battelle partnership that manages the US Department of Energy's Brookhaven National Laboratory, has appointed John Hill director, effective 21 May. A condensed-matter physicist who joined the laboratory as a postdoc in 1992, Hill led its X-ray Scattering Group for more than a decade and directed the National Synchrotron Light Source II from 2015 to 2023. He became deputy director for science and technology in 2023 and interim laboratory director in September 2025, in which capacity he presided over the final collisions of the Relativistic Heavy Ion Collider (RHIC) in February.

IUPAP honours Latacz and Qu
The International Union of Pure and Applied Physics (IUPAP) has named Barbara Latacz (CERN) and Huilin Qu (Tsung-Dao Lee Institute, Shanghai Jiao Tong University) among the recipients of its 2026 Early Career Scientist Prizes. Latacz is recognised for her contributions to the first coherent spectroscopy of a single trapped antiproton spin in the BASE experiment, work that established the first antimatter quantum bit. Qu is recognised for developing advanced machine-learning algorithms that identify the decays of boosted heavy particles.

Gruber prize for supernovae
The 2026 Gruber Cosmology Prize has been awarded to Alexei Filippenko (University of California, Berkeley), Ken'ichi Nomoto (University of Tokyo) and Stanford Woosley (University of California, Santa Cruz), for "transforming supernovae from poorly understood stellar explosions into the basis for a quantitative, predictive, and empirically validated framework". Filippenko's observations and the independent theoretical work of Nomoto and Woosley together established the physics of Type Ia and core-collapse supernovae and nucleosynthesis.

EPS honour for Cifarelli
During its May Council in Vilnius, the European Physical Society (EPS) has named Luisa Cifarelli (pictured; University of Bologna) an Honorary Member for 2026. The award recognises a career of five decades, from CERN's ISR –


L Cifarelli

the first proton–proton collider – through hadron-physics and proton–structure work at DESY and CERN, to a leading role in the ALICE experiment at the LHC. Cifarelli was president of the Italian Physical Society from 2008 to 2019 and of the EPS from 2011 to 2013. The same council named Vladimir Fomin (IFW Dresden) and Zsolt Fülöp (Atomki, Debrecen) EPS Fellows, for condensed-matter and nuclear-astrophysics work, respectively, and awarded the EPS Early Career Prize to Jayadev Vijayan (University of Manchester) for his work at the intersection of ultracold atom physics and levitated optomechanics.

Altarelli award for 2026
On 8 May, at the Deep Inelastic Scattering workshop (DIS2026) in Bologna, Thomas Cridge (University of Manchester) and Ana Rosario Cueto Gomez (Autonomous University of Madrid) received the 2026 Guido Altarelli Award, in theoretical and experimental physics, respectively. The award, given to early-career researchers, recognises Cridge's work on global analyses of parton distribution functions, the maps of quark and gluon momentum inside the proton, and Cueto Gomez's studies of final-state photons and Higgs-boson decays to photon pairs, including the use of effective field theory in precision tests of QCD and the Standard Model.

INFN medal for Maiani
The Italian Istituto Nazionale di Fisica Nucleare (INFN) has awarded its INFN Medal, reserved for those who have shaped the Institute's history, to Luciano Maiani (Sapienza University of Rome), for his pioneering contribution to the understanding of quark interactions. The medal was presented on 3 June during the study days of the INFN triennial plan in Padova. With Sheldon Glashow and John Iliopoulos, he proposed the Glashow–Iliopoulos–Maiani (GIM) mechanism, which required a fourth quark and anticipated the charm quark found four years later. He served as INFN


J-L Caron, CERN

president from 1993 to 1998 and as CERN Director-General from 1999 to 2003.

Accelerator prizes awarded
On 21 May, the European Physical Society Accelerator Group (EPS-AG) presented its four European Accelerator Prizes at IPAC'26, in Deauville. The Rolf Wideröe Prize for lifetime achievement went to Elena Shaposhnikova (pictured; CERN) for her work on radiofrequency systems, longitudinal beam dynamics and impedance identification, which enabled beyond-design beam brightness in the LHC and its injectors. The Gersh Budker Prize for a recent, significant contribution went to Wentao Wang (Shanghai Institute of Optics and Fine Mechanics) for the first demonstration of free-electron lasing driven by a laser–plasma accelerated beam. The Frank Sacherer Prize for


E Shaposhnikova

early-career work went to Patrick Rauer (DESY) for leading the first cavity-based X-ray free-electron laser at the European XFEL, and the Bruno Touschek Prize to Andrea Frazzitta (Sapienza University of Rome and PSI) for inventing the plasma discharge undulator, a new concept for plasma-based radiation sources.

Kavli prize for mergers
The Norwegian Academy of Science and Letters has awarded the 2026 Kavli Prize in Astrophysics to Vasily Belokurov (University of Cambridge), Amina Helmi (University of Groningen) and Rodrigo Ibata (CNRS and University of Strasbourg), for uncovering the evidence of past mergers, proving that the Milky Way grew by absorbing smaller galaxies. Combining stellar positions, velocities and chemical abundances from the Sloan Digital Sky Survey and ESA's Gaia mission, the laureates identified long trails of stars, left behind where the Milky Way's gravity tore apart accreted dwarf galaxies, and traced them back to the ancient mergers that produced them. Ibata's 1994 discovery of the Sagittarius dwarf gave the first clear evidence that the Milky Way is still absorbing its satellites. Belokurov mapped a web of such trails across the sky, and Belokurov and Helmi independently identified Gaia-Enceladus, the remains of the last major merger our galaxy underwent. The prizes will be presented in Oslo in September.

PEOPLE OBITUARIES

Bernard Royce French 1931–2025

An insatiable enthusiast for physics

Bernard French, a CERN physicist who worked on and led numerous experiments, especially at the OMEGA spectrometer, died on 5 November 2025 at the age of 94. Bernard was born in Watford in the UK on 23 April 1931 and gained his PhD at Imperial College London in 1958, staying there as a research fellow before joining CERN as an associate on 1 October 1961. After becoming a staff member on 1 May 1962, he remained at CERN until his retirement in 1996.

Bernard first worked on the analysis of bubble-chamber data, focusing on the search and study of meson resonances. Then, in 1967, he joined a group proposing the OMEGA spectrometer. Conceived as an electronic bubble chamber, OMEGA offered a large magnetic volume, initially filled with spark chambers and later with wire chambers, operating with a variety of triggers and incident beams in the West Area experimental hall. The group included physicists Aldo Michelini, Emanuele Quercigh and Werner Beusch, with technical coordinator Otto Gildemeister and Mario Morpurgo – who designed the superconducting magnet. OMEGA recorded its first collisions in 1972 and ran until the end of 1996. Bernard contributed to many of the experiments performed at the spectrometer, first using beams from the PS and later from the SPS.


CERN

Bernard French, seen here in 1976 with Lothar Hoffmann (left) and Alan Astbury (right), led numerous experiments at CERN.

Bernard was known by his colleagues for his ability to do back-of-the-envelope calculations that were often better than the final calculations, as well as his remarkable pattern-recognition ability – he always claimed that if he couldn't resolve the tracks by eye, no computer was ever going to do it! He was also known for his large collection of old cars and his lovely house on the lake, complete with a small jetty. Bernard would often be seen in the CERN canteen, even in his 90s, and his insatiable enthusiasm for physics continued until the end.

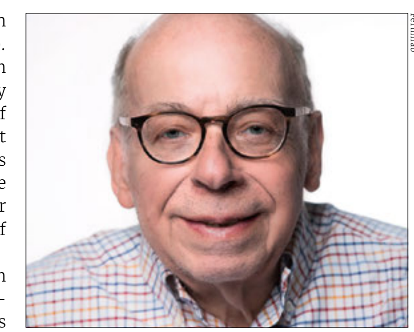
His former colleagues and friends.

Marvin Marshak 1946–2026

A pioneer of underground physics

We were sad to hear of the passing of Marvin Marshak, who died on 2 April at the age of 80. Marshak was born in Buffalo, New York, on 11 March 1946. He attended Cornell University as an undergraduate and the University of Michigan for his PhD in physics, completing it in 1970. He then started a long and illustrious career at the University of Minnesota, where he served as chair of the physics department for a decade and as provost and vice-president of the university for a year.

Motivated by grand unified theories, which predicted that protons could decay with measurable rates, Marshak led one of several projects that took particle physicists away from accelerator laboratories to underground facilities – where rare processes could be studied with substantially lower cosmic-ray backgrounds. He negotiated the use of the Soudan mine in Northern Minnesota, which was being oper-


Fermilab

Marvin Marshak is remembered for his energy, charm and perpetual smile.

ated as a tourist attraction. Some 600 m underground, it became, from 1981, the site of the Soudan 1 and 2 experiments and later the MINOS long-baseline neutrino experiment, using the NuMI beam from Fermilab. Finally, the NOvA experiment, using the same beam, was located nearby on the surface.

Marshak's research at the Soudan mine began by putting together a collaboration of US and UK scientists, motivated by the search for nucleon decay and the opportunity to build unique detectors in the search for new physics. While the search for nucleon decay proved unavailing, the atmospheric neutrino background serendipitously became a treasure trove of evidence for neutrino oscillations, using the differing path lengths of neutrinos from opposite sides of the Earth, created when cosmic rays strike the atmosphere. It was Soudan 2 that first confirmed the discovery of neutrino oscillations by Super-Kamiokande in 1998. The mine then became the ideal location for far detectors in the long-baseline neutrino ▷

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oscillation experiments MINOS and NOvA, to which Marshak made key contributions. He also played a leading role in using underground detectors in novel ways to search for the astrophysical sources of cosmic rays. Recently, he played an important role in helping to organise the international DUNE collaboration by serving several years as the chair of the institutional board for the precursor Long-Baseline Neutrino Experiment.

Marshak had an amazingly varied skill set that helped particle physics overcome increasingly complex challenges. He had a keen intuition for worthwhile problems and for which issues to tackle. He became an expert in the challenges of underground construction engineering. He could deal with administrators and politicians at the state and federal level, successfully obtaining money for ambitious projects, and he managed the installation of the 14,000 tonne NOvA Far Detector.

However, he will be remembered best for his one-on-one interactions with students and colleagues. When he gave a seminar, his enthusiasm was infectious. He knew when to provide direction for his graduate students and when to stand back and let them struggle to find their own limitations. He could motivate undergraduates in a classroom and then find them a role in an exciting experiment. He would always take his share of the unsensational work that is required on any project, such as scanning the not-too-frequent neutrino interactions and categorising them. But what is remembered most of all by his friends and colleagues is his indomitable energy, his charm and the perpetual smile on his face.

Maury Goodman *Argonne National Laboratory.*

MANNQUE RHO 1936–2026

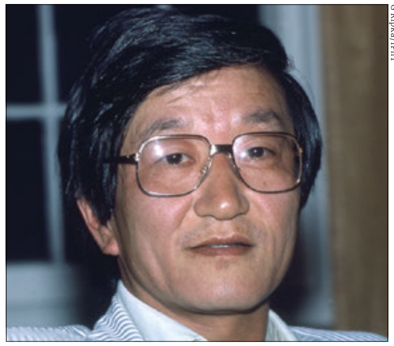
A renowned theorist of the nuclear medium

Mannque Rho, a world-renowned theoretical nuclear physicist from the Republic of Korea and distinguished member of the Institut de Physique Théorique (IPhT) at CEA Saclay, passed away in Paris on 19 March 2026, at the age of 89.

Born on 14 December 1936 in Hamyang, Gyeongnam Province, Rho was the eldest of eight children. He initially studied political science at Seoul National University and later moved to the US, completing his undergraduate education at Clark University with a Bachelor of Arts in chemistry in 1960. He obtained his PhD from the University of California, Berkeley, on 21 October 1963.

At Berkeley, Rho met Vincent Gillet, who invited him to take up a postdoctoral position at the Service de Physique Théorique (SPhT), the predecessor of IPhT at CEA Saclay. He moved to France in 1964 on a Joliot-Curie fellowship, to work at the Laboratoire Joliot-Curie in Orsay and at the SPhT. There, he joined the theoretical nuclear-physics team led by Claude Bloch, becoming a permanent member on 1 June 1965. This institute remained his intellectual home throughout his career.

Rho's work spanned chiral symmetry in nuclear media, effective field theories and topological approaches to strongly interacting matter. In the early 1970s, he initiated a long-lasting collaboration with Gerald E Brown at Stony Brook University. Together, in 1979, they developed the "little bag" model, providing a conceptual bridge between quark degrees of freedom and the pion cloud surrounding nucleons.



G Ripka/IPhT

Mannque Rho was a central figure in clarifying the role of chiral symmetry in nucleons, nuclei and dense nuclear matter.

He is best-known for the Brown–Rho scaling (1991), which describes the in-medium modification of hadron masses in hot and/or dense matter. This influential result has shaped modern approaches to dense nuclear matter, with important implications for heavy-ion collisions and neutron-star physics. Rho also made major contributions to the construction of effective field theories rooted in quantum chromodynamics, and conducted pioneering work on skyrmion matter and hidden local symmetries.

Over his career, Rho published more than 200 scientific articles, which have received over 11,000 citations. He authored the *Chiral Nuclear Dynamics* trilogy (with Maciej A Nowak, Ismail Zahed and Yong-Liang Ma) and edited several volumes of collected works.

Rho held visiting positions at leading institutions worldwide, including CERN, Stony Brook University, Seoul National University and the University of Tokyo – as a JSPS professor. He served as professor at the Korea Institute for Advanced Study and chair professor at Hanyang University.

His scientific achievements were recognised through numerous honours: the Paul Langevin Prize (1985), the Gay-Lussac–Humboldt Prize (1995), the Korean National Academy of Sciences Award (1999) and the Ho-Am Prize (2002). He received the Order of Civil Merit in 1997, an honorary Doctor of Science degree from Clark University in 2003 and the KBS Overseas Korean Award in 2004. He was a member of the Korean Academy of Science and Technology.

Remarkably, Rho remained scientifically active into his final years, working on super-dense baryonic matter as recently as November 2025. The IPhT deeply regrets his loss, but his legacy will endure in theoretical nuclear physics. We extend sincere condolences to his family, colleagues and students.

His colleagues at IPhT.

MICK STORR 1949–2026

The face of CERN's teacher programmes

It was with profound sadness that we learned about the passing of Mick Storr on 7 June 2026, in Geneva. A deeply respected member of the CERN family and an extraordinary educator, he touched the lives of generations of teachers worldwide.

Mick was born in Farsley, a village in the Leeds district of West Yorkshire, England, on 11 February 1949. After completing his PhD at the University of Birmingham in 1975, Mick immediately came to CERN as a user affiliated with Lancaster University, working in the Photon Beam Collaboration at the OMEGA Spectrometer. He stayed on as a fellow and then a staff member in the Data Handling Division, joining the emulator effort in its early days. There, he developed key translator, trigger, testing and interface software, work that fed the 168E emulators used in UA1 during the years of the discovery of the W and Z bosons, and later the CERN–SLAC collaboration on the 3081E emulators.

From 1989 he joined the Electronics and Computing for Physics Division, where he ▷

pioneered the use of object-oriented programming in high-energy physics and supported the World Wide Web development team. As divisional training officer, he began the move to the second part of his CERN career.

For nearly a decade from 1997, Mick oversaw the technical training programme, keeping it up to date with courses that met the evolving needs of the CERN community. With Michelangelo Mangano, he co-founded and ran the CERN High School Teachers (HST) programme. Mick had a unique gift for helping teachers overcome any sense of intimidation and recognise their essential role in CERN's mission, reminding them that they lay the foundations for the scientists and engineers of tomorrow. Through his vision and dedication, the CERN teacher programmes grew into a worldwide community built on curiosity, friendship and international collaboration.

His retirement from CERN in 2013 opened only a new chapter. Returning to his alma mater as an honorary senior research fellow, he continued to contribute to science education as an active CERN user.

Many learned a great deal from Mick – a mentor, guide and constant source of encouragement. Much of what makes CERN's teacher programmes so special today reflects the principles he championed, his values and his unwavering belief in the importance of teachers and education. Many will remember his lectures and storytelling, his songs and barbecues, the countless moments in which he made every

A Pantelia/CERN

Mick Storr was a mentor to teachers around the world.

participant feel welcomed and valued. Mick had a remarkable ability to connect with people from every country and background, and always with an unmistakable smile.

One of his best-known sayings was: "At CERN, we never say goodbye, we only say au revoir." Those words are hard to hear today, yet they capture the extraordinary legacy he leaves through the many teachers whose lives he touched, inspired, encouraged and welcomed at CERN over so many years.

Beyond his professional achievements, Mick had a wide range of interests. A squash player invited to the Swiss national team, a lifelong footballer and later a coach, he was also active in the Geneva Amateur Operatic Society, rising from the back row of the chorus to leading roles. In winter, he skied most weekends with the CERN ski club, and even took up snowboarding in his fifties. He is survived by his daughters Sophie and Scarlett and his grandchildren Isabelle and Max, who were a source of great pride and joy to him.

Merci et au revoir, Mick, and thank you for 51 remarkable years at CERN.

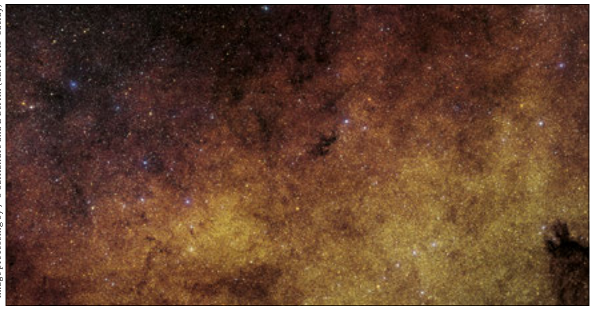
His friends and colleagues.

BACKGROUND

Notes and observations from the high-energy physics community

Close to the heart

ESA/Euclid/Euclid Consortium/NASA, CFHT, image processing by J-C Cuillandre and E Bertin (CEA Paris-Saclay)



Galactic core *Euclid's mosaic of the Milky Way's central bulge.*

The European Space Agency's Euclid mission released the largest and most detailed visible-light view of the Milky Way's centre on 24 June (pictured). Captured on 23 March 2025 in about 26 hours, the mosaic spans nine pointings, each larger than the full Moon, and resolves more than 60 million stars. Built to map dark matter and dark energy across distant galaxies, Euclid turned briefly to the galactic bulge, the prime ground for microlensing searches for exoplanets.

70 Years since Frederick Reines and Clyde Cowan discovered the electron antineutrino

Media corner

"My job in the next 2 years is to take the project forward and get it to the point where we can bring it to council for a hopefully positive decision."

Mark Thomson (CERN Director-General), on the next steps after the updated European Strategy for Particle Physics named the FCC-ee its preferred flagship (*Science*, 22 May).

"The previous and well accepted measurements were, in fact, fine and our current understanding of the fate of the universe remains robust."

Phil Wiseman (University of Southampton), on rebutting the 2025 claim that cosmic expansion had begun to slow (*Royal Astronomical Society*, 11 June).

"We can now compare the properties of matter and antimatter with ever greater sensitivity, putting the deepest principles of physics to the test."

Germano Bonomi (INFN Pavia and University of Brescia), on ALPHA's hundredfold-improved measurement of antihydrogen's hyperfine structure (*ANSA*, 28 May).

"Without magic, things are a little too simple."

John Preskill (Caltech), on the quantum property called "magic" (*Quanta Magazine*, 3 June).

"We started to have a high-quality physics data almost at the first shot."

Yifang Wang (IHEP Beijing and JUNO spokesperson), on JUNO's first oscillation results (*Science*, 10 June).

From the archive: July/August 1986

After LEP?

CERN X821.4.86 by G Cachin

Light at the end of the tunnel for LEP, with finishing work well underway.

Work for the LEP collider at CERN continues to drive ahead with the aim of achieving first colliding beams towards the end of 1988. However, LEP is far from being the last word in CERN's long term plans. A clue was in the LEP Design Study '... by the adoption of a beam height of only 80 cm, there is enough room left (in the tunnel) for the installation of a second machine at a later stage...'.

The idea emerged for a ring of superconducting magnets, installed above the LEP ring, to collide protons together (or protons with antiprotons) at as high an energy as possible. Using 10 T dipole bending magnets, collision energies of 17 TeV (8.5 TeV per beam) could be achieved. A 'two-in-one' aperture solution for the superconducting magnets is recommended for economy and compactness.

The superstring syndrome

A recent epidemic among the elementary particle theorists is the 'superstring syndrome', which causes Kaluza–Klein symptoms. The pathogen is said to be much smaller than any virus known and is ring- or string-shaped. Young and cheerful people are observed to be more susceptible to this disease.

The disease was also epidemic more than ten years ago, but the damage was minor, since it was not associated with the Kaluza–Klein symptoms. Eventually Yang–Mills was found to be an excellent remedy. However, the current wave is much more severe [and] Yang–Mills can cause undesirable side-effects rather than cure.

Adding further to the worries is the fact that the brain may be affected. Victims believe that 'anomalies' are at the root of everything. In contrast to healthy people, who regard normality as such and observe anomalies as deviations from the norm, superstring syndrome cases prefer anomalies and observe normality as an aberration.

● Text adapted from *CERN Courier* July/August 1986 p5 and p24.

Compiler's note

LEP was indeed followed by a proton–antiproton collider using superconducting magnets in the same tunnel – the LHC. In the end, the decision was taken to remove LEP from the tunnel to allow room for the LHC. And rather than the ambitious beam energy of 8.5 TeV, it runs at 6.8 TeV per beam. However, this has proved enough to reveal the Higgs boson, as well as to make other fascinating discoveries. As for the superstring syndrome, the virus still seems to be around, affecting both young and old, if not at the level of an epidemic!

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