WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the November/December 2026 issue of *CERN Courier*.

The universe is thought to have spent its first microseconds as a plasma of quarks and gluons. CERN announced evidence of that state in 2000, the same year the Relativistic Heavy Ion Collider (RHIC) began colliding gold ions at Brookhaven National Laboratory. By 2005, RHIC's experiments had found the plasma to be a near-perfect liquid with almost no internal friction. The machine delivered its last collisions in February, after a quarter century of discovery (p25).

While CERN transforms the LHC and its experiments to collect several times more data (p47), medicine seeks to make its accelerators smaller, more reliable and easier to maintain. Research at CERN and beyond aims to provide them, and so to narrow the gap in access to modern radiotherapy between higher- and lower-income countries (p37).

This edition of *CERN Courier* also turns to arXiv, which has left Cornell University to become an independent non-profit. Meanwhile, submissions are surging, a growing number of them written or assisted by artificial intelligence (p33).

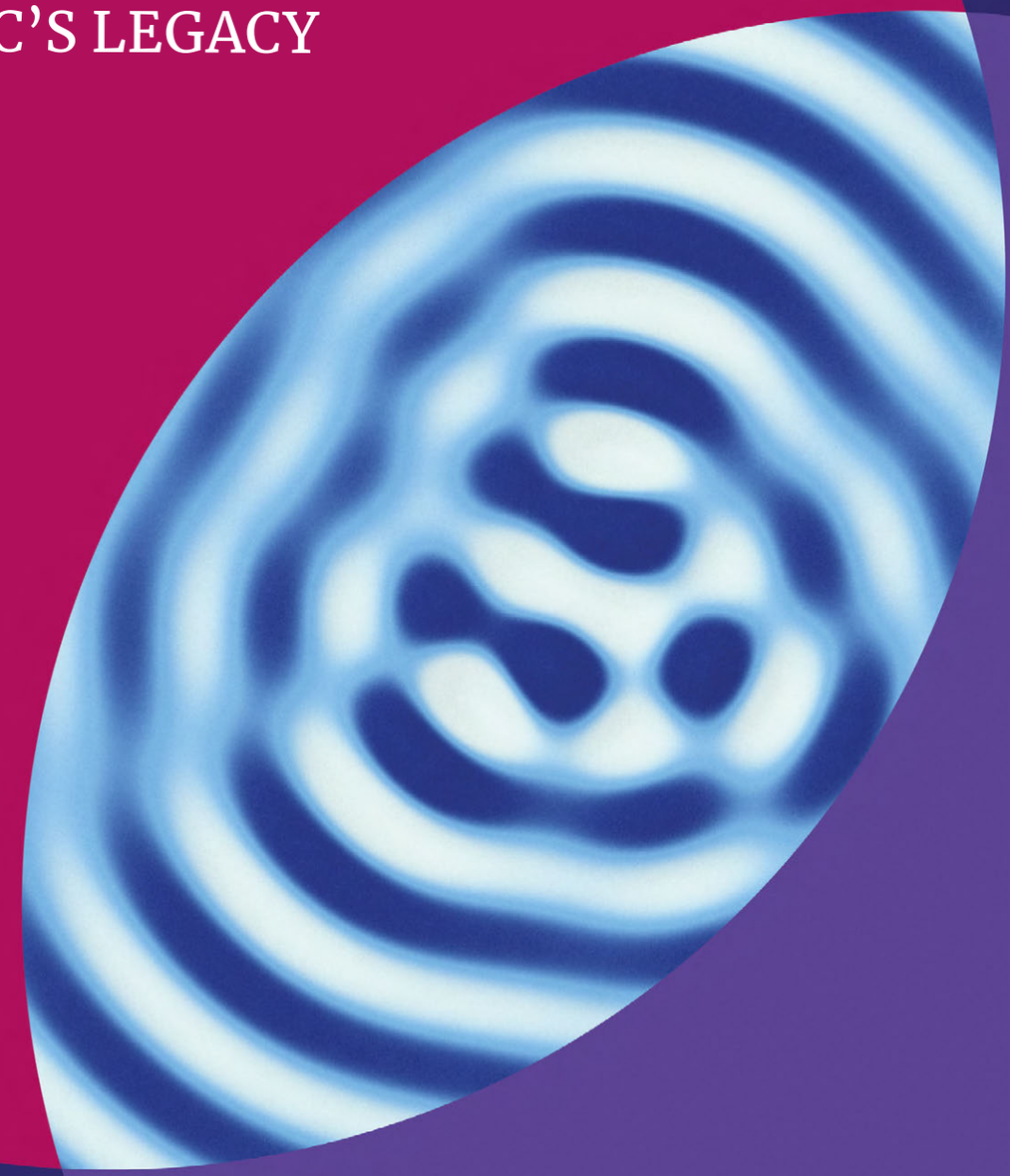
The 2026 Nobel Prize in Physics went to Francis Halzen (p8), for showing – in his own words – that neutrino astronomy "exists". Around 1990, he and colleagues proposed freezing photomultipliers into the Antarctic ice. The idea grew into IceCube, where a recent search found no sign of extra dimensions in neutrino oscillations. The notion of a fifth dimension curled up too small to see goes back to 1926, when Oskar Klein closed it into a circle only a few hundred Planck lengths around (p42).

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EDITOR: DAVIDE DE BIASIO

CERN COURIER
November/December 2026 cerncourier.com Reporting on international high-energy physics

AT A GLANCE
RHIC'S LEGACY



Accelerators against cancer • A century of compact dimensions • arXiv looks forward

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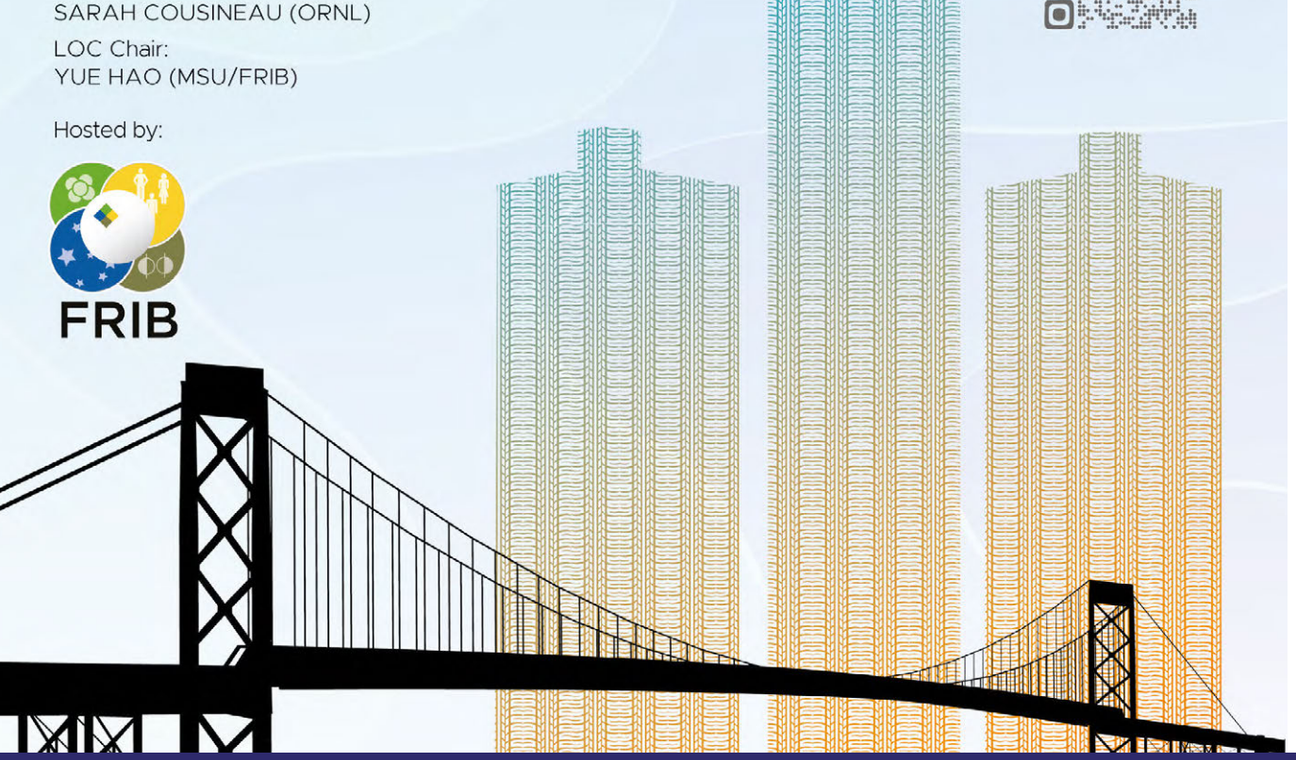
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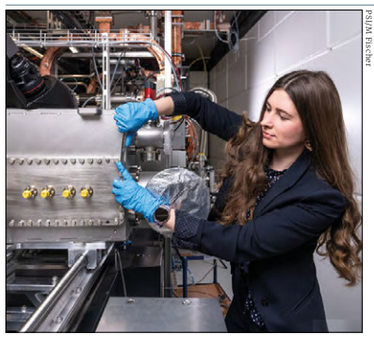
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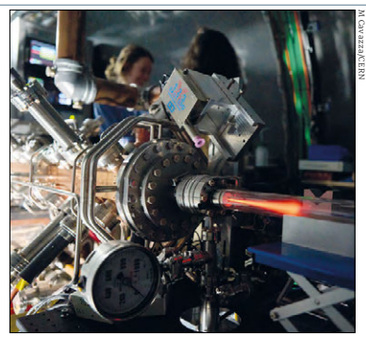
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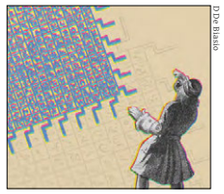
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A new way to
design your quantum vacuum system
for cold/neutral atom trapping
and for ion trapping.



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Discover more

FROM THE EDITOR

In the beginning, a fluid

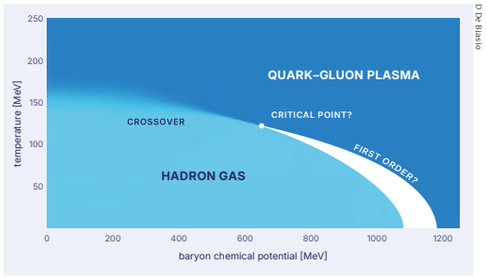


Davide De Biasio
Editor

The universe is thought to have spent its first microseconds as a plasma of quarks and gluons. Some 13.8 billion years later, experiments at CERN's Super Proton Synchrotron found evidence of that state by firing lead ions – with a total energy of 33 TeV – on fixed targets. The announcement came in February 2000. Later that year, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in the US collided its first gold ions. By 2005, RHIC's experiments had found the quark–gluon plasma to be a near-perfect liquid with almost no internal friction. The machine worked through 12 pairs of species, from polarised protons to uranium, at 18 energies, delivering its last collisions in February. Its tunnel, one of its two rings and its injectors will now pass to the Electron–Ion Collider. James Dunlop and Wolfram Fischer recount a quarter century of discovery at the first collider specifically built for heavy ions (p25).

The LHC joined the study of the quark–gluon plasma in 2010, and will return to it after Long Shutdown 3 (LS3). Jean-Philippe Tock, head of the LS3 Coordination Team, explains how the next four years of work across the laboratory were planned, in places down to the half-day (p47). While CERN transforms the LHC and its experiments to collect several times more data, medicine seeks to make its accelerators smaller, more reliable and easier to maintain. Maurizio Vretenar describes the research at CERN and beyond that aims to provide them, and so to narrow the gap in access to modern radiotherapy between higher- and lower-income countries (p37).

This issue also turns to arXiv. Born in 1991 to circulate preprints among string theorists, the platform has now left Cornell University to become an independent non-profit organisation. Meanwhile, submissions are surging, a growing number of them written or assisted by artificial intelligence. Scientific director Steinn Sigurðsson and board member Greg Morrisett told the *Courier* what independence will bring, and how arXiv intends to keep pace (p33).



Borderlands *Part of the expected phase diagram of nuclear matter, which RHIC scanned in search of a critical point.*

Through the ice

This year's Nobel Prize in Physics went to Francis Halzen (p8), for showing – in his own words – that neutrino astronomy "exists". Around 1990, he and colleagues proposed freezing photomultipliers into the Antarctic ice, betting it would be clear enough to see the faint light from neutrino interactions. The idea grew into IceCube, which reported the first high-energy astrophysical neutrinos in 2013.

To reach the detector, neutrinos can cross thousands of kilometres of matter – enough, perhaps, for small new-physics effects to build up along the way. A recent IceCube search looked for the imprint of extra dimensions on their oscillations and found none, setting limits that join those of ATLAS, CMS and other experiments. The idea of a fifth dimension curled up too small to see goes back to 1926, when Oskar Klein closed it into a circle only a few hundred Planck lengths around. Jeroen van Dongen and Robert van Leeuwen trace its fading and revival over the century since (p42).

Elsewhere in this issue, PSI captures positrons for the FCC (p7), LZ records an event where almost none was expected (p10), Tetiana Hryn'ova recounts more than a century of Ukrainian physics (p46), and much more.

This year's Nobel Prize in Physics went to neutrino astronomy

Reporting on international high-energy physics

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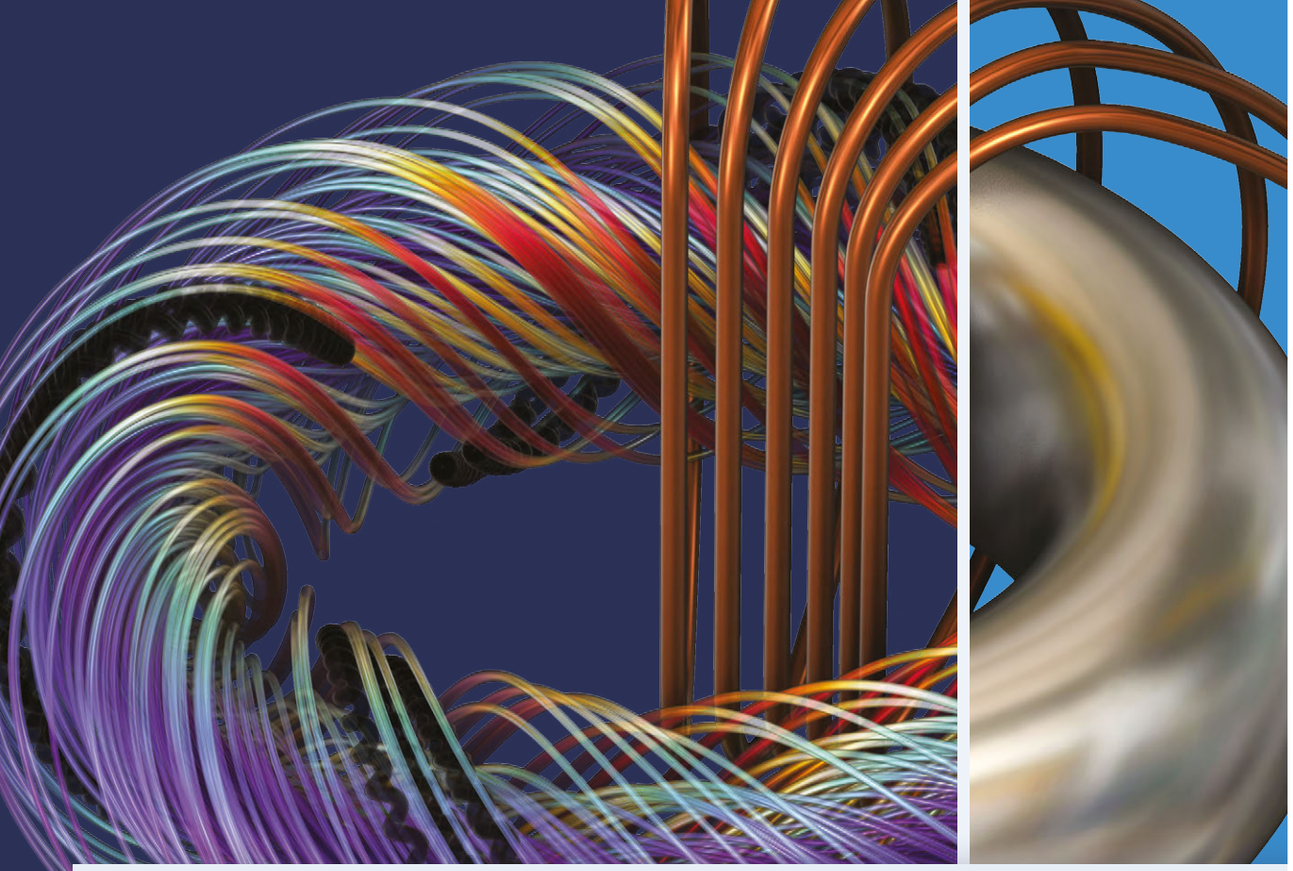
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NEWS ANALYSIS

ACCELERATORS

PSI captures positrons for the FCC

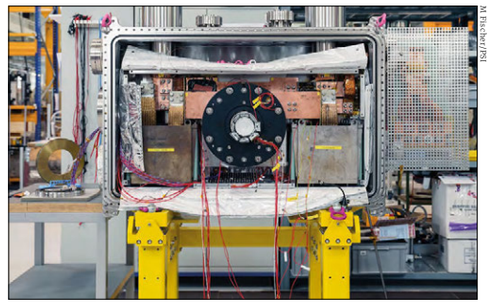
In July, an experiment at the Paul Scherrer Institute (PSI) in Switzerland produced, captured and transported positrons using a system developed for CERN's proposed Future Circular Collider (FCC). The results from the PSI Positron Production (P^3) experiment at SwissFEL, the laboratory's X-ray free-electron laser user facility, show that the key elements of the FCC positron-source concept can operate together.

"These are the first positrons for the FCC project, so it's an important milestone," says Paolo Craievich from the PSI Center for Accelerator Science and Engineering, who is co-leader of the P^3 project.

The electron–positron FCC (FCC-ee), recommended by the CERN Council as the preferred option for CERN's next flagship project (*CERN Courier* July/August 2026 p7), would collide electrons and positrons in a 90.7 km ring at the Z pole, the WW threshold, the ZH production peak and the top-quark pair threshold. One of the major technical challenges for the FCC is its positron source. While positrons can be produced easily by firing electrons into a dense target, capturing them in large numbers and efficiently channelling them into a tight beam is much more difficult. "The positrons fly out at large angles, and typically many are lost," says Craievich. "With our new technology, we should be able to significantly increase the positron yield."

Capture magnets

At the Z pole, each of the two collider rings would hold 11,200 bunches, kept full by continuous top-up injection from a booster in the tunnel. The injector would supply the booster with pulses of four bunches at 100 Hz, with up to 5 nC per bunch, through a damping ring that reduces the transverse emittance of the positron beam by four orders of magnitude and a high-energy linac that takes it to 20 GeV. The yield of the positron source, the number of positrons captured for each electron sent to the target, sets the charge and power of the drive beam and the heat load on the target. The capture magnets of existing sources are pulsed normal-conducting magnets known as flux concentrators.



M. Fischer/PSI

Positron capture *The high-temperature superconducting solenoid of the P^3 test source at SwissFEL, photographed before its completion and commissioning in 2025. Electrons strike a tungsten target inside the magnet, which channels the emerging positrons into radiofrequency structures.*

In the beam

Between May and August this year, proponents of the IDEA (Innovative Detector for e^+e^- Accelerator) detector concept for the FCC tested several prototypes of detector components using secondary beams from the Super Proton Synchrotron and the Proton Synchrotron.

Tracking the position of muons in the outermost layers of the FCC-ee detectors is essential, and one beam test explored a prototype based on micro-resistive WELL (micro-RWELL) technology, which offers a spatial resolution as fine as 50 µm. In parallel, a team working on the IDEA drift chamber, which would track and identify particles in the central part of the detector, analysed the performance of a technique called cluster counting that counts the primary ionisation clusters along a track in a helium-based gas mixture to separate particle species.

The FCC-ee physics programme also requires the energy of particle jets to be determined with a precision beyond that of conventional hadron calorimeters. This is driving the development of dual-readout calorimeters, which read out scintillation and Cherenkov light separately to measure the electromagnetic fraction of each hadronic shower. The beam tests at CERN offered the first opportunity to evaluate the full calorimeter concept under study for IDEA, a fibre prototype with about 10,000 silicon photomultipliers and a crystal electromagnetic section, both of which showed promise for future large-scale developments.

In the P^3 setup, electrons from the SwissFEL linac strike a tungsten-target system designed, produced and assembled by CERN, generating a shower of positrons travelling in many different directions. A superconducting magnet surrounding the target then captures as many of them as possible. To meet the stringent technical requirements of the FCC positron source, PSI researchers developed a compact solenoid made of high-temperature superconductors, which reaches a field up to 15 T.

The magnet's five coils are wound from rare-earth barium copper oxide (REBCO) tape. The turns are not insulated from each other, so that if a spot in the tape loses its superconductivity, the current can cross to the neighbouring turn and flow around it, instead of heating the spot further and quenching the coil. The system is cooled to 15 K by two cryocoolers and has a warm bore 72 mm wide, in which the target sits 3 cm downstream of the centre, at 12.7 T. From there, the field decreases along the beam direction, converting the large angles of the positrons into a larger beam size that fits the aperture of the accelerating structures. Additional components guide, separate and measure the positrons. Radiofrequency cavities accelerate and bunch them so that they can be transported and, eventually, injected into a collider. The two cavities are S-band standing-wave structures with 40 mm irises, inside normal-conducting solenoids of 0.45 T. Simulations give a yield of about four positrons per electron, and up to seven with superconducting solenoids of 1.5 T in their place.

State of the art

The drive beam of 200 pC bunches at 6 GeV reached a screen in front of the target on 13 May. The solenoid was switched on at the end of June, the cavities were conditioned, and the first positrons were recorded in July on the broadband pickups, scintillating screens and Faraday cups along the line. "Each piece of technology is state of the art," says Craievich. "For example, it would never have been possible in the past to reach such a high magnetic field without the new high-temperature superconducting solenoids."

"My congratulations go to the P^3 team and the many colleagues across PSI who made this achievement possible, ▷

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together with their collaborators from CERN, IJCLab–Université Paris–Saclay and KEK," says Michael Benedikt, FCC project leader at CERN. "This work also reflects the vital support of the Swiss CHART programme in helping to build the expertise and advanced technologies needed to turn the FCC vision into a technically credible project."

The next step for the P^3 team is to increase the beam intensity and optimise the system, with the aim of scaling up positron production to the levels required for the FCC. P^3 runs with 200 pC bunches at 1 Hz, while the FCC-ee injector would send bunches of up to 5 nC to its target, four per pulse at 100 Hz. Validation of the positron-source yield is one of the deliverables of the FCC's reference design phase, during which many other parts of the collider and its experiments are being developed. Six concepts for the FCC-ee detectors are being studied at institutes across the world, and this year prototypes for one of them were tested with beam at CERN (see "In the beam" panel).

Each piece of technology is state of the art

Beyond the FCC, the high-temperature superconducting magnet technology developed for P^3 is also being investigated for applications in proton therapy and fusion research.

Further reading

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J Kosse *et al.* 2025 *Supercond. Sci. Technol.* **38** 035008.
FCC Collab. 2025 arXiv:2505.00274.
IDEA Study Group 2025 arXiv:2502.21223.

NEUTRINO ASTRONOMY

Francis Halzen wins the Nobel Prize

On 6 October, Francis Halzen of the University of Wisconsin–Madison was awarded the 2026 Nobel Prize in Physics "for decisive contributions to the IceCube Neutrino Observatory and the discovery of high-energy neutrinos of astrophysical origin". The observatory, a cubic kilometre of instrumented ice beneath the South Pole, reported the first evidence for high-energy astrophysical neutrinos in 2013. It has since traced them to a flaring blazar, to the active galaxy NGC 1068 and to the plane of the Milky Way.

"The prize was a fantastic opportunity to advertise that this was a large project, and that it only happened because all the milestones we had to reach were overcome by some brilliant people who solved problems along the way," says Halzen. He and colleagues at Madison – later joined by physicists at Berkeley – had proposed, around 1990, to freeze photomultipliers into the Antarctic ice sheet to catch the Cherenkov light from neutrino interactions. At the time, whether the ice was clear enough for this to work was unknown. "The real miracle, which nobody anticipated, was an absorption length of 100 metres and more for Cherenkov light. That's why we are sitting here."

The first South Pole array, the Antarctic Muon And Neutrino Detector Array (AMANDA), was deployed in the 1993–1994 Antarctic summer at depths between 800 and 1000 m, where air bubbles scattered the light too strongly for tracks to be reconstructed. The answer was to go deeper, betting that the bubbles would give way to clear ice, and AMANDA's later strings hung mostly between 1500 and 2000 m. Between 2005 and 2010, a hot-water drill melted 86 holes into the ice, and a string of 60 optical modules was lowered into each, to hang between 1450 and 2450 m. There, IceCube records about 275 neutrinos a day from the Earth's atmosphere. Two events of about 1 PeV, reported in 2013, stood out from that background and gave the first indication of an astrophysical flux. Nicknamed Bert and Ernie, they were joined by 26 more in the data from 2010 to 2012, and the sample ruled out a purely atmospheric origin at 4σ. A third year of data raised the significance to 5.7σ in 2014.



Ilya Bodo, IceCube/NSF

Ice station *At the South Pole, the IceCube Laboratory collects signals from more than 5000 optical sensors frozen into the ice.*

Work on the calibration of the ice and on the reconstruction software then helped to bring sources into view. One of them, the active galaxy NGC 1068, first emerged in 2020 and reached 4.2σ in 2022, with far fewer TeV gamma rays than neutrinos (*CERN Courier* January/February 2023 p10). The deficit points to the absorption of gamma rays in the dense region at the core of the galaxy. "The most exciting future lies in the synergy between observatories and multi-messenger astrophysics," says Teresa Montaruli of the University of Geneva, member of the IceCube collaboration, "combining electromagnetic radiation, neutrinos and gravitational waves to explore the most extreme phenomena in the universe." Beyond astronomy, atmospheric neutrinos lend themselves to other precision studies. "IceCube has measured neutrino cross sections through their absorption in the Earth, complementing measurements by experiments such as FASER," says Montaruli.

The collaboration completed an upgrade of the detector in the 2025–2026 Antarctic summer. Six new strings, more densely instrumented than the original ones, went into its centre to calibrate the ice and to test the optical modules designed for a proposed extension, IceCube-Gen2. The project would take the observatory to about eight times its instrumented volume and add a radio array for the highest energies.

"This Nobel Prize recognises Francis Halzen's decades of vision and persistence in making high-energy neutrino astronomy a reality," says Erin O'Sullivan of Uppsala University, spokesperson of the IceCube collaboration. "We are proud to share this moment with Francis, and excited about what lies ahead for neutrino astronomy, particularly with IceCube-Gen2."

HIGGS PHYSICS

Z bosons entangle in Higgs decays

The ATLAS and CMS collaborations have found evidence that the two Z bosons from a Higgs-boson decay are entangled. Using data from the second and third runs of the LHC, ATLAS rejects the hypothesis of a non-entangled pair at 4.7σ, and CMS excludes the only configuration in which the pair would not be entangled at more than 6σ. Both results rest on assumptions about the CP properties of the Higgs boson, in line with what the two collaborations have measured since its discovery.

The experiments had already observed quantum entanglement between top quarks and antiquarks produced in pairs. Since the top quark has spin ½, a measurement of its spin projection along any given direction has only two possible outcomes, +½ or −½. The Z boson, by contrast, is a massive particle with spin 1, so the corresponding measurement can give +1, 0 or −1. When a Higgs boson, which has spin zero, decays into two Z bosons – one of them off shell – their spin projections along the decay axis must cancel out, and remain correlated whichever common direction they are measured along.

Quantum tomography

Neither spin projection can be measured directly. Z bosons decay almost immediately, occasionally into pairs of electrons or muons that can reach the ATLAS and CMS detectors. Owing to the chirality of the weak interaction, which couples the Z boson differently to left-handed and right-handed particles, information on their spin passes to the leptons, and the directions of the four of them carry the spin state of the pair. Over many decays, their angular distributions allow the spin-density matrix of the two Z bosons to be reconstructed – a procedure known as quantum tomography.

CMS measured the matrix in 138 fb^{-1} of data at 13 TeV and 62 fb^{-1} at 13.6 TeV, including the degree of longitudinal polarisation of the two Z bosons. With a significance above 6σ, the data rule out purely longitudinal or purely transverse Z-boson configurations. "Assuming CP symmetry holds, that means the Z-boson pair is entangled. We also tested for CP violation in the decay and found the results to be consistent with CP conservation, justifying our assumption," says Zhiyuan Huang of Johns Hopkins University. The main challenge, she explains, "was to extract the quantum information from the decay without letting it be distorted by potential differences in the Z-boson masses or by detector effects." The same polarisation analysis can be applied to Z-boson pairs from other processes. "This study establishes a systematic framework for investigating spin correlations and quantum entanglement through polarisation measurements and moment methods," says Leyun Gao of Peking University. "For example, future studies could investigate quantum entanglement in Standard Model (SM) ZZ production and vector-boson scattering (VBS) processes involving two Z bosons."



D Dominguez/CERN

Never let me go *An artistic impression of quantum entanglement between two Z bosons.*

Curiosity and collaboration

ATLAS combined its full Run 2 data set with 164 fb^{-1} of Run 3 data at 13.6 TeV. "There were only a couple of thousand events of this type produced at ATLAS during Run 2 and Run 3, and those are reduced further by acceptance and efficiency selections, leaving fewer than 500 Higgs-signal events for the ATLAS analysis," says Alan Barr of the University of Oxford. Too few, that is, to determine all 80 parameters of the spin-density matrix. Assuming the Higgs boson to be a CP-even scalar, however, leaves the pair only one non-entangled state, and ATLAS tested the full four-lepton angular distribution against it and against the SM prediction. "The data were found to be consistent with the entangled hypothesis, the one predicted in the SM, but inconsistent, at the 4.7σ level, with the only non-entangled state," says Barr. "In early 2023, we began exploring this idea within the ATLAS Higgs physics group, bringing together a small team of experimentalists and theorists," remarks Theodota Lagouri of Yale University. "It is truly rewarding to see how our initial scientific curiosity, combined with the enthusiasm, close collaboration and dedication of young researchers, evolved into an exciting measurement of quantum entanglement in Higgs-boson decays."

The measurement is but one instance of a wider programme

A question of qutrits

Both analyses describe the decay at tree level, with the two Z bosons as a pair of three-state quantum systems, or qutrits. Since the Higgs boson is lighter than two Z bosons combined, however, at least one of the pair is off shell. "Once we go beyond the tree-level description of the process, complications arise that can make both the interpretation in terms of two qutrits and the tomography more subtle," says Fabio Maltoni of the University of Bologna and UCLouvain. In a paper posted in September, he and his colleagues trace the difficulty to the interference of photon- and Z-mediated contributions in the off-shell lepton pair, and show that a lower bound on the entanglement survives beyond leading order. "We argue that we reached an understanding of why these problems arise and provided a safe and robust definition of entanglement which, for practical purposes, is very close to what has been used by CMS and ATLAS," he says.

For Maltoni, the measurement is but one instance of a wider programme. "In theories beyond the SM, these quantum properties can be modified," he says. "Quantum observables may therefore provide additional sensitive tests for new physics by probing aspects of the dynamics that are complementary to more traditional observables. One example that is now being investigated is decoherence: the loss or degradation of quantum coherence and entanglement through interactions with additional degrees of freedom or with an effective environment."

Further reading

ATLAS Collab. 2026 *Phys. Rev. Lett.* **137** 111804.
CMS Collab. 2025 CMS-PAS-HIG-25-011.
J A Aguilar-Saavedra *et al.* 2023 *Phys. Rev. D* **107** 016012.
M Del Gratta *et al.* 2026 arXiv:2609.25217.

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UNDERGROUND PHYSICS

LZ records an intriguing event

On 16 June 2023, the LUX–ZEPLIN (LZ) experiment, 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota, recorded an event consistent with a nuclear recoil of about 250 keV, in a region of its data where known backgrounds predict almost none. The observation, reported on 1 September, emerged from 220 live days of data examined up to energies above those targeted by conventional searches, with a global significance against the background-only hypothesis of 2.6σ.

LZ uses seven tonnes of ultrapure liquid xenon to look for dark matter in the form of weakly interacting massive particles (WIMPs) from the galactic halo. When a particle scatters off a xenon nucleus, the recoil produces scintillation light and ionisation electrons. An electric field then drifts the electrons into the gas above the liquid, where they generate a second light signal through electroluminescence. The ratio of the two signals distinguishes a genuine recoil off a nucleus from a scatter off an atomic electron, which is what most backgrounds produce.

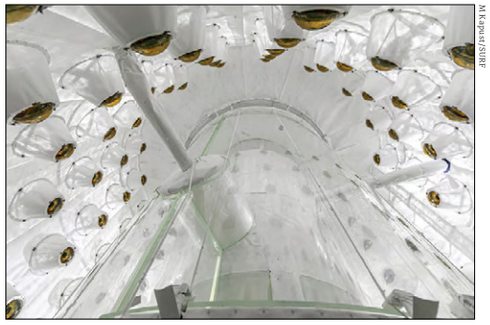
Conventional searches concentrate on recoils below about 100 keV, where a WIMP would scatter coherently off the nucleus as a whole. LZ's large target mass allows it to investigate a broader range of possible interactions, including weaker couplings that would grow with the momentum transfer and so become more prominent at higher recoil energies. The recent study explored energies up to 270 keV.

"We found a single event remaining in the analysis, at around 250 keV," says Richard Gaitskell, a physicist at Brown University and spokesperson for the LZ collaboration. "It would be consistent with dark matter interacting through a slightly more complicated coupling than usual, one that favours large momentum transfers. I should add that with a single event, a dark-matter interpretation is only one possibility."

The collaboration considered numerous potential sources of background, including accidental coincidences between scintillation light and single ionisation signals, coherent scattering of atmospheric neutrinos, multiple scattering within the detector and high-energy neutrons. "The one that we found most likely, although rare, is multiple scattering," says Gaitskell. "What we are concerned about is if one of the scattering vertices happened in a region of the xenon where no charge is collected." In that case, the event would lose part of its ionisation signal and look more like a nuclear recoil. The experiment's underground location and shielding, with the detector inside 229 tonnes of water and an active liquid-scintillator detector around the xenon, help suppress unwanted signals.

"We are at the level where the probability that the event is background leakage is expected to be about 1 in 200," says Gaitskell, who – nonetheless – does not exclude a background of a kind not yet identified. "With one event, you have to hold all those possibilities in mind."

Several theoretical interpretations have been proposed for the LZ event, including the higgsino, a candidate motivated by supersymmetric extensions of the Standard Model. To scatter off a nucleus at the rate needed to produce the LZ event, the higgsino would have to turn from its stable state into a second one, a few hundred keV heavier. Since only the fastest particles in the halo carry the energy to do so, most would never scatter, and the few that did would leave high-energy recoils.



M Kapust/SURF

Deep underground *The LUX–ZEPLIN experiment sits 1.5 km below the surface at SURF, in South Dakota. Seen here from inside its water tank, the acrylic vessels of the outer detector surround the cryostat that holds the seven-tonne liquid–xenon target.*

"The higgsino model has really only one free parameter, the energy/mass splitting between the two neutral states, and once that is fixed, it fits the data fairly well," says Tracy Slatyer, theoretical physicist at the Massachusetts Institute of Technology. "However, for a higgsino you would expect to see more events at higher energy in LZ. The details depend on the velocity distribution of dark matter, which is uncertain, but there is some tension there. Perhaps more importantly, as Maxim Pospelov and Harikrishnan Ramani pointed out, the dark matter in the higgsino model can also annihilate, so for the parameter choices that fit the LZ event you would expect a flux of high-energy neutrinos from the Sun, which has not been observed." Variations of the model can evade these bounds. "Perhaps the simplest is just increasing its mass, although this makes it a bit more complicated to generate the correct dark-matter abundance," says Slatyer.

"We now have more than three times as much data available," says Gaitskell. "We can use that larger exposure to analyse in more detail whether additional events are occurring and whether their signature is consistent with dark matter." Complementary searches may also be possible with other liquid-xenon experiments, including XENONnT at Gran Sasso, PandaX-4T and its 20-tonne successor at Jinping in China. Meanwhile, design studies are being carried out for a detector of 60 to 80 tonnes of xenon, referred to as XLZD.

Further reading

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K Freese and D P Theodosopoulos 2026 arXiv:2609.01583.
N L Rodd *et al.* 2026 arXiv:2609.04175.
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ASTROWATCH

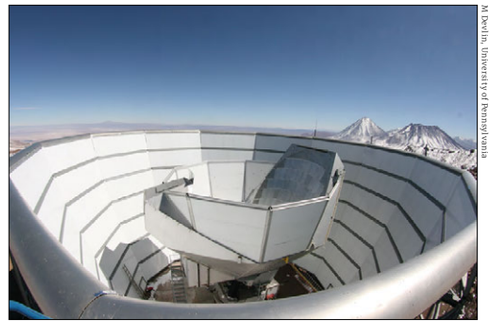
A headwind for dark matter

The ΛCDM model describes a universe dominated by cold dark matter and dark energy, represented by the cosmological constant Λ. From a small set of parameters, constrained by observations of the cosmic microwave background (CMB), it predicts how the nearly uniform early universe developed into the galaxies, clusters and filaments seen today.

Despite the model's remarkable agreement with a wide range of observations, small cracks have begun to emerge. Alongside the well-known Hubble tension, now exceeding five standard deviations (*CERN Courier* March/April 2025 p28), CMB observations interpreted within ΛCDM generally predict a universe in which matter is slightly ▷

more strongly clustered than indicated by weak gravitational-lensing surveys. The difference, commonly expressed through a parameter known as S_8, is modest, typically at the level of two to three standard deviations, but its persistence across multiple datasets has prompted an important question: could the growth of cosmic structure reveal physics beyond ΛCDM?

The model, for instance, takes dark matter and neutrinos to interact only through gravity, an assumption experiments have yet to test. Dark matter accounts for approximately 85% of the matter in the universe, but its microscopic identity remains unknown. Neutrinos, by contrast, are known particles, but several of their properties are only partially understood. Neutrinos were produced in enormous numbers in the early universe, and this relic population should still fill the cosmos today, outnumbering baryons by roughly a billion to one.



M Devlin, University of Pennsylvania

Fine detail *From 5190 m in the Chilean Andes, the Atacama Cosmology Telescope measured the cosmic microwave background at the small angular scales where a coupling between dark matter and neutrinos would leave its mark.*

Dark acoustics

Extensions of the Standard Model can introduce new mediator particles that couple dark matter to neutrinos, allowing them to scatter elastically. The process would have mattered most in the early universe, when neutrinos – still relativistic – formed a rapidly moving background through which cold dark matter attempted to collect in gravitational potential wells. Scattering with this background would act as a drag, slowing the growth of dark-matter-density perturbations. On sufficiently small scales, the pressure of the relativistic component in the coupled dark matter–neutrino fluid could cause perturbations to undergo dark acoustic oscillations rather than grow freely under gravity, in analogy with the acoustic oscillations imprinted on the CMB. Diffusion damping would further suppress fluctuations on the smallest scales.

As the universe expanded and its density decreased, the interaction would eventually become inefficient. Dark matter would then behave like an ordinary collisionless component, recovering the conventional picture. The early coupling would nevertheless leave a scale-dependent suppression of the matter distribution and, consequently, a reduced abundance of structure at late times. This is the type of effect that could lower the value of S_8 inferred from the early universe and bring it closer to late-time weak-lensing measurements.

Cosmological surveys are beginning to test how dark matter behaves and what it interacts with

Previous analyses of high-resolution CMB measurements from the Atacama Cosmology Telescope (ACT) had already identified a mild preference for non-zero scattering between dark matter and neutrinos. The effect was driven mainly by the small angular scales, or high multipoles, measured by ACT, which are particularly sensitive to changes in the evolution of primordial perturbations.

In a study published earlier this year, we investigated whether the same interaction could also account for measurements of matter clustering in the late universe. To do so, we combined large-scale CMB information from Planck with smaller-scale data from ACT, baryon acoustic oscillation distance measurements, and cosmic-shear data from the first three years of the Dark Energy Survey (DES Y3).

Cosmic shear is the coherent distortion of the apparent shapes of distant galaxies caused by the intervening matter. Unlike galaxy clustering, it does not rely on galaxies as faithful tracers of the underlying matter density. It therefore provides a comparatively direct view of how matter, dark and luminous, is distributed across the universe. The DES Y3 data mildly favour interaction strengths that overlap with the range independently preferred by the CMB. The two probes measure different physical quantities at very different epochs, but point towards a similar suppression of structure.

The full combination favours non-zero scattering between dark matter and neutrinos at close to the three-standard-deviation level. The preferred interaction is small, but strong enough to leave signatures in both the high-resolution CMB spectra and the late-time clustering. It is also sufficient to reconcile the CMB and weak-lensing constraints on S_8.

The implications would extend well beyond cosmology. Many particle-physics models allow dark matter and neutrinos to communicate through new mediator particles or a hidden sector, including scenarios with sterile neutrinos. Cosmological observations are sensitive to such couplings because they probe the cumulative evolution of the universe over billions of years, and they can often test interaction strengths inaccessible to laboratory experiments.

At the same time, caution is warranted. The current preference remains below the threshold required to claim a discovery of new physics, and alternative explanations, including unknown observational systematics or different extensions of the standard cosmological model, cannot yet be ruled out. Further observations will therefore be crucial to determine whether the preference persists.

Galactic mapping

New weak-lensing surveys from the Vera C. Rubin Observatory, Euclid and Xuntian – the Chinese Space Station Telescope (CSST), which will co-orbit with the Tiangong space station – will map billions of galaxies, while next-generation CMB experiments will sharpen our view of the early universe. Our forecasts indicate that Rubin and CSST should either confirm the preferred interaction region or impose stringent limits on the best-motivated possible connection between known particles and dark matter. Either outcome would be valuable.

More broadly, cosmological surveys, once limited to weighing the universe's components, are beginning to test how dark matter behaves and what it interacts with. Whether forces that have so far escaped laboratory detection connect the visible and invisible sectors of the cosmos is now an observational question.

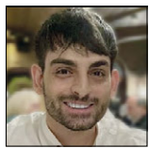
Further reading

L Zu *et al.* 2026 *Nature Astron.* doi:10.1038/s41550-025-02733-1.
W Giarè *et al.* 2024 *Phys. Rev. D* **109** 063516.
P Brax *et al.* 2023 *Phys. Dark Univ.* **42** 101321.
P Brax *et al.* 2023 *Mon. Not. R. Astron. Soc.* **527** L122.

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cividec
Instrumentation

Instrumentation for Detector Development

By Erich Griesmayer

There's a lid for every pot – and an amplifier for every detector.

The development of particle detectors requires dedicated analogue readout instrumentation, which falls into three categories:

1. Broadband amplifiers measure the transient current pulse of a detector. The current is converted into a voltage at the amplifier's 50 Ω input, amplified, and displayed on an oscilloscope. These are voltage amplifiers built from several stages. They are AC-coupled with a gain of typically 40 dB (linear gain factor 100) so that a detector current of 1 µA appears as a measurement voltage of 5 mV. 20 dB amplifiers (linear gain factor 10) are used as intermediate buffer amplifiers.

2. Charge amplifiers measure the charge produced by an ionisation event. To accommodate high rates, the inherently slow charge integration is followed by a shaping stage that shortens the signal while preserving its amplitude as a measure of the detector charge. Instrumentation charge amplifiers are AC-coupled, and their gain is expressed in volts per coulomb. A charge of 1 fC is typically converted into 10 mV.

3. Current amplifiers convert the detector current into a measurement voltage using the transimpedance stage of an operational amplifier. The gain is specified in volts per ampere, or ohms, and represents the sensitivity of the instrument. Measuring dark currents, leakage currents, or bias currents of detectors in the sub-picoampere range requires a sensitivity in the gigaohm range, converting 1 pA into 1 mV.

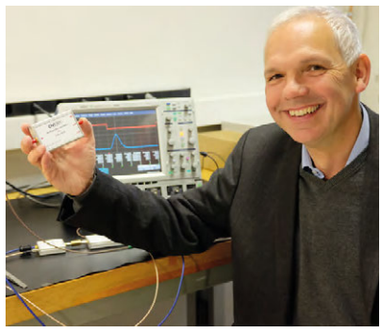
Operating parameters. Amplifiers have a finite analogue bandwidth and gain. The gain-bandwidth product is the limiting factor: gain constrains bandwidth, and, conversely, bandwidth constrains gain. The linear range is another key parameter, with bipolar input and output signals preferred to achieve independence from the detector signal polarity. Fast amplifiers – broadband and charge amplifiers – are operated with a 50 Ω measurement impedance, where the voltage is limited to typically ±2 V to keep power consumption and heating under control. Current amplifiers, operated with 1 MΩ measurement impedance, allow a linear range of ±10 V.

Input protection. Detector development is prone to sparking in the detector structure when high operating voltages are applied. CIVIDEC has solved this with the Double-Input Protection System (DIPS®), which absorbs sparks and protects the input stage of the amplifier from damage.

Bias tee. AC-coupled amplifiers incorporate a bias tee for the detector bias voltage. This allows the readout from the detector's ground side, which is essential for a proper measurement of the detector's leakage current.

Together, the three amplifier categories form a complete analogue readout chain. They cover everything from the sub-picoampere leakage current of a biased detector to the nanosecond current pulse of a single ionising particle. Broadband amplifiers resolve the pulse shape directly, so they can be used to study charge-carrier drift velocities, trapping and space-charge effects with the transient-current technique (TCT). Charge amplifiers provide the energy resolution needed for spectroscopy and for calibration with radioactive sources. Current amplifiers characterise the static behaviour of the detector under bias. CIVIDEC supplies instrumentation for all three categories. The amplifiers have bipolar signal ranges, and the fast amplifiers additionally offer 50 Ω matching, integrated bias tees and DIPS® input protection. This lets them move from the laboratory bench to test-beam areas and accelerator environments.

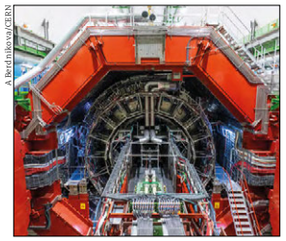
Detailed specifications and technical characteristics of CIVIDEC's products are available at www.cividec.at. Documentation of this instrumentation, in particular for diamond detectors, is in preparation as a book in the Springer Nature Smart Sensors, Measurement and Instrumentation series, to be published next year.



Erich Griesmayer is an electronics engineer who has been working at CERN for several decades. He is the founder of CIVIDEC Instrumentation GmbH and a lecturer at the Vienna University of Technology.

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NEWS DIGEST



A Berdnikova/CERN

The ALICE detector in August 2026.

Signs of gluon saturation

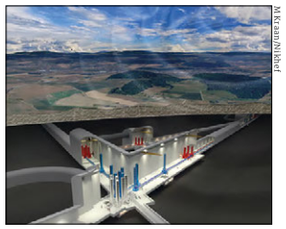
In July 2026, the ALICE collaboration published evidence that incoherent J/ψ photoproduction off lead nuclei grows more slowly with energy at large momentum transfer $|t|$ (ALICE Collab. 2026 *Phys. Rev. Lett.* **137** 052301). In ultraperipheral Pb–Pb collisions, where the nuclei pass too far apart to interact strongly, a photon from one nucleus can produce a J/ψ off a single nucleon in the other nucleus, which then breaks up. In coherent production, by contrast, the photon interacts with the full nucleus. Larger $|t|$ probes smaller transverse scales, and the highest interval probed by ALICE, $0.81 < |t| < 1.44\,\text{GeV}^2$, reaches inside the nucleon. The observed energy dependence resembles that predicted by gluon-saturation models (*CERN Courier* January/February 2025 p31), while a nuclear-shadowing calculation that describes coherent production is disfavoured by the incoherent data.

ISOLDE ramps up

CERN is using Long Shutdown 3 to raise the energy of the protons that drive ISOLDE, its facility for low-energy beams of radioactive nuclides, from 1.4 to 2 GeV. The Proton Synchrotron Booster that supplies them has run at 2 GeV since the previous Long Shutdown, but ISOLDE has had to wait for new beam dumps and for the reconfiguration of its transfer line, originally designed for 1 GeV. By the end of September, 10 of the line's magnets – among them 8.5-tonne dipoles – had been removed, an operation complicated by three decades of shielding and services in the target area. At the higher energy, spallation and fragmentation reactions in ISOLDE's targets should give significant gains for several neutron-deficient isotopes. Operation at 1.4 GeV will remain available for nuclides whose production cross-sections are higher at the lower energy.

Triangle or double L

On 7 October 2026, the *Geometry Comparison Report* for the Einstein Telescope (ET), a planned gravitational-wave observatory, was submitted to the project's Board of Governmental Representatives. The effort, coordinated by the Einstein Telescope Organisation, involved over 200 experts from more than 20 institutions. The report compares a single triangular detector with 10 km sides and two L-shaped interferometers with 15 km arms at two distinct sites – roughly 1200 km apart. Both designs meet ET's science requirements, but the double-L layout addresses the broadest range of key science cases, and its instrumentation is estimated to cost less. The board will assess the findings before governments choose, in the second half of 2027, among candidate sites in Sardinia, the Euregio Meuse–Rhine and Saxony.



M Maarten/Nikhef

An artist's view of the triangular design for the Einstein Telescope.

Cooled muons gain speed

On 31 August 2026, the Japan Proton Accelerator Research Complex (J-PARC) announced that researchers had accelerated cooled positive muons to 0.3 MeV at its Materials and Life Science Experimental Facility. A 4 MeV muon beam stops in silica aerogel and forms muonium, the bound state of a positive muon and an electron, which an ultraviolet laser then strips away. The freed muons, at 25 meV, about 160 million times less energetic than the incoming beam, then enter a radio-frequency accelerating system. The muons reached three times the energy of the 2024 demonstration, at 200 times its rate, about 10 muons per second. The team aims to reach 4 MeV around 2027–2028.

Neutrinos down to 17 keV

On 31 August 2026, the XENON collaboration reported a 5.0σ observation of solar neutrinos scattering off electrons in the XENONnT detector, 1400 m underground at the Gran Sasso National Laboratory (XENON Collab. 2026 arXiv:2608.29450). The signal is dominated by pp neutrinos from the proton–proton fusion that powers the Sun, and the analysis reaches neutrino energies down to about 17 keV. At such energies the signal is feeble, and two backgrounds dominate, lead-214 from radon at lower energies and the two-neutrino double-beta decay of xenon-136 at higher energies. From 2.46 tonne-years of exposure, the collaboration measured a pp neutrino flux of $(10.2 \pm 2.0) \times 10^{10}\,\text{cm}^{-2}\,\text{s}^{-1}$. The planned XLZD detector, with an order of magnitude more target mass, is projected to measure this flux to better than 1%.

Free fall in superposition

On 2 September 2026, an international team reported the first direct measurement of the quantum phase of a freely falling object in Ron Folman's atom-chip group at Ben-Gurion University of the Negev (O Dobkowski *et al.* 2026 *Sci. Adv.* **12** eaec8045). In the team's Quantum Galileo Interferometer, microwave pulses place ultracold rubidium atoms in a superposition beneath an atom chip. Magnetic fields from the chip hold one part of each atomic wave at rest in the laboratory, while the other is pushed upwards into a ballistic trajectory and then left to fall freely under gravity. Recombining the two parts reveals a phase difference that matches the prediction obtained by applying Einstein's equivalence principle to a matter wave.



Ben-Gurion University of the Negev

The atom chip that holds and launches the atoms in the Quantum Galileo Interferometer.

Fission beyond 104

Researchers at GSI/FAIR have measured, for the first time, how superheavy nuclei beyond rutherfordium (Z = 104) split in fission (J Khuyagbaatar *et al.* 2026 Phys. Lett. B **881** 140873). Elements up to Z = 118 have been observed, but fission-fragment mass distributions were known only up to Z = 104. The team's set-up, ANSWERS, stops the atoms in gas at atmospheric pressure and flushes them into a narrow channel between two sets of silicon detectors, where the atoms are adsorbed onto the detector surfaces. When a nucleus fissions, its two fragments strike opposite detectors, and their masses are reconstructed from the measured kinetic energies. The measurements show that californium-242 and nobelium-252 split asymmetrically, whereas the heavier lawrencium-264 and dubnium-268 divide almost evenly, with large total kinetic energies.

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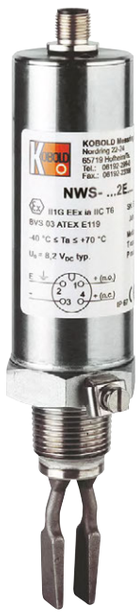
To the limit

NWS KOBOLD liquid level switch

Even under difficult conditions, the NWS-type liquid level switch from Hofheim-based KOBOLD Messring GmbH provides reliable monitoring of threshold levels for liquid media using the oscillating fork principle. With this tried and tested process for reporting threshold levels, two symmetrical paddles are brought into permanent oscillation. As soon as the device is covered with a liquid, the oscillation changes. This is recorded by the electronics and an appropriate switch signal is transmitted. A red LED also indicates the switch condition and correct function.







Without any moving mechanical parts, the devices are virtually maintenance- and wear-free. Due to the permanent oscillation, the device is also extremely insensitive to vibrations and deposits. Since different viscosities and/or the conductivity of the products do not have any influence, it is very easy to quickly change the product without any ensuing problems. The robust devices can withstand operating pressures of up to 45 bar, and in the version suitable for CIP can also withstand short-term temperatures of up to 150° C.

An extensive range of typical industrial connections, in addition to connections that are suitable for use in food production, means they can be used for a variety of applications such as securing tanks and reservoirs against overfilling. The sensors are available in two different lengths and models. It is also possible to choose between two- or three-line technology and the corresponding electrical connection technology. Devices with stainless-steel casing with protection type IP 67 or IP 68, and those with ATEX approval for explosive/combustible areas round off the extensive range available.

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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

LHCb

A photon probe of B mesons

The LHCb collaboration has performed the first search at a hadron collider for a B meson decaying to a muon, a neutrino and a photon ($B^+ \to \mu^+\nu\gamma$), together with the first ever search for its B_c counterpart. No signal was found, but the sensitivity achieved rivals that of the electron–positron machines that have long held this territory.

Predictions in flavour physics are often limited by the strong-interaction effects that bind quarks into hadrons. In $B^+ \to \mu^+\nu\gamma$, however, no hadron appears in the final state, and the photon is radiated predominantly by the B meson's light quark. The emission rate depends on the quark's typical momentum λ_B, which is among the least well-known inputs to precision B-physics, with estimates spanning from 200 to 600 MeV. The decay is thus best placed to probe the structure of B mesons.

The process has never been observed, as only about one in a million B mesons decays this way, and the few that do are hard to reconstruct. The neutrino is invisible, the photon leaves only a deposit in the calorimeter and the muon's track – on its own – marks no decay point. As a result, the two handles LHCb normally relies on to identify a signal are lost. The parent meson's mass cannot be reconstructed, and without a displaced vertex the decay cannot be picked out of the flood of particles from the proton–proton collision. At electron–positron machines, B mesons are produced in pairs and with no other particles, so the missing neutrino momentum can be retrieved by reconstructing everything else in the event, including the other B decay. This technique cannot be used at the LHC.

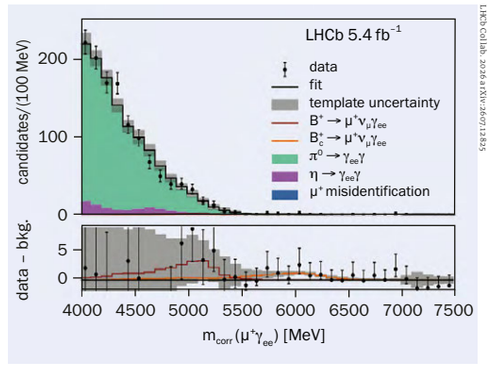


Fig. 1. *Corrected-mass distribution of $B^+ \to \mu^+\nu\gamma$ candidates in 2016–2018 data. The fit (black) comprises the B^+ (red) and B_c (orange) signals, and the neutral-pion (green), eta-meson (purple) and muon-misidentification (blue) backgrounds, each shown at its fitted yield. The lower panel shows the data after background subtraction.*

LHCb has overcome these challenges by using photons that convert into an electron–positron pair in the material of the vertex-locator detector. The resulting two tracks, together with the muon, fix a displaced decay vertex and hence the meson's flight direction. A corrected mass, built from the visible mass plus the momentum missing transverse to the B flight direction, then recovers a peak near the B mass. Normalising to $B^0 \to K^*(892)^0\gamma$, a well-measured radiative decay reconstructed the same way, cancels the poorly known conversion efficiency.

LHCb has a realistic chance of a first direct determination of λ_B

The dominant background comes from B decays in which a neutral pion or eta meson takes the place of the photon, passing for it when one of its two decay photons escapes detection. The shape of this background was obtained from events in which the second photon is found in the calorimeter, and validated on a large sample of charm decays. No significant excess was observed in the data recorded by LHCb in 2016–2018 (see figure 1). For photon energies above 1 GeV in the meson rest frame, the resulting upper limits at 90% confidence are 4.0×10^{-6} for the B^+ and 1.6×10^{-3} for the B_c.

The first limit is comparable with the best previous limit of 3.4×10^{-6} from Belle, and close to the Standard Model expectation. The second, on the B_c mode, is still 20 to 80 times above the predicted rate. The B_c is expected to decay this way far more readily, since its quark transition is much less suppressed. However, B_c mesons are produced a hundred times more rarely and live a third as long. Likelihood curves and efficiency maps have been published, so both results can be reinterpreted in any structural model.

With the larger Run 3 dataset, and triggers now sensitive to the electron channel too, LHCb has a realistic chance of first evidence for this decay and a first direct determination of λ_B, a measurement the experiment was never expected to make.

Further reading

LHCb Collab. 2026 arXiv:2607.12825.

CMS

The muon system as a calorimeter

Most of the unstable particles produced in LHC collisions decay promptly. Some theories of physics beyond the Standard Model (SM), however, predict particles that interact only feebly with ordinary matter and can therefore travel a measurable distance before decaying. These long-lived particles (LLPs) have long been a target in the search for physics beyond the SM (*CERN Courier* July/August 2015 p9). The CMS collaboration has now presented a search for LLPs using a dedicated trigger for high-multiplicity showers in its muon system. This technique improves the trigger efficiency by a factor of 10, extending sensitivity to a previously inaccessible region of low missing transverse momentum.

The new trigger broadens the range of LLP scenarios CMS can explore

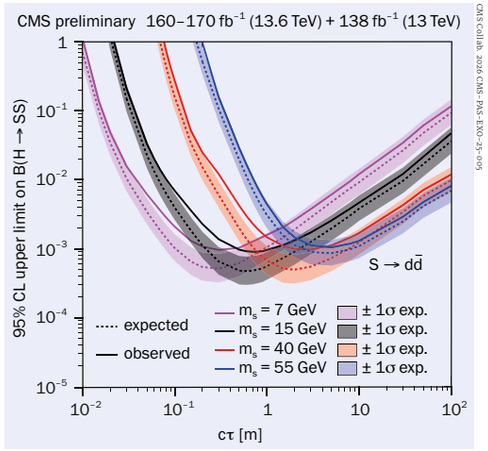
The search relies on the structure of the CMS muon system, with detectors interleaved with the steel of the magnet's return yoke, where an LLP can decay and initiate an electromagnetic or hadronic shower. Secondary particles from the shower would then pass through the gas-filled detector chambers, producing a large number of localised hits. ▷

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By searching for clusters of these hits, the collaboration can effectively turn the muon system into a sampling calorimeter for particles that would otherwise be difficult to detect.

This unconventional approach was first demonstrated in 2021 (*CERN Courier* November/December 2021 p19). That study used 137 fb^{-1} of data collected during 2016–2018 and improved sensitivity to GeV-scale particles by up to a factor of six. The method also allowed CMS to search for LLPs decaying several metres from the interaction point, with proper decay lengths of up to about 1 km. The latest CMS search took this approach further by introducing a dedicated high-multiplicity trigger for muon detector showers in Run 3.

The analysis searches for pairs of muon detector showers with a high-hit multiplicity. The substantial amount of material interleaving the muon detectors provides substantial shielding from SM particles that can mimic the signature of an LLP. Requiring showers with a large number of hits further suppresses backgrounds, such as muons, that radiate in the detector and hadrons that penetrate the calorimeters. The remaining background is estimated directly from collision data using control regions, avoiding reliance on a detailed simulation of these rare detector effects.



CMS Collab. 2026 CMS-PAS-EXO-25-005

Fig. 1. *Observed (solid) and expected (dotted) 95% CL upper limits on the branching fraction of Higgs-boson decays to a pair of long-lived particles, B(H → SS), as a function of the particle's proper decay length cτ, for decays to down quarks. The curves correspond to masses of 7 (magenta), 15 (black), 40 (red) and 55 GeV (blue).*

The new search uses up to 170 fb^{-1} of proton–proton collision data collected by CMS at 13.6 TeV between 2022 and 2024. No significant excess above the predicted SM background is observed in the data. The study sets 95% CL upper limits on the branching fraction of Higgs-boson decays to a pair of LLPs, reaching sensitivity to branching fractions at the sub-percent level (see figure 1). For LLP masses below 10 GeV, it provides the most stringent limits from LHC data to date.

The new dedicated trigger also broadens the range of LLP scenarios that CMS can explore. In 2024, for instance, it was extended to collect events in which an LLP is produced alongside a lepton or photon. Looking ahead to the HL-LHC, the collaboration is developing further triggers and new reconstruction techniques, including machine-learning methods that make greater use of the information recorded in the muon detectors. Together, these developments will extend the reach of the LHC programme's sensitivity to increasingly long-lived and weakly interacting forms of new physics.

Further reading

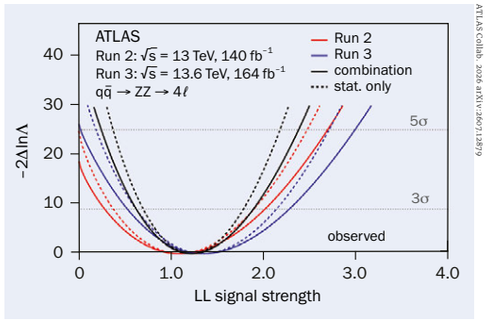
CMS Collab. CMS-PAS-EXO-25-005.

ATLAS

A longitudinal view on symmetry breaking

The Brout–Englert–Higgs (BEH) mechanism, the cornerstone of electroweak symmetry breaking, gives the W and Z bosons their masses. With them comes a longitudinal polarisation, which sets the weak bosons apart from photons and other massless particles, thus providing a direct probe of the BEH mechanism. The ATLAS collaboration has now studied this longitudinal mode in two analyses of di-boson events, providing new insight into rare electroweak processes. The results are based on proton-proton collision data from the full Run 2, with 140 fb^{-1} at 13 TeV, and from part of Run 3, with 164 fb^{-1} at 13.6 TeV.

The first result targets the rare production of two Z bosons, selecting events where both decay into electron or muon pairs. Since the leptons' angular distributions reflect the parent bosons' polarisation, researchers trained a multivariate classifier on these observables to distinguish events containing two longitudinally polarised Z bosons from those with other polarisation combinations. The combined Run 2 and Run 3 analysis achieved a 6.5σ observed significance (5.6σ expected), marking the first observation of this rare process (see figure 1). The team also measured the Z-boson polarisation fractions for the full dataset and in different ranges of the four-lepton invariant mass. The measured results agree well with the Standard Model (SM), which predicts such events to become increasingly rare at higher energies.



ATLAS Collab. 2026 arXiv:2607.12879

Fig. 1. *Likelihood ratio as a function of the signal strength, defined as the production rate of longitudinally polarised Z-boson pairs relative to the SM prediction, for Run 2 (red), Run 3 (blue) and combined (black) data. Dotted lines mark the 3σ and 5σ thresholds.*

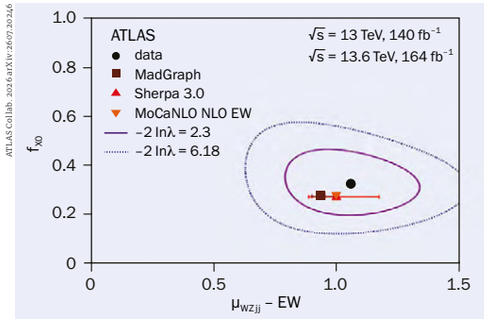
The second result concerns polarisation in WZ diboson events with leptonic decays to electrons and muons, produced in association with two hadronic jets. The phase space is enriched in electroweak WZjj production, which includes processes where the two vector bosons scatter off one another. The scattering of two longitudinally polarised bosons can occur via Higgs-boson exchange, which prevents the SM calculations for this process from diverging at high energies. If the Higgs boson deviated from the SM prediction, new physics – such as new resonances – would be necessary to restore physical behaviour. This makes the study highly sensitive to new physics in the electroweak sector.

The experimental challenge lies in the rarity of the electroweak production process. Even after a dedicated selection, only 13% of the resulting events are predicted to stem from it. To address this, researchers used a two-dimensional plane with axes representing a signal-versus-background discriminator and a polarisation discriminator, both derived via a deep neural network. A maximum-likelihood fit extracted the integrated electroweak WZjj cross section in the fiducial phase space. It also measured the fractions of longitudinal W and Z polarisations, each independently of ▷

the polarisation of the other boson in the pair, and the double longitudinal diboson polarisation fractions.

ATLAS found evidence for longitudinally polarised Z bosons with an observed (expected) significance of 4.0 (2.9) standard deviations, and an observed (expected) longitudinal Z-polarisation fraction of (32 ± 9)% ((27.45 ± 0.08)%) (see figure 2). The measured electroweak WZjj cross section agrees with predictions. No evidence was found for longitudinally polarised W bosons, regardless of the Z-boson polarisation, and upper limits were set on these fractions. All measurements remain consistent with SM predictions within 2.4 standard deviations.

Both analyses benefited from a collaboration with theorists to obtain predictions at next-to-leading order in the electroweak coupling, using the MoCaNLO framework. With more data from Run 3 and beyond, future analyses will sharpen tests of the BEH mechanism, improve sensitivity to potential deviations, and further expand the frontier of weak-boson polarisation physics.



ATLAS Collab. 2026 arXiv:2607.20246

Fig. 2. *Measured fraction of longitudinally polarised Z bosons against the electroweak WZjj cross section relative to its prediction (black dot), with 68% (solid magenta) and 95% (dotted blue) confidence contours. Predictions from MadGraph (square), Sherpa 3.0 (upward triangle) and MoCaNLO (down triangle) are shown for comparison.*

Further reading

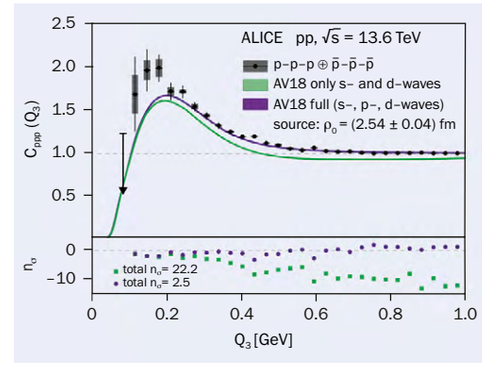
ATLAS Collab. 2026 arXiv:2607.12879.
ATLAS Collab. 2026 arXiv:2607.20246.
A Denner *et al.* 2026 *JHEP02* 120.

ALICE

A genuine three-proton business

The ALICE collaboration has measured the dynamics of three unbound protons at femtometre-scale distances, where the strong interaction is at play. Until now, three-nucleon interactions have been studied mainly in bound nuclear systems and through nucleon–deuteron scattering. However, bound states provide information only at specific energies and quantum numbers. Nucleon–deuteron scattering probes a wider kinematic range, but the deuteron has isospin 0, restricting measurements to total isospin 1/2. The isospin-3/2 channel has therefore remained directly unexplored, as it requires three unbound protons or neutrons.

ALICE has overcome this limitation using femtoscopy. In high-energy proton–proton collisions at the LHC, hadrons are produced at mutual separations of only a few femtometres. After production, their mutual interactions modify their momenta, leaving measurable correlations that reveal the forces acting between them. Extending femtoscopy to three particles is challenging because interactions primarily affect the kinematic region where their relative momenta, quantified by the hypermomentum Q_3, must be low. Such triplets are rare. In proton–proton collisions at 13.6 TeV, only about one event in 30,000 contains three protons with $Q_3 < 1.4$ GeV. During Run 3, dedicated software triggers therefore recorded all such events over the full integrated luminosity. Using these data, ALICE measured the p–p–p correlation function and isolated the genuine three-proton signal by subtracting background contributions estimated from the data.



ALICE Collab. arXiv:2608.05708

Fig. 1. *The genuine p–p–p correlation function with statistical (bars) and systematic uncertainties (boxes). The magenta and green bands show calculations using the AV18 potential with and without the p-wave component, respectively. The bottom panel gives the number of standard deviations between theory and data in each bin, with totals for the full Q_3 range.*

This is the first direct test of nuclear interaction in the isospin-3/2 three-nucleon system

The resulting correlation function behaves as expected for an effective three-to-three scattering process (see figure 1). The data are compared with three-body calculations including quantum statistics, Coulomb repulsion and the proton–proton interaction described by the Argonne v18 potential (AV18), a model of the nuclear force fitted to nucleon–nucleon scattering data. Three-body forces, which account for about 10% of the binding energy of light nuclei, are negligible here, because the Pauli exclusion principle keeps the three identical protons from all coming too close together. The two-body interaction depends on the relative orbital angular momentum l of the pair, and its contributions are classified as s-wave (l = 0), p-wave (l = 1) and higher partial-wave interactions. Calculations without the p-wave contribution fail to describe the data, whereas those with the full interaction agree well, showing that the measurement is sensitive to these partial waves. This is the first direct test of the nuclear interaction in the isospin-3/2 three-nucleon system.

The data also reveal an unexpected feature. At large Q_3, only the long-range Coulomb repulsion should act among the three protons, so the correlation function should approach unity from below. Instead, the data show an attraction due to the short-range nuclear force, as if it had acquired an effective long-range component. The explanation is geometric. Even when the three-body system is spatially extended, two of them can remain close enough to interact. This is the first experimental signature of such an effect in a system of three unbound protons.

The method can now be extended to strange three-baryon systems such as p–p–Λ and p–p–Ξ, whose interactions remain poorly constrained. Such systems matter for neutron stars, whose dense cores may contain hyperons. Their appearance would lower the predicted maximum mass of these stars below the values established by astronomical observations, but repulsive hyperonic three-body forces could counteract this effect. With the much larger Run 3 data sample, three-baryon femtoscopy can now constrain such forces directly.

Further reading

ALICE Collab. 2026 arXiv:2608.05708.

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FIELD NOTES

Reports from events, conferences and meetings

ICHEP 2026

A new continent for ICHEP

The 43rd International Conference on High Energy Physics (ICHEP) took place in Natal, Brazil, from 30 July to 5 August 2026. It was the first edition held in Latin America in a history going back to Rochester in the 1950s, and the strength of the region's groups was visible throughout the week. Overall, the 1210 registered participants and 1060 accepted abstracts reflected a large and diverse community.

The conference opened just weeks after the LHC completed Run 3 and, with 16 years of operation behind it, entered the long shutdown that will turn it into the High-Luminosity LHC (*CERN Courier* July/August 2026 p8). The ATLAS, CMS, ALICE and LHCb collaborations presented around 100 new results, mostly based on Run 2 and partial Run 3 data. More than 500 fb^{-1} of proton–proton collisions have now been delivered to ATLAS and CMS, and much of the analysis still lies ahead.



Wide angle *The participants of the 43rd International Conference on High Energy Physics, the first to be held in Latin America.*

The end of an era

For ATLAS and CMS, the legacy Run 2 analyses close an era of discovery and open one of precision in Higgs physics. The Higgs-boson mass is known to about 0.1%, the global signal strength to about 6%, and the couplings to vector bosons and third-generation fermions to 5–6% and 6–21%, respectively – all consistent with the Standard Model. A purely CP-odd coupling of the Higgs boson to top quarks has been excluded at more than 5σ, ATLAS and CMS have combined evidence for the rare decay $H \to Z\gamma$, and the second generation is coming within reach, with evidence for $H \to \mu\mu$ and the charm Yukawa coupling now constrained to less than 3.5 times its Standard Model value.

Higgs-boson pair production is the direct route to the Higgs self-coupling and the shape of the Higgs potential. ATLAS and CMS presented new results in $HH \to bb\tau\tau$, now including Run 3 data, with individual channels beginning to match the sensitivity of the full Run 2 combination. The HL-LHC is expected to sharpen the self-coupling constraint by roughly an order of magnitude (*CERN Courier* January/February 2026 p31).

ATLAS and CMS have both observed an excess of top-quark pairs near the production threshold, consistent with toponium, a short-lived quasi-bound state of a top quark and its antiquark. Normally, the top quark decays too quickly for this to happen. Near threshold, however, the quark and antiquark emerge almost at rest with respect to each other, and non-relativistic QCD predicts that the strong interaction can hold them together briefly. The measured cross-sections lie somewhat above predictions, and a new elementary pseudoscalar particle is not yet excluded.

The ATLAS, CMS, ALICE and LHCb collaborations presented around 100 new results

Heavy-ion physics delivered a long-sought result: jet quenching in oxygen–oxygen and neon–neon collisions, whose nuclei contain only 16 and 20 nucleons. Even these light nuclei create a medium dense enough to sap energy from traversing partons, an effect previously established only in collisions of large nuclei. Small systems were already known to show collective flow, but without quenching. With both signatures now seen by all four LHC experiments, the question is how small a system can be and still produce a quark–gluon plasma.

LHCb announced a new particle at the conference, the $B^*_{s0}(5700)^0$, which appears lighter and narrower than quark-model calculations predict. Its properties resemble those of the $D^*_{s0}(2317)^+$, discovered two decades ago, raising the question of whether similar effects are at work in the charm and beauty sectors. At BESIII, new results have strengthened the evidence for the X(2370) resonance as a candidate pseudoscalar glueball, a hadron whose dominant component consists of gluons (*CERN Courier* September/October 2026 p7). Its mass agrees with lattice-QCD predictions, while its decay patterns favour a glueball-dominated interpretation over conventional quark–antiquark explanations.

Precision probes

The quark-mixing parameters were overconstrained from several directions, and remain remarkably consistent. CMS joined the precision programme in time-dependent CP violation, measuring the angle β with a precision comparable to that of LHCb, and a Belle II analysis of $B^0 \to \pi^0\pi^0$ decays exploiting the quantum entanglement of B-meson pairs improved the determination of α, the least precise angle of the unitarity triangle. New measurements from Belle II and BaBar brought $R(D^*)$, a test of lepton universality in B-meson decays, to within about 2σ of the Standard Model. LHCb's observation of CP violation in baryon decays, at 5.2σ, has opened a new sector of flavour physics, and NA62 presented its sharpened measurement of $K^+ \to \pi^+\nu\bar{\nu}$, a rare, precisely predicted decay that probes mass scales far beyond the reach of direct searches.

The search for new physics now spans many orders of magnitude in mass, targeting both strongly and feebly cou- ▷

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pled states. At the energy frontier, ATLAS and CMS continued systematic searches for directly produced particles, such as narrow dilepton resonances, and for the indirect imprint of heavier states, with no significant deviation from the Standard Model so far. ATLAS and CMS now exclude sequential Z′ bosons, heavy partners of the Z with the same couplings, below about 5.5 TeV.

At lower masses and couplings, a growing programme targets feebly interacting particles, light states that appear in models addressing dark matter, neutrino masses and baryogenesis, with fixed-target, beam-dump, forward and collider experiments covering complementary regions from the MeV to the TeV scale. FASER presented the first LHC search for quirks, hypothetical particles connected by a new confining interaction, excluding quirk masses up to about 180 GeV for specific model assumptions.

Mass matters

ICHEP came only weeks after JUNO released new results from 207 days of data. Δm^2_{21} is now measured to 1.1% and $\sin^2\theta_{12}$ to 2.1% – the most precise determinations of the solar oscillation parameters to date – and Δm^2_{31} is determined at the percent level. T2K reported a 95% confidence-level exclusion of CP conservation in neutrino oscillations, and most data currently lean towards the normal mass ordering. Hyper-Kamiokande is expected to begin data-taking in 2028, followed by the DUNE beam programme around 2031. Together with JUNO, these experiments are expected to determine the neutrino mass ordering and substantially improve sensitivity to leptonic CP violation.

Beyond oscillations, the absolute scale of neutrino mass remains unknown, as does whether neutrinos are their own antiparticles. The second question would be settled by the observation of neutrinoless double-beta decay, and current searches set upper limits on the effective Majorana mass of roughly 30–120 meV. The next generation of experiments, including LEGEND-1000, KamLAND2-Zen and CUPID, aims to cover the full region allowed for an inverted mass ordering. On the first question, KATRIN has set the most precise laboratory limit, 0.45 eV at 90% confidence level, and its full 1000-day dataset is expected to reach a sensitivity below 0.3 eV.

ICHEP offered a view across the full landscape of fundamental physics

Dark-matter and neutrino physics are now converging. Following hints from XENONnT and PandaX-4T, the LZ collaboration reported the first evidence, at 4.5σ, of coherent elastic scattering of solar neutrinos in a dark-matter detector. These tonne-scale xenon experiments are approaching the neutrino fog, where scattering of solar and atmospheric neutrinos mimics the signal of a weakly interacting massive particle. The proposed XLZD experiment aims to cover the remaining parameter space down to it. Quantum calorimeters and superfluid-helium detectors are beginning to open up the sub-GeV mass range, while axion haloscopes have reached sensitivity to benchmark QCD-axion models in specific mass windows.

The cosmic frontier is expanding too. KM3NeT's record 220 PeV neutrino, the most energetic ever detected, still lacks an identified source, and the Pierre Auger Observatory reported that cosmic-ray composition becomes heavier at the highest energies, a key constraint on their still-unknown sources. Gravitational waves, first detected only a decade ago, have become a catalogue science, with around 300 candidate mergers in the latest LIGO–Virgo–KAGRA observing run (*CERN Courier* September/October 2026 p11), including one between black holes of about 100 and 140 solar masses, in or near the range where standard stellar evolution predicts none. In precision cosmology, individual datasets remain broadly consistent with ΛCDM, while comparisons between Hubble-constant measurements and DESI distances continue to show tensions. The coming decade should bring verdicts: Rubin, Euclid and Roman will decisively test whether dark energy evolves, while next-generation gravitational-wave observatories, the Einstein Telescope and Cosmic Explorer, will measure the Hubble constant to percent precision.

The road ahead

ICHEP also looked ahead. With Run 3 complete, CERN has entered long shutdown 3, during which the LHC will be equipped with Nb_3Sn quadrupoles and crab cavities, while the experiments install substantially upgraded detectors (p47). The HL-LHC is expected to begin operation in 2030, delivering five times the data collected so far over the following decade. The 2026 update of the European Strategy for Particle Physics, adopted by the CERN Council in May, recommends the electron–positron Future Circular Collider (FCC-ee) as the preferred option for CERN's next flagship collider, with a descoped FCC-ee as the preferred alternative if the full project proves unfeasible (*CERN Courier* July/August 2026 p7). Very high luminosities from the Z pole to the top-quark threshold would make Higgs, electroweak, flavour and top measurements sensitive to new physics beyond the direct reach of the HL-LHC, and the same tunnel would keep the path open to a future FCC-hh at the energy frontier.

As always, ICHEP offered a view across the full landscape of fundamental physics, from underground laboratories to observatories of the cosmos. The picture that emerged was of a field measuring the Standard Model in ever greater detail while exploring a wide range of possibilities for new physics, with a new generation of experiments under construction.

Florencia Canelli *University of Zurich.*

LATTICE 2026

Lattice theorists converge on Maryland

From 26 July to 1 August, the 43rd International Symposium on Lattice Field Theory (Lattice 2026) drew researchers from across the world to the University of Maryland, College Park, to present and discuss the latest advances in lattice quantum chromodynamics (QCD). Launched with a small workshop at CERN in 1982, the series has since grown far beyond its original scope, to span hadron spectroscopy and structure, QCD thermodynamics, physics beyond the Standard Model (SM), algorithms, computer architectures and machine-learning techniques and, increasingly, quantum computing and tensor networks.

Spectral-density reconstruction was a main highlight

This year's edition, hosted for the first time at the University of Maryland, offered a moment to recall that history. ▷

Steven Gottlieb (Indiana University) honoured the legacy of Robert L Sugar, who was central to the formation of USQCD – the US lattice-QCD collaboration – and to the development of the Φ-algorithm at the core of modern simulations of fermions on the lattice.

The programme reflected the breadth of the field, with sessions ranging from muon g–2 hadronic contributions to neural networks and quantum computing.

Plenary talks by Alaina Green (University of Maryland) and Christian Bauer (Lawrence Berkeley National Laboratory) highlighted progress in quantum computing. Green argued that the question is no longer whether quantum computers can be applied to lattice field theory, but how to co-design lattice formulations, algorithms and hardware together so that quantum computing becomes useful. One new direction is the possibility of using qudits, quantum units with more than two levels, where current hardware already reaches more than 10 levels in ions and in superconducting systems.



University of Maryland

Gauge group *The participants of Lattice 2026 outside the Adele H. Stamp Student Union at the University of Maryland, College Park.*

Game changer

Spectral-density reconstruction was a main highlight of the conference. As Andreas Jüttner (CERN) put it, "spectral-reconstruction methods are a game changer – but loads of development is still required". The challenge is that spectral densities, which describe how the states of a system are distributed in energy, cannot be calculated directly on the lattice. Instead, they have to be reconstructed from correlation functions, a notoriously difficult inverse problem. Shoji Hashimoto (KEK) explored the challenges and the rapid progress being made, from new mathematical ideas to improved numerical methods and their first phenomenological applications. The potential payoff is considerable, as these methods would make it possible to compute quantities long thought to be beyond reach, such as inclusive decay rates, hadronic amplitudes and energy-smeared versions of the R-ratio, the ratio of the cross-sections for electron–positron annihilation into hadrons and muons. Such quantities are central to precision tests of the SM, offering new ways to determine quark-mixing matrix elements and to study the hadronic vacuum polarisation that enters the muon g–2.

Additional highlights were the lattice-QCD determination of $|V_{cb}|$ from inclusive B_s semileptonic decays, reported by Alessandro De Santis (Helmholtz Institute Mainz), and new results on the smeared R-ratio from Francesca Margari (University of Rome Tor Vergata). Experiments disagree on the cross-section for electron–positron annihilation into two pions, which dominates the R-ratio at low energies, and preliminary lattice results agree better with experiment when the KLOE and BaBar data are replaced by those of CMD-3.

Xin-Yu Tuo (Brookhaven National Laboratory) reported progress in lattice calculations of radiative corrections to weak decays. A puzzle in the radiative decay of a pion or a kaon into an electron and a neutrino was resolved through the inclusion of collinear photons, emitted almost parallel to the electron, showing that radiative corrections must account for experimental details. Another topic, addressed by Andrea Shindler (RWTH Aachen University) and in several parallel talks, was the gradient flow, which has evolved from a technical smoothing procedure into a general QCD framework. Flow time restores rotational symmetry, with the benefit that continuum symmetries are easier to preserve. Avoiding mixing with lower-dimensional operators has made computations of higher Mellin moments for the pion and nucleon possible. Other applications of flow time range from quark masses and B-meson mixing to operators related to electric dipole moments. Shindler also raised the possibility of using the flow time as a genuine factorisation scale, rather than as an auxiliary parameter to be taken to zero.

Robert Perry (MIT), William Detmold (MIT) and Michael Wagman (Fermilab) addressed the problem of spectral incompleteness. The central realisation is that a statistically precise determination of an energy level is not necessarily reliable if the operators used in the calculation miss some of the states contributing to the correlation function. Spectral bounds can separate what the lattice data establish from what depends on assumptions about the spectrum. The controversy over whether two-nucleon systems are bound at the heavy pion masses used in some simulations served as a motivation.

The breadth of the field was reflected, from muon g–2 hadronic contributions to neural networks and quantum computing

In his talk on physics beyond the SM, Simon Catterall (Syracuse University) discussed how lattice theories can faithfully encode subtle anomaly structures, and how these anomalies may determine when fermions can acquire mass without breaking any symmetry. This opens a potentially new route to nonperturbative formulations of chiral gauge theories, in which left- and right-handed fermions interact differently, as in the SM, and to new-physics model building.

Accelerated solutions

Machine learning, reviewed by Daniel Hackett (Fermilab), was another recurring theme – although in a rather different guise than the current excitement surrounding generative AI. Rather than replacing established numerical methods, machine learning is becoming an additional tool that accelerates first-principles calculations, speeding up the solution of the Dirac equation by learning the setup of multigrid solvers, inverting the Laplace transform that relates correlation functions to spectral densities or, most ambitiously, generating entire gauge configurations with normalising flows, a goal not yet reached for realistic QCD simulations.

The next symposium will be held in Nicosia, Cyprus, from 20 to 26 June 2027.

Constantia Alexandrou *University of Cyprus and The Cyprus Institute,* **Antonio Evangelista** *University of Cyprus and* **Francesco Sanfilippo** *INFN Roma Tre.*

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SUPERGRAVITY AT 50

Supergravity turns fifty

From 2 to 4 June, an international conference at the Simons Center for Geometry and Physics at Stony Brook University celebrated the 50th anniversary of supergravity, the theory of local supersymmetry, which necessarily includes gravity. Supergravity was discovered in 1976 by Daniel Freedman and Peter van Nieuwenhuizen at Stony Brook, and Sergio Ferrara of CERN. A month later, Stanley Deser and Bruno Zumino, both at CERN, found a useful reformulation. Since those early days, supergravity has opened many fertile areas of research in classical and quantum field theory, particle physics, gravitation, cosmology and mathematics. All these areas are still active today, and all were discussed at the conference, whose talks are available on the Simons Center website.



Stony Brook University

Super group *Participants of Supergravity at 50 at the Simons Center for Geometry and Physics, Stony Brook University.*

The implications of supersymmetry for quantum field theory, perturbative and non-perturbative, carry over to supergravity, but in ways that have led to new insights. One example is the appearance of gravitational chiral anomalies, quantum effects that would break the coordinate invariance of general relativity and make a theory inconsistent, and their first cancellation, in type-IIB supergravity in 10 dimensions. This was followed by the discovery of anomaly cancellation, suggested by string theory, in supergravities with the minimal amount of supersymmetry, leading to the first superstring revolution of 1984. From then on, supergravity was largely seen as the low-energy limit of superstring theory.

Strong–weak dualities

For most of the next decade, then, features of supergravity theories absent from string theory were generally viewed as artefacts of a low-energy approximation. However, the early 1990s brought advances in the understanding of strong-weak dualities in supersymmetric gauge theories – equivalences showing that a theory with strong, intractable interactions can describe the same physics as one with weak, calculable ones. In their wake, generalisations of classical superstrings to two-dimensional membranes and higher-dimensional objects began to be considered as potentially relevant to the search for a unified theory.

Another example of new insights discussed at the conference is U-duality, which unifies the non-perturbative S-duality of gauge field theory, which exchanges strong and weak coupling, with the perturbative T-duality of string theory, which relates string theories on large and small compact dimensions. Combined in this way, the two dualities form a quantum version of symmetries that supergravity had revealed in its early years, and that extend the familiar duality between electric and magnetic fields. Such dualities turn strings into other extended objects, called branes, so superstring theory must contain these as well. Branes had appeared before, as solutions of the supergravity equations describing black holes. Dualities and branes led directly to a unification of superstring theories, and to the inclusion of 11-dimensional supergravity as a low-energy approximation to a new and still elusive M-theory.

New infinite-dimensional algebras and superalgebras, mathematical structures used to describe symmetries, emerged from supergravity theories. One of them, the E10 algebra, is closely related to cosmological singularities, which Vladimir Belinski, Isaak Khalatnikov and Evgeny Lifshitz analysed in detail. In line with their analysis, the E10 symmetry of maximal supergravity, the version with the most supersymmetry, is expected to appear approaching the space–time singularity, in a limit analogous to the high-energy limit of gauge theories such as the Standard Model (SM). This insight might lead to concrete scenarios for the emergence of space and time in quantum gravity.

Supergravity has also provided an arena for exploring models of inflation, a proposed period of rapid expansion in the very early universe, and for work in mathematics. An important part of the early developments was the coupling of supergravity to matter, which revealed new geometric structures governing how matter fields interact. Several of the global symmetries of supergravity theories could also be gauged, that is, made to vary from point to point, with a profound influence on contemporary research. The resulting potential energy of the scalar fields allows for vacua with the geometry of anti-de Sitter space, which brings gauged supergravities to centre stage in the AdS/CFT correspondence, the equivalence between gravity in such a space and a quantum field theory on its boundary. Its diverse applications, as discussed in several talks, range from holographic renormalisation-group flows, which track how a theory changes with energy scale, to black-hole attractors, entropy computations and microstate counting.

Supergravity has become a scaffolding on which our best account of quantum gravity is built

Exceptional theories

The original aim of supergravity was to yield a finite theory of quantum gravity, and to explain the structure of the SM. The infinities, or ultraviolet divergences, of the largest supergravity theory, the N = 8 model in four dimensions, cancel up to and including five loops, and their study has contributed new techniques now used for SM calculations. From a supergravity perspective, superstring theory is the ultraviolet completion, valid at all energies, of certain quantum field theories. But direct insight into the Standard Model and the detection of supersymmetric partners have not yet been achieved. One approach has been to revive the century-old ideas of Theodor Kaluza, Oskar Klein, Vladimir Fock and others (p42), curling up extra dimensions to reduce the 10- and 11-dimensional theories to our world. A first result was the natural appearance of the exceptional groups E7, E6 and others, which "exceptional" field theories now make manifest from the start.

Finally, speakers reviewed the status of three approaches to supergravity – conformal tensor calculus, the superspace formulation and the group-manifold approach.

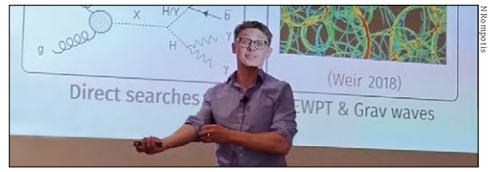
Supergravity is no longer mainly a theory of particle physics. It has become something more useful still, a scaffolding on which our best account of quantum gravity is built and a framework for quantum field theory, string theory and mathematics. Above all, the Stony Brook conference was a measure of how far supergravity has come.

Luis Álvarez-Gaumé *and* **Peter van Nieuwenhuizen** *Stony Brook University.*

EXTENDED SCALAR SECTORS FROM ALL ANGLES 2026

The Higgs looks for company

Fourteen years on, the 125 GeV Higgs boson is still the only known fundamental scalar. Whether it will remain so, is the business of a community spanning collider physics, phenomenology, cosmology and particle astrophysics. From 1 to 5 June, the second edition of Extended Scalar Sectors From All Angles brought 132 of its members to CERN to assess the theories that call for additional scalars and the searches that constrain them.



Nikolaos Rompotis

Effective field theories

David Sutherland (University of Glasgow) argues that many models which feature extended scalar sectors, probed with a combination of direct searches and precision measurements, can be tested at next-generation experiments.

Discussions ranged from ongoing searches at the LHC to the prospects offered by future facilities. ATLAS and CMS supplied most of the experimental talks, covering their direct searches for new scalars as well as their indirect ones, through precision studies of the Higgs boson's CP properties and rare decays. LHCb presented searches for light scalars produced in b-hadron decays, while FASER, which sits far downstream of the ATLAS collision point to catch light, long-lived particles, reported searches probing new scalars with masses down to a few GeV.

A recurring theme was the close interplay between theoretical ideas and experimental discoveries, with new theoretical developments inspiring novel search strategies and increasingly precise measurements guiding the exploration of new physics. Examples came from the recent searches for the Inert Doublet Model by the CMS experiment, corresponding to the first dedicated study for this model using LHC data. Many presentations focused on how additional scalar particles could help address outstanding puzzles in modern physics, such as the nature of dark matter and the origin of the asymmetry between matter and antimatter, the latter – for example – by allowing for CP violation in the extended scalar sector that leads to a viable mechanism of baryogenesis.

The conference also reflected the growing importance of precision measurements. A striking example was a CERN theory colloquium by David Sutherland (University of Glasgow), embedded in the conference programme. Sutherland argued that although we know that nature is Standard Model–like around the vacuum expectation value of the Higgs boson, it may be very different at different values. Searching for extended Higgs sectors will cover this possibility and has to be done both directly, through searches for new resonances, and indirectly, by constraining effective field theories with precision measurements.

While no definitive evidence for new scalar particles has yet emerged, the conference conveyed a strong sense of optimism and momentum. With the High-Luminosity LHC on the horizon and future collider projects under active consideration, the search for an extended Higgs sector remains one of the most promising paths towards physics beyond the Standard Model.

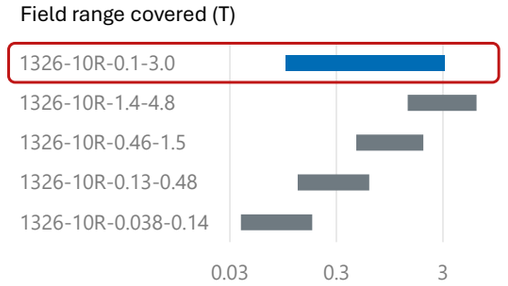
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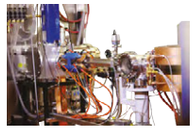
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Ring out *The open end of a magnet string in the RHIC tunnel in May 2026. One of the accelerator's two rings is being dismantled as the first step towards the Electron–Ion Collider. (Credit: D Rahner/Brookhaven National Laboratory)*

THE MANY LIVES OF RHIC

Last February, the Relativistic Heavy Ion Collider delivered its last colliding beams. James Dunlop and Wolfram Fischer recount a quarter century of discovery at the first collider built for heavy ions, and the only one to have run with polarised protons.

The proton–proton collider ISABELLE, at Brookhaven National Laboratory, was cancelled in July 1983 with its 3.8 km tunnel already constructed (*CERN Courier* July/August 2026 p22). Within the year, the nuclear-physics community had proposed reusing it for a quantum-chromodynamics (QCD) machine capable of producing the quark–gluon plasma (QGP) – a state in which quarks and gluons are no longer confined within protons and neutrons. Thus began, in 1991, the construction of the Relativistic Heavy Ion Collider (RHIC), which became the first collider designed specifically for heavy ions and the only one to collide polarised protons (see "Bird's-eye" figure).

When RHIC's first gold ions collided in 2000, the BRAHMS, PHENIX, PHOBOS and STAR experiments observed strong collective motion and a suppression of high-transverse-momentum particles, evidence for matter at record energy density. Because the suppression could also have originated in the structure of the gold nuclei themselves, the four experiments turned to deuteron–gold (d–Au) collisions, in which no hot matter was expected to be created but any effects from the gold nuclei would still be apparent. By examining different aspects of the events, they observed no suppression and proved that the effect seen in gold–gold (Au–Au) collisions was due to jet quenching – the loss of energy by

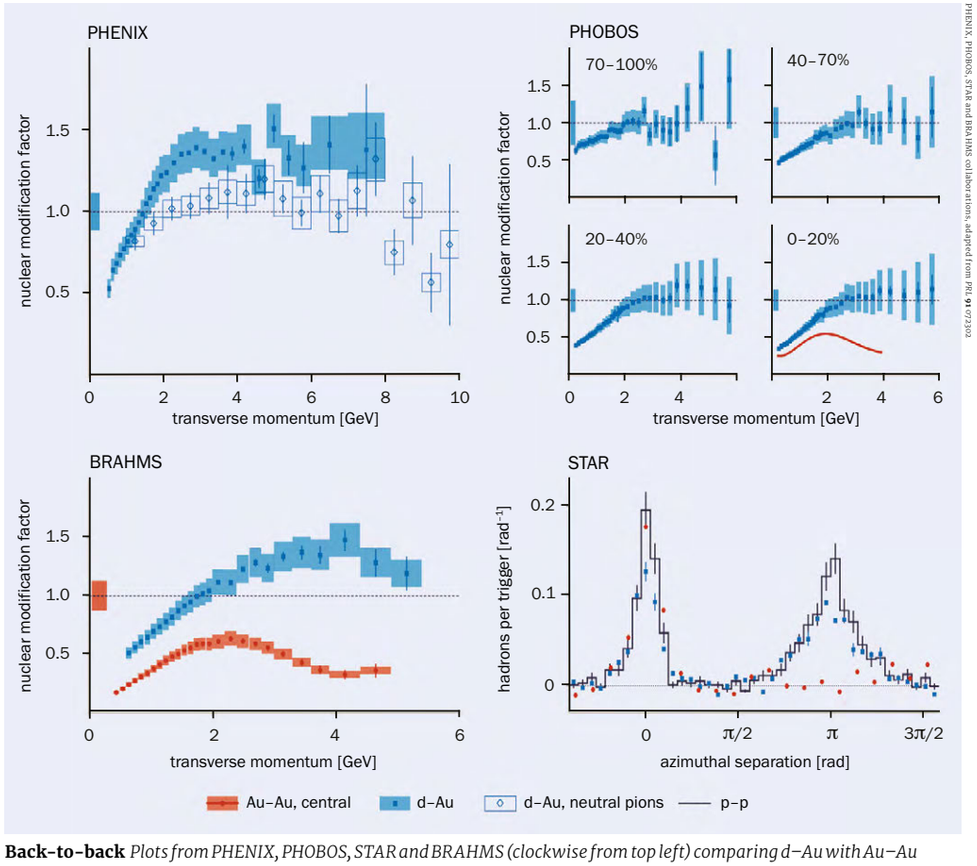
THE AUTHORS

James Dunlop *and* **Wolfram Fischer**
Brookhaven National Laboratory.

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The latest datasets allow for the exploration of the three-dimensional spin-dependent structure of the proton



PHENIX, PHOBOS, STAR and BRAHMS collaborations, adapted from *PRL* **91** 072302

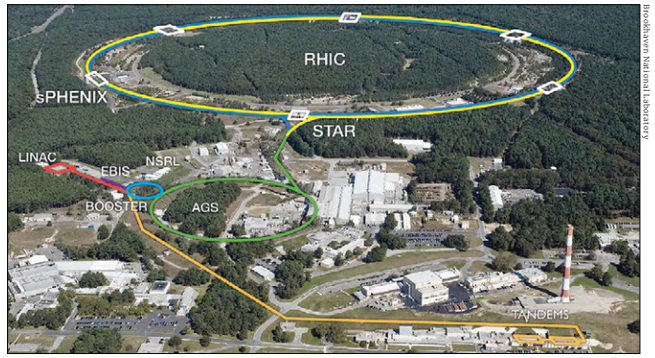
Back-to-back *Plots from PHENIX, PHOBOS, STAR and BRAHMS (clockwise from top left) comparing d–Au with Au–Au collisions at RHIC. PHENIX shows the nuclear modification factor (the yield per nucleon–nucleon collision relative to proton–proton collisions) in d–Au collisions for charged particles and neutral pions. The PHOBOS panels run from the most peripheral collisions (70–100%) to the most head-on (0–20%). STAR plots the azimuthal angle between an energetic particle and each accompanying one above 2 GeV. BRAHMS compares d–Au collisions with the most head-on Au–Au collisions (0–10%). The bars and boxes show statistical and systematic uncertainties, respectively. The suppression of high-momentum particles and disappearance of back-to-back correlations seen in central Au–Au collisions are absent in d–Au collisions.*

fast quarks and gluons in the dense QGP medium. The complementarity of their results was made explicit in August 2003, when the cover of *Physical Review Letters* displayed a plot from each (see "Back-to-back" figure). In 2005, the experiments published white papers on their collected measurements, which revealed that the matter created at RHIC behaved not as the anticipated weakly interacting gas, but as a strongly interacting, nearly perfect liquid, flowing with almost no internal friction. These remain among the most highly cited papers in nuclear physics.

Snakes in the rings

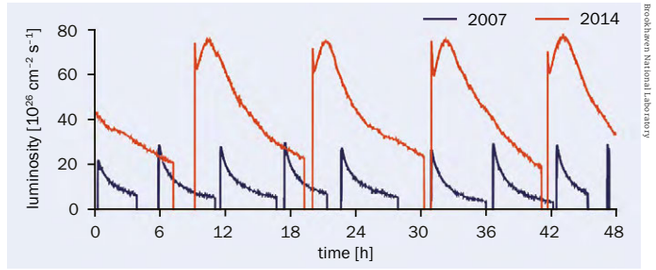
The RHIC spin programme, which collided beams of spin-aligned protons, was started in 2001, in response to the so-called "proton-spin crisis" – the 1988 finding by the European Muon Collaboration that quarks could only account for a fraction of a proton's spin. Polarised collisions were not part of RHIC's original design, and much of the required technology had yet to be demonstrated. A high-intensity optically pumped polarised ion source (OPPIS) produced beams with up to 83% polarisation. At the same time, partial Siberian snake magnets kept the proton spins aligned as the beam gained energy in the Alternating Gradient Synchrotron (AGS) without elaborate resonance-by-resonance corrections. At RHIC, two full Siberian snakes in each ring allowed protons to reach 255 GeV with little polarisation loss. Spin rotators provided longitudinal polarisation at the experiments, while proton–carbon and polarised hydrogen-jet polarimeters monitored the beam polarisation (*CERN Courier* October 2005 p15).

After more than a decade of development of luminosity, polarisation and measurement techniques, the STAR and PHENIX collaborations decisively established that gluon polarisation contributes to the spin of the proton and, from parity-violating W decays, found an unexpected difference between the polarisations of the up and down antiquarks within a polarised proton. The observation of large transverse single-spin asymmetries at high energy and the exploration of their connection to the transverse-momentum-dependent structure of the proton will be a lasting legacy of RHIC. The latest datasets, taken with transverse polarisation, allow for the exploration of the three-dimensional spin-dependent structure of the proton, developing techniques that will be used at the future Electron–Ion Collider (EIC).



Brookhaven National Laboratory

Bird's-eye *An aerial view of RHIC's two rings (blue and yellow) and the chain of accelerators that fed them. Protons started in the 200 MeV linac (red). Ions came from the tandem accelerators (orange) until 2012, and mainly from the electron beam ion source (EBIS, purple) after that. Both then passed through the Booster (light blue) and the Alternating Gradient Synchrotron (AGS, green) before entering the collider. White squares mark the six points where the beams crossed, two of which housed STAR and, from 2023, sPHENIX, the two detectors still in operation when the final beams circulated. The Booster also supplied beams to the NASA Space Radiation Laboratory (NSRL).*



Brookhaven National Laboratory

Cooler and brighter *The curves show RHIC's Au–Au luminosity over two days of running in 2007 (dark blue) and 2014 (orange). With stochastic cooling in both rings, the 2014 stores dipped briefly after each fill, then grew brighter as the cooling took hold, and lasted twice as long.*

Stochastic cooling

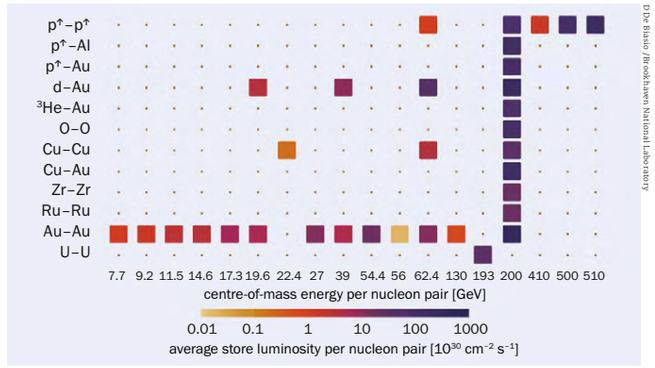
Heavy ions in a stored beam scatter off each other, causing the beam size to grow and the collision rates to drop, so that the machine requires frequent refilling. To counteract this effect, stochastic cooling systems, which sense variations within the beam at one point of the ring and correct them with kicks at another, were installed in RHIC between 2006 and 2014, to act in both the transverse and the longitudinal directions. While stochastic cooling had previously been used at much lower energies for unbunched beams, RHIC was the first machine to apply it to bunched beams and the first hadron collider to cool both of its beams.

The system demonstrated its full capabilities during RHIC's uranium–uranium (U–U) run in 2012 (*CERN Courier* October 2012 p17) and subsequently enabled a large increase in Au–Au luminosity, eventually reaching 44 times the design value for the average store luminosity (see "Cooler and brighter" figure). Stochastic cooling also allowed more ions to be stored. As a result, RHIC could operate with high luminosity near the "burn-off" limit, where almost all ions are lost through collisions with those in the opposing beam.

The high luminosity, together with the silicon-detector upgrades operating in PHENIX from 2011 and in STAR from 2014, enabled next-generation studies of the QGP created at RHIC, including precise observations that charm quarks flow along with the nearly perfect liquid, measurements of electromagnetic probes to constrain its temperature and space–time evolution, and measurements of quarkonia as a major probe of deconfinement. The control over the beams that cooling brought also underpinned many of the later runs with novel beam combinations.

New ions, new questions

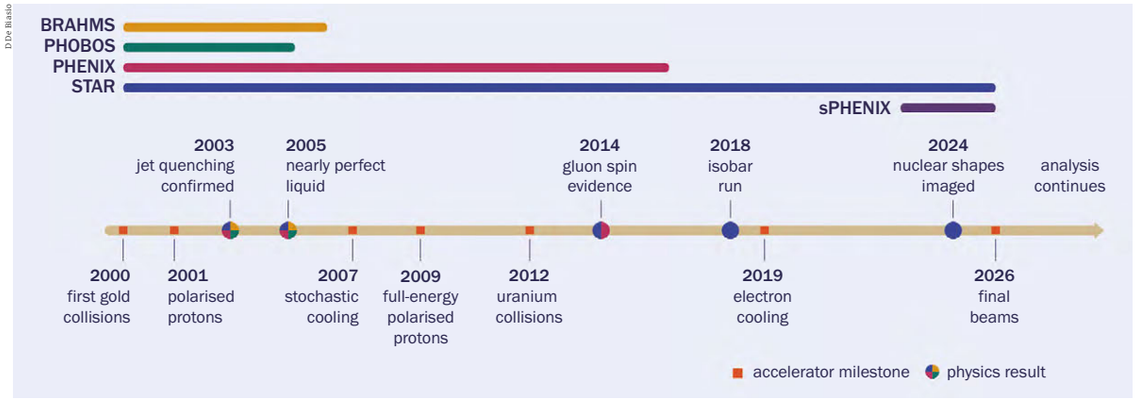
RHIC was designed for flexibility. Its two superconducting rings operated almost independently, coupled only by two dipole magnets in each of the six interaction regions, which brought the beams into collision and separated them again. The ion sources and injector chain could deliver beams ranging from polarised protons to uranium ions and switch rapidly between species for asymmetric collisions. Over its lifetime, the machine collided 12 different pairs of species, five of them asymmetric and three involving at least one polarised beam, at 18 centre-of-mass energies, for a total of 33 distinct combinations of species, energy and collision configuration (see "Thirty-three ways"



D De Blasio/Brookhaven National Laboratory

Thirty-three ways *Every combination of colliding species and centre-of-mass energy run at RHIC between 2000 and 2026, coloured by the average store luminosity per nucleon pair between one filling of the rings and the next. The nominal injection energy corresponds to a centre-of-mass energy of 19.6 GeV.*

D De Blasio



Long runs *A timeline of RHIC from its first collisions to its last, with horizontal bars marking the years each experiment took data. The orange squares on the axis mark accelerator milestones, and each disc is a physics result divided among the experiments that produced it. Analysis of RHIC data continues after the final beams.*

A quarter century of RHIC beam operations ended on 6 February 2026 with a replay of the 2021 O–O collisions, the only ion species run in common with the LHC

figure). The STAR detector also operated in fixed-target mode, with gold beams at 13 energies from 3.85 to 100 GeV/nucleon.

The ability to collide nuclei of varying sizes and shapes has opened a new window on their structure. Starting with the U–U run, the near-perfect liquidity of the QGP has been used with increasing precision to take snapshots of nuclear shape. The method works because collective flow encodes the geometry of the initial overlap region in the momenta of the emitted particles, allowing the shapes of the initial nuclei to be inferred. Comparisons of p–Au, d–Au and ^{3}He–Au collisions extended this to small systems, providing evidence of fluid behaviour in small QGP droplets, while the isobar run took it to high precision by comparing ^{96}Ru–^{96}Ru with ^{96}Zr–^{96}Zr.

That two-month-long run used stochastic cooling and levelling to alternate between the two isobars daily, with 20-hour stores at constant luminosity. Beyond the shape differences of the two nuclei, the uniform data-taking conditions allowed for subtle measurements of charge versus baryon transport. These provide indications that topological configurations called baryon junctions, rather than valence quarks, carry baryon number in high-energy collisions. A quarter century of RHIC beam operations (see "Long runs" figure) ended on 6 February 2026 with a replay of the 2021 O–O collisions, the only ion species run in common with the LHC (*CERN Courier* May/June 2026 p10).

The phase diagram

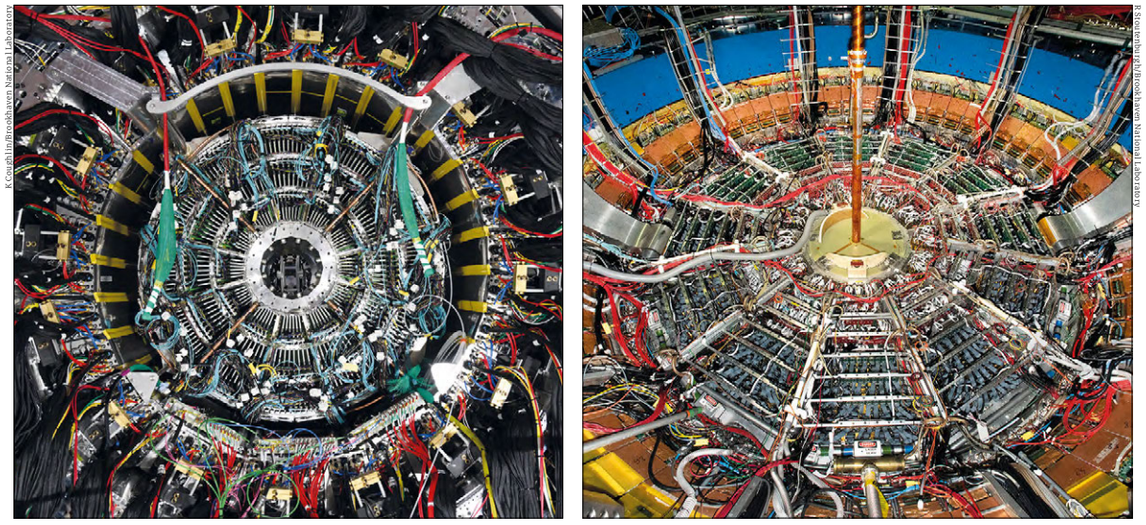
Colliders normally aim for the highest possible collision energy. RHIC also pushed the other way, far below its nominal injection energy. Operating there is challenging, since larger beam sizes, increased superconducting magnet field errors, and stronger space-charge and intrabeam-scattering effects all reduce collision rates. The effort called for extensive optimisation of machine and beam parameters. To increase the luminosity at the lowest energies, the new Low Energy RHIC electron Cooler (LEReC) was built, in which a beam of electrons travelling alongside the ions draws heat from them.

This was the world's first electron cooler based on an electron beam accelerated by radio-frequency (RF) systems. Earlier coolers relied on electrostatic acceleration to produce the very small momentum spread required for effective cooling. RF acceleration can reach much higher energies, but produces a large momentum spread, requiring multiple RF correction stages before the beam can be used for cooling. By overcoming this limitation, the RHIC electron cooler established a technology critical for the EIC.

The QCD phase diagram, when viewed on the axes of baryon chemical potential and temperature, is potentially quite rich (p5). At the highest RHIC energy, where the baryon density is small, lattice QCD calculations suggest that the phase transition from QGP to bound hadronic matter is a smooth crossover (*CERN Courier* September/October 2026 p41). At high baryon density, instead, effective models of QCD indicate that the transition should be first order. If a crossover and a first-order transition line both exist, they meet at a QCD critical point. Its signature would be a non-monotonic variation with collision energy of the event-by-event fluctuations in the number of net protons produced. The second phase of RHIC's beam energy scan, enabled at its lowest energies by electron cooling, searched for it in collisions from 7.7 to 19.6 GeV, as well as in fixed-target collisions from 3 to 13.7 GeV. RHIC's Beam Energy Scan has provided the world's most systematic

K Coughlin/Brookhaven National Laboratory

R Stoltenburgh/Brookhaven National Laboratory



Double exposure *The time projection chambers of sPHENIX (left) and STAR (right), which track the charged particles from each collision and measure their momenta. The sPHENIX chamber is 1.6 m across, the STAR chamber 4 m.*

exploration of the QCD phase diagram at finite baryon density, including measurements of fluctuations, correlations and collective observables sensitive to the possible critical point and to the nature of the transition. Beyond the search for the critical point, the broad, high-statistics dataset has enabled precision studies of how the fluid responds to baryon doping – the excess of baryons over antibaryons that grows as the collision energy falls – and under what conditions fluidity breaks down.

Enter sPHENIX

The sPHENIX detector, which took over PHENIX's hall in 2023 with a superconducting solenoid, latest-generation tracking detectors and calorimeters for measuring jets, required the highest possible luminosity in a limited vertex range of ±10 cm. To meet these requirements, a full crossing angle of 1 mrad was implemented, and the machine protection system was upgraded to safeguard the new silicon detectors close to the beam pipe.

In the 2025 run, sPHENIX took more than 200 PB of data, more than all previous RHIC raw datasets combined. High luminosity was also delivered to STAR, with the crossing angle switched between 0 and 1 mrad during the store (see "Double exposure" figure). While sPHENIX is still in the calibration phase for the bulk of its data, it has made standard-candle measurements of transverse energy and multiplicity in Au–Au collisions and has submitted for publication measurements of isolated photons and – for the first time at RHIC – fully corrected dijet momentum-imbalance measurements in p–p collisions. sPHENIX was designed to perform the full suite of jet-related measurements that have developed in the decades since the original jet-quenching discovery, such as fully reconstructed jets, jet substructure and jets containing heavy flavour. The statistical precision of the sPHENIX dataset will allow jet properties to be compared between RHIC and the LHC as a function of energy scale, to tease out the emergence of near-perfect fluidity from the interactions of quarks and gluons.

RHIC has combined sustained collider innovation with a constantly evolving scientific programme. It leaves a unique legacy in relativistic heavy-ion and polarised-proton physics, accelerator science and technology, as well as detector and computing development. Its impact extends from fundamental research and broader applications to the future EIC, which will collide polarised electrons with polarised protons and with nuclei to map the gluons inside them. The machine will build directly on RHIC by reusing one of its superconducting rings, its tunnel and the hadron injector complex. Moreover, while beam operations have ended, the rich RHIC dataset will continue to be analysed for at least another decade. ●

Further reading

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PHOBOS Collab. 2003 *Phys. Rev. Lett.* **91** 072302; PHENIX Collab. 2003 *Phys. Rev. Lett.* **91** 072303; STAR Collab. 2003 *Phys. Rev. Lett.* **91** 072304; BRAHMS Collab. 2003 *Phys. Rev. Lett.* **91** 072305.
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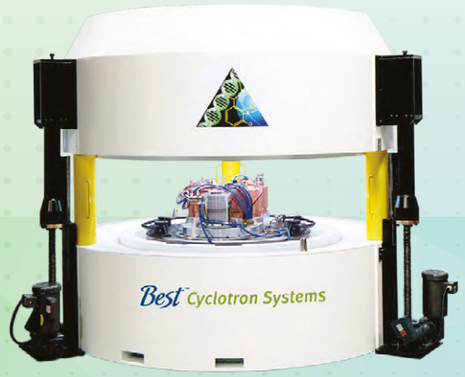
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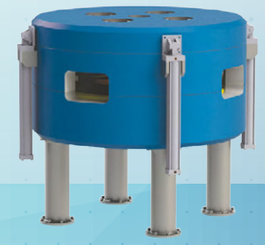
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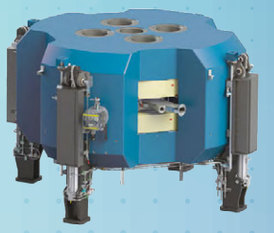
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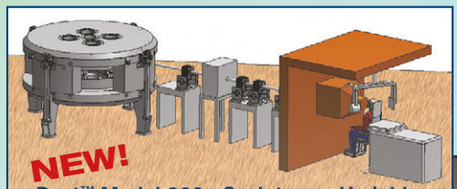
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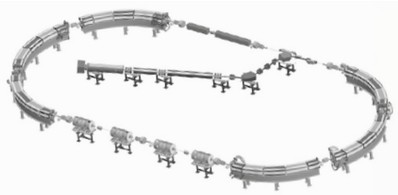


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Maintaining control over distributed data often presents unexpected hurdles for technology leaders. Improving a hybrid-cloud platform involves establishing clear security policies and continuous performance monitoring. By utilising centralised management tools, IT teams can oversee all resources from a single console. This proactive approach reduces complexity and keeps your daily operations running smoothly.

Avoiding vendor lock-in remains a top priority for organisations planning long-term growth. Expanding hybrid-cloud solutions requires the adoption of open standards and the prioritisation of cloud interoperability. Structuring your architecture to support multiple cloud services allows you to choose the absolute best environment for each specific task. This method empowers your business to maintain a true competitive advantage.

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AT THE BEND IN THE CURVE

At 35, arXiv has left Cornell University to become an independent non-profit. Scientific director Steinn Sigurðsson and board member Greg Morrisett discuss its origins as a mailing list for theorists, the critical role of its volunteer moderators and the strain artificial intelligence puts on the platform's trust-based model.

A generation of physicists has never done research without arXiv. Where did it come from?


Cornell University

Steinn Sigurðsson *is professor of astronomy and astrophysics at Penn State and scientific director of arXiv.*

Steinn Sigurðsson arXiv came out of the custom of circulating paper preprints. In the 1980s, the major institutes would post the week's preprints in an envelope, and because that cost money, they only sent them to their friends (see "Paper trail" figure). Harvard sent a single copy of each to Princeton or Berkeley, but not to every university, so there were literally fights over them. As a graduate student, I remember sitting in the hallway, waiting for a professor to finish with the preprints and toss them out.

Then string theory became extremely hot and people did not want to wait for results. Joanne Cohn, then a postdoc at the Institute for Advanced Study, was sending the TeX source of new papers around by email, but the list had grown cumbersome. In the summer of 1991, we were at the Aspen Center for Physics, and somebody said, "This is stupid. We have computers. Why don't you automate it?" Paul Ginsparg, then at Los Alamos, was intrigued, and by the next day he had written the scripts. All of this happened before the web.


CERN

Paper trail *Library staff working on the catalogue of newly arrived preprints at the CERN Central Library in 1968. Long before arXiv, the library collected unpublished manuscripts from institutes around the world, sorted them by subject and put them on display for researchers at the laboratory.*

Peer review is often presented as a guarantee of scientific reliability. In practice, physicists read an article on arXiv first, and often only there. What responsibility does that place on the platform?

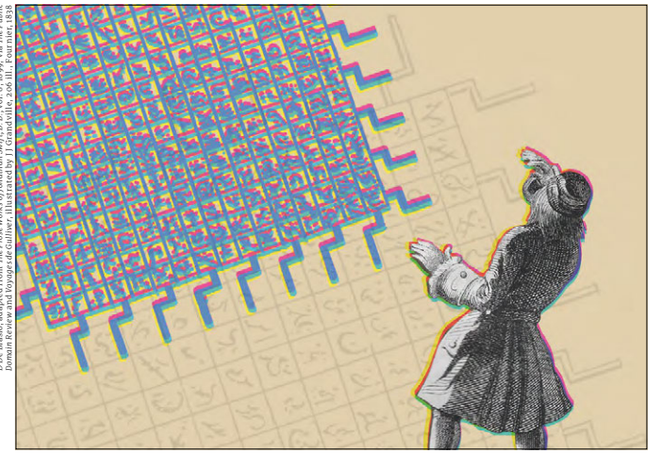
Steinn The early adopters were professional researchers, so arXiv ran on reputational risk. You put a paper on arXiv when you were ready, on the assumption that if you screwed up we would know, and if you screwed up a lot you were a screw-up.

Multiple studies over the years have found that most papers do not change much through peer review. Although, as I like to point out, adding the word "no" is a tiny change that is very substantive. On the theory side, it may also matter more to be interesting than correct. Many of the big breakthrough papers were concept papers with flaws, and the ones that survived are the ones whose flaws got cleaned up. That distinction is going to matter in the artificial intelligence (AI) world, where there will be a lot of papers that are correct but that nobody cares about.

THE AUTHOR

Interview by
Davide De Biasio
editor.

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D De Biasio, adapted from *The Prose Works of Jonathan Swift, D. D.*, vol. 8, 1899, via *The Public Domain Review* and *Voyages de Gulliver*, illustrated by J J Grandville, 1composé 26 ill., Fournier, 1838

Without genius or study *In* Gulliver's Travels *(1726), Jonathan Swift envisaged The Engine (left), a machine capable of continually rearranging words. According to its inventor, "the most ignorant person, at a reasonable charge, and with a little bodily labour" could use it to write books on philosophy, poetry, politics, law, mathematics and theology.*

Most researchers click submit, go to bed and find the paper online in the morning. What happens in between?

Steinn If you are an established author and your papers have gone through without problems, your next paper usually passes unless something raises a concern. We rely on trust. New authors get a closer look. Most of the time the moderator glances at the title and abstract, sees what it is about, often knows the people involved, and it is fine.

A smaller fraction needs follow-up and is put on hold. The paper may belong in a different category, fall outside arXiv's scope, be completely deranged rubbish, or simply contain something weird that needs checking. And taking a look is not fun. It can be fascinating, but it is not enjoyable. The hold queue has to be cleared as fast as it fills, and that is where arXiv is breaking down, because the holds are building up faster than we can clear them.



Cornell University

Greg Morrisett *is dean and vice provost of Cornell Tech and a member of arXiv's board of directors.*

Greg Morrisett If I can add to that, there are also lots of well-meaning people submitting things that do not belong on arXiv. Students, for instance, post final projects that may be fascinating documents but are not research for the audience arXiv serves. Many people think arXiv is just a website, when it is really a community of some 270 volunteer moderators and 25 staff. Paul Ginsparg recognised early that the attention of the readers is what is valuable, and moderation protects that attention.

Steinn Exactly. If every introductory computer-science instructor told students to put their term projects on arXiv to learn how submitting to arXiv works, then arXiv would die.

On 1 July, arXiv left Cornell University to become an independent non-profit. Why?

Greg Paul moved from Los Alamos to Cornell in 2001 and brought arXiv with him. The university was never quite sure where to put it, because it is neither an institute nor a research centre. It started in the library, and eventually the provost handed it to me when I was dean of computing and information science. As a computer scientist, I valued arXiv immensely, so I was happy to take it on.

Meeting arXiv's funding needs was always difficult, and we were limited in our ability to hire developers. I love universities, but they are not set up to run a production web service, an archive and a volunteer community. There was a good argument for staying. Universities endure, and that matters to something that is supposed to last. But there was also a risk that a future dean might not value arXiv as much as I did.

So we created an independent non-profit and moved the staff across from Cornell, with the Simons Foundation and others stepping up to fund it for its first three years. The aim is to give arXiv clearer leadership, more flexibility to hire and a structure built around its own mission, rather than leaving it as an unusual service inside a university.

What will users notice?

Greg Everybody worries about this. On 1 July, hopefully nobody noticed anything more than a change of colour, because we took the Cornell seal off the webpage. That was intentional, because the core mission is exactly the same. There were concerns that arXiv would suddenly be supported through advertising. Not at all.

There will be small changes that add capabilities. The HTML renderer we developed for accessibility turned out to be useful to everybody, and we want better tools for moderation and discovery. But we are not expecting the experience of submitting or reading a paper to change substantially.

Could somebody one day buy arXiv and turn it into something else entirely?

Greg A famous billionaire, who has since passed away, once tried to buy arXiv. We said no. The new organisation has a board drawn from the arXiv community, so that it understands the core mission and ethos. Who knows what the future holds, but no, I do not expect arXiv to sell out. Like any non-profit, it will have to live within its means.

Submissions are surging (see "Overtaken" figure), and AI now writes or assists some of them. From the inside, how much has that changed arXiv?

Steinn The short answer is that things are changing faster than we can deal with them, week by week. We went very quickly from many submissions that were mostly garbage slop to highly polished fluff, a mix of correct although

Many people think arXiv is just a website, when it is really a community of volunteer moderators

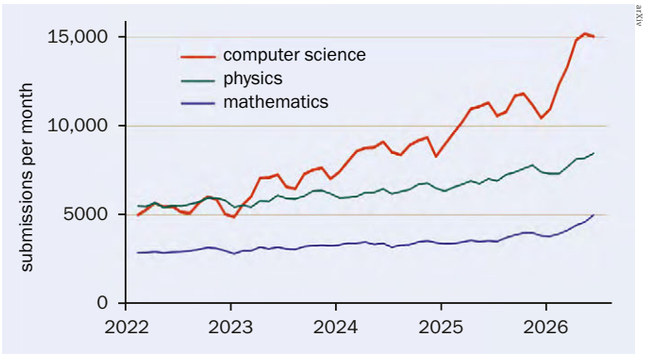
trivial results, but recently including some increasingly substantive and even novel research results (see "Without genius or study" figure). My canonical example is a high-schooler who grabs a public dataset of X-ray images of cancer patients, runs a slightly modified open-source model and concludes it does 1% better at diagnosing cancer. It looks like a paper. It has a claim and a result, but it is done by someone who does not understand what they are doing.

At the same time, genuinely interesting results are arriving at a higher rate. Projects people had set aside, what I call graduate-student test projects, interesting and worth doing but not top of the queue, are being wrapped up in days by teams of AI agents. In modelling or theory, something that might once have been a chapter of a PhD thesis can now take anything from hours to a few days. You can do it live. I was sitting in a meeting the other day and asked Claude, "How about this as an alternative explanation of what the speaker just said?" Claude said, "No, there is this one problem." So I asked Gemini, "Is Claude right?" Gemini said, "Yes, but there is a way around it." There was a concept for a paper in 40 minutes.

Disruptive results from AI-assisted work are near. We have hit the bend in the curve. Our current mantra inside arXiv is that the only thing that scales like AI is AI.

AI is also breaking the alignment of incentives. Counting papers is going to become meaningless. If I took this afternoon off, I could probably send out five papers today. So we need to identify the papers on which other researchers actually build. We are going to use knowledge graphs and semantic analysis to see where ideas are going and what later work depends on.

The difficult part is that some of the mechanisms that work can also be retrogressive. Some journals are already moving towards systems where you need people to vouch for you before you can submit. That takes us back towards the 19th century and the idea that somebody has to say you belong to the club.



Overtaken *Monthly submissions to arXiv in its three largest fields, averaged over three months. Computer science overtook physics at the start of 2023, and in each month of the first half of 2026 it received more papers than physics and mathematics combined.*

Greg, what can arXiv itself do?

Greg We were already writing more than people were reading, and that has now exploded. The scarce resource is the attention of readers, their eyeballs and their time. I do not think anybody yet has an answer to how readers should deal with that onslaught.

One change we have made goes back to trust. An academic email address used to be a useful heuristic. Whoever had one was probably a researcher, so we let it fly. Since January, we have asked for endorsement of new authors, including those with academic addresses, to put some of that reputational pressure back into the system. It seems to have helped a little.

There are also things we can automate. We can scan for dangling references and other signs that something is wrong, then give moderators better evidence about what deserves a closer look. But the social incentives matter just as much. For 30 years, if you posted crap on arXiv, your reputation suffered and people trusted you less.

Endorsement works, but it is antithetical to one of our principles, which is to be open and accessible to the whole world. That tension will be a challenge no matter what.

This year, arXiv turns 35. How would you like to see it at 50?

Greg Still serving the communities and surfacing the research people want to read. I would love to see arXiv expand into adjacent areas, but that takes a willing community with the preprint ethos. You cannot simply add a category to a menu.

I would also like moderators to enjoy the role again. Tom Dietterich used to describe the excitement of having the great papers cross your desk first. We now get around 100 machine-learning papers a day, and no human can read them all and keep a sense of the field. Moderators need sophisticated automation, and readers need better tools to find papers, make connections, summarise and translate.

Paul's taste in setting up arXiv also matters. LaTeX was not an obvious choice, but it means that papers from 30 years ago can still be rendered in new ways. He was also wise not to compete with journals. I would welcome more open journals overlaid on arXiv, with arXiv remaining the distribution layer and peer review sitting above it.

When you show the site to a non-scientist, they say, "This looks like 1990s HTML," and we say, "Yeah, exactly." We are not trying to be flashy. It serves the community well, and we do not want to mess that up.

Steinn I agree with Greg. I would add that arXiv is now a large repository of knowledge, but its primary purpose is to serve up new science. Somebody is going to be doing science, somebody is going to be parsing that science and somebody is going to use it to do more science. arXiv should be there in the middle, enabling that at speed and scale. ●

arXiv is now a large repository of knowledge, but its primary purpose is to serve up new science

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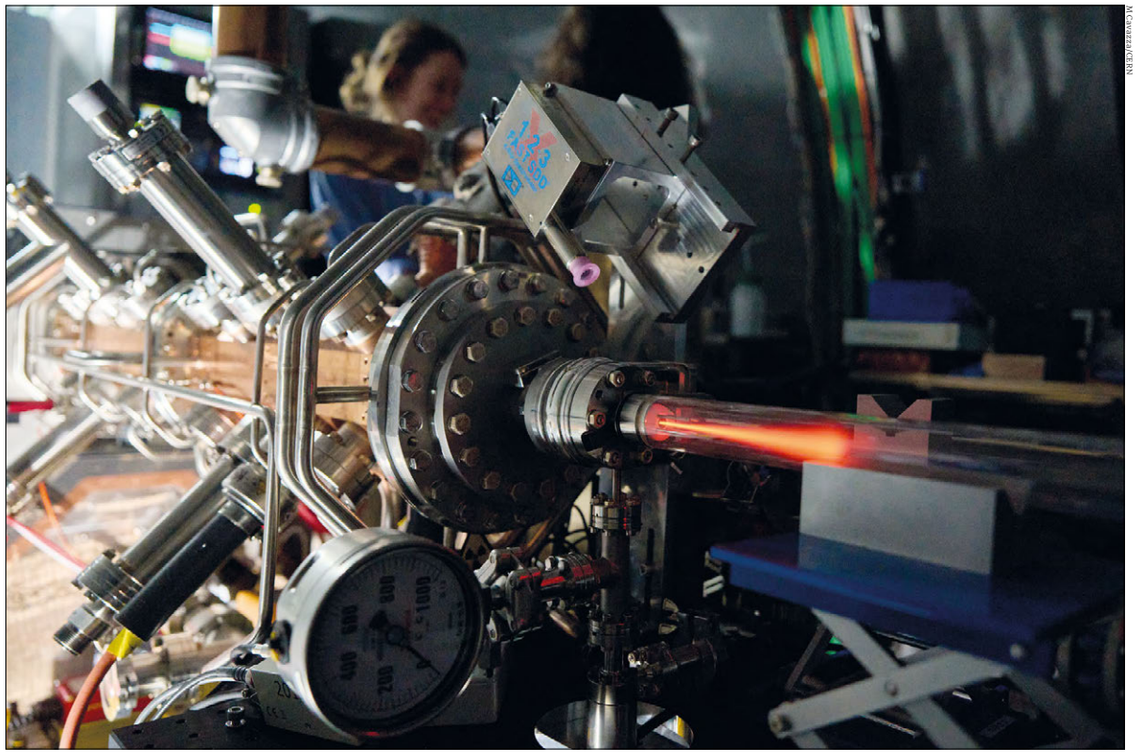
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THE ACCELERATOR GAP IN CANCER THERAPY

Each generation of cancer-therapy machines has been more precise than the last, and more demanding to own and operate. Maurizio Vretenar describes the accelerator research at CERN and beyond that aims to break the pattern.



M Cavineza/CERN

Peak out *A low-energy proton beam from ELISA, a one-metre accelerator at CERN, ionises a few centimetres of air. The glow is brightest at the end of its range, where the protons deposit most of their energy. The same effect, at higher energies, allows proton therapy to target tumours while sparing healthy tissue.*

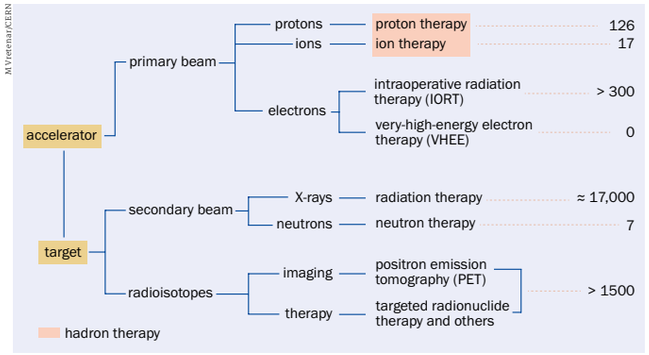
Cancer is responsible for nearly 10 million deaths a year – about one in six worldwide – and the number of new cases is expected to rise from roughly 20 million in 2022 to more than 35 million by 2050, driven by population growth, aging and the increasing prevalence of risk factors. Mortality, however, has been falling steadily. In the United States, for instance, cancer-related death rates dropped by as much as 34% between 1991 and 2022.

The trend hinges on access to modern technologies for early detection, diagnosis and treatment. Among them, particle accelerators take centre stage. Positron emission tomography (PET) relies on radioisotopes produced by particle accelerators to detect tumours with high sensitivity. Radiotherapy – one of the three main pillars of cancer treatment, along with surgery and chemotherapy – targets them with high-energy X-rays or charged particles, such as protons and heavier ions.

The large majority of medical accelerators are compact

THE AUTHOR
Maurizio Vretenar
CERN.

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M Vretenar/CERN

Family tree *The medical uses of particle accelerators, with approximate worldwide counts. Primary beams of protons, ions and electrons treat patients directly, and X-rays and neutrons are produced on a target. Radioisotopes are made mostly in compact cyclotrons, and can be shipped far from the production site to supply imaging and radiopharmaceutical therapy.*

machines used for conventional X-ray radiotherapy, with about 17,000 units operating worldwide (see "Family tree" figure). Far fewer large units deliver protons or carbon ions for hadron therapy, while few small, low-energy electron accelerators are used for intraoperative radiation therapy. More than 1500 accelerators, typically small cyclotrons, are in operation worldwide to produce radioisotopes for imaging, therapy or the combination of the two, known as "theranostics" (*CERN Courier* May/June 2026 p30).

Behind these encouraging numbers, however, lies a striking geographical imbalance (see "Unequal doses" figure). Data from the Directory of Radiotherapy Centres of the International Atomic Energy Agency (IAEA) show that most of the radiotherapy equipment is concentrated in high- and upper-middle-income countries. While one of the reasons for this disparity is their higher average age, which makes cancer a more prominent cause of death, it is clear that low- and middle-income countries lack access to modern accelerator-based medical technologies.

Collateral damage

The workhorses of radiation therapy are X-ray linacs. They are compact, roughly one-metre-long linear electron accelerators reaching an energy between 5 and 25 MeV. Their electron beam impinges on a tungsten target, where it produces high-energy X-rays that destroy cancer cells. In most of them, the accelerator is of the "side-coupled" type, developed in the 1960s at the Los Alamos Meson Physics Facility (USA) for studies of nuclear and subnuclear matter. This compact design delivers a stable and reproducible beam by packing the accelerating cells closely and keeping the field between them steady. Although the accelerator at their core is relatively simple, radiotherapy linacs incorporate many sophisticated subsystems and require significant operating infrastructure and regular maintenance. Moreover, X-ray radiation attenuates only slowly as it passes through the body, and reaching deep-seated tumours requires a beam to traverse large portions of healthy tissues. Collimators and multi-angle

The large majority of medical accelerators are compact machines used for conventional X-ray radiotherapy

The limited availability of accelerator-based therapies is related to their cost and complexity

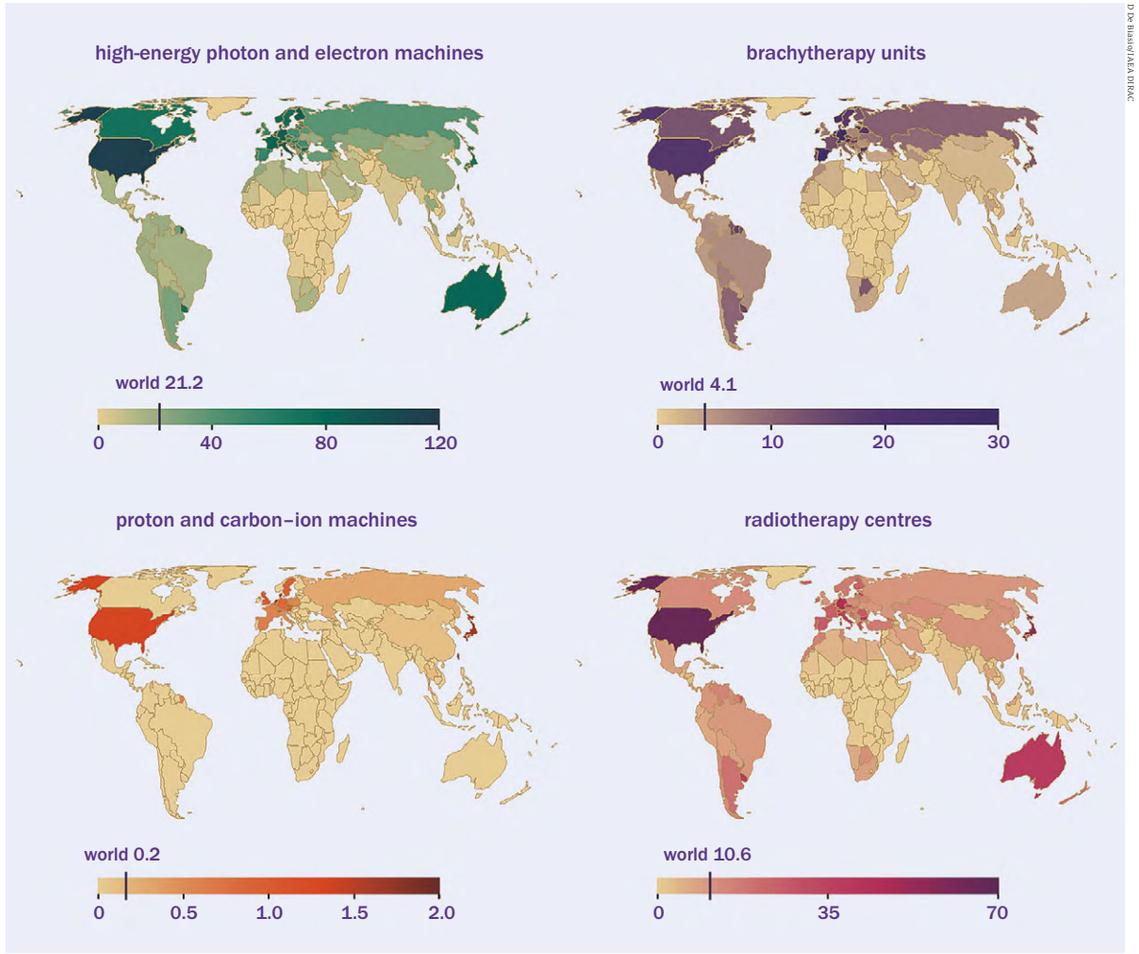
delivery can limit this exposure, but some collateral damage is unavoidable.

For this reason, protons or light ions have been proposed as an alternative to X-rays, taking advantage of the Bragg peak – the characteristic energy deposition of heavy particles in matter, which exhibits a sharp maximum at a well-defined depth (see "Stopping power" figure). To reach tumours deep within the body, however, these particles must enter with considerable energy, about 250 MeV for protons and 420 MeV per nucleon for carbon ions, the only two species currently licensed for clinical use. Because of the greater particle mass, proton- and ion-therapy accelerators are considerably larger and more expensive than electron linacs for X-ray production. While a treatment room equipped with a conventional X-ray linac has a footprint of about 50 m^2, a single-room proton therapy system requires – shielding included – about 500 m^2, and a carbon-ion therapy facility with three treatment rooms can occupy 10 times as much. While proton therapy is now commercially available, carbon-ion therapy is by contrast only accessible in custom-built centres equipped with large synchrotrons of more than 20 metres in diameter, only a few of which have a gantry for multiple-angle beam delivery. Two new pre-commercial carbon-ion therapy facilities are, nonetheless, under construction: a synchrotron-based one built by Hitachi for Mayo Clinic (Florida, US), and a cyclotron-based one built by IBA and Normandy Hadrontherapy in Caen, France.

Specialised conditions

The limited availability of accelerator-based therapies is related to their cost and complexity. High initial capital investment is followed by heavy operational expenses, often sustained through costly annual service contracts. The machines also require a clean and stable environment, particularly in terms of electricity supply, and both operation and maintenance call for highly specialised personnel. Many of these conditions are lacking in low- and middle-income countries, where there are documented cases of radiotherapy units donated to hospitals that were never installed, or that ceased operation when faults could not be repaired. These constraints are most severe for particle therapy. By the end of 2024, 126 proton and 17 carbon-ion therapy facilities were operating in 25 countries, growing by about eight and fewer than one per year, respectively. Two limitations beyond cost and complexity further contribute to this slow growth.

The first stems from the Bragg peak itself, which is inherently precise but requires comparable or greater precision in tumour imaging and localisation, as well as in patient positioning and motion control – for example, to account



D De Blasio/IAEA DIRAC

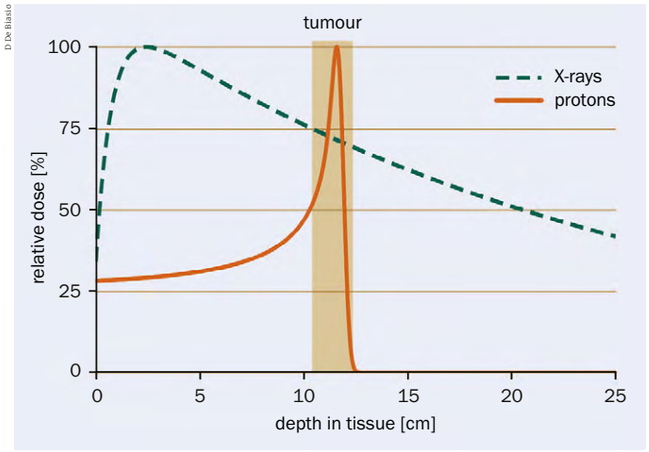
Unequal doses *Radiotherapy resources reported to the IAEA Directory of Radiotherapy Centres, per 10 million people in each country. Clockwise from top left, the maps chart high-energy photon and electron machines, brachytherapy – a treatment modality using radioactive sources instead of accelerators – centres, and proton and carbon-ion machines, each with its own scale and a tick at the world average.*

for breathing during treatment. The second arises from the therapeutic goal of particle therapy, which is not to increase the dose delivered to cancerous cells with respect to conventional X-ray therapy, but rather to spare healthy organs. This, in turn, brings an improved quality of life and reduces the likelihood of complications or secondary cancers, which is the reason why particle therapy is recommended for paediatric patients. Quality of life, however, is difficult to quantify, requires long-term follow-up and, for part of the medical community, does not yet justify the higher cost of treatment. As a result, particle therapy is currently recommended only for a selected range of cancer types, although research – in particular through clinical trials – keeps expanding it. One area where the use of particles is fully justified is the treatment of radioresistant large solid tumours, which survive X-ray therapy and require particles with high linear energy transfer.

To increase access to particle therapy, progress is also needed on the clinical and pre-clinical side, as well as in the way particle beams are delivered to patients. Perhaps the most intriguing new direction is FLASH therapy. Recent research shows that delivering a radiation dose in milliseconds rather than minutes can spare healthy tissues, while producing the same effect on a tumour as conventional radiotherapy. Although still to be demonstrated clinically, this discovery has triggered intense work to understand the underlying biological mechanisms, as well as to adapt accelerator designs for possible future use with FLASH (*CERN Courier* November/December 2025 p45). The most promising particles for FLASH are high-energy electrons, for which the production of short high-intensity pulses is easier. Tests of FLASH extraction with proton and carbon–

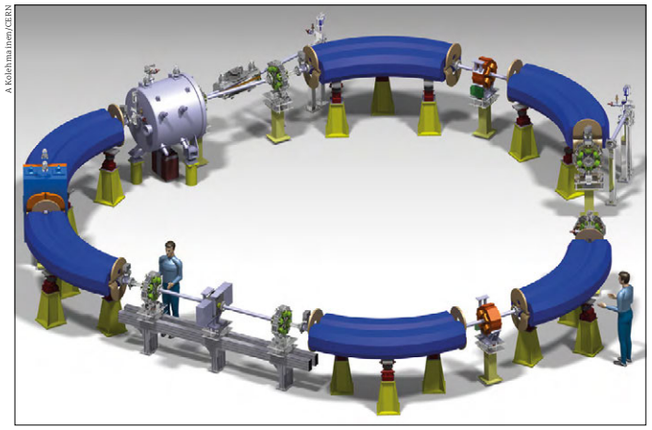
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D De Biasio



Stopping power *Schematic dose profiles of an X-ray beam (green dashed) and a proton beam (orange) as a function of depth in tissue. Protons deposit most of their dose in the sharp Bragg peak at the end of their range and almost nothing beyond it, while the X-ray dose falls off gradually and irradiates everything on its path.*

A Kolehmainen/CERN



Ring of helium *Rendering of the compact synchrotron studied within NIMMS, optimised for helium ions with protons and lower-energy carbon as further species. Bending magnets are shown in blue, focusing magnets in green and the single radio-frequency cavity in grey.*

ion beams are also underway in several laboratories, with the aim of combining the advantages of the Bragg peak and the FLASH effect in the so-called "conformal FLASH".

Studies at GSI in Darmstadt are exploring mixed helium–carbon beams for real-time imaging during treatment, using helium to traverse the body for imaging while carbon delivers the therapeutic dose. An alternative approach involves the use of radioactive ion beams, which can be visualised by scanners. Beyond proton and carbon, work is progressing on helium and heavier ions, to increase the effectiveness of the dose and the accuracy of its distribution. Vertical irradiation of seated patients is also being investigated as a way to avoid the cost and complexity of large proton and ion gantries, while the combination of ion therapy with immunotherapy could enhance and exploit the immune response that follows particle treatment.

Still, accelerators remain the most clearly defined technical components to optimise. The main challenges concern reliability, ease of operation, compactness, integration of new treatment modalities and, of course, cost. While reliability matters for all radiotherapy accelerators, it is particularly critical for expanding access to conventional X-ray therapy in low- and middle-income countries. A major effort to make radiotherapy linac design more robust is that of the STELLA collaboration (Smart Technologies to Extend Lives with Linear Accelerators), launched by the International Cancer Expert Corps together with CERN, UK scientific institutions and partners in African countries. STELLA aims to redesign radiotherapy linacs to make them more modular, serviceable and resilient, particularly for use in demanding operating environments where power instability, heat, dust and scarce spare parts can put conventional machines out of service for months at a time. The project is currently in the design/pre-engineering phase, aiming at a first prototype to be installed at the STFC Daresbury Laboratory in the UK.

Another avenue for increasing access to both X-ray and particle therapy lies in simplifying accelerator operation and integrating it more closely with treatment through machine learning and artificial intelligence (AI). Such tools can improve operational reliability by detecting anomalies early and guiding preventive maintenance, while enabling automated operation with minimal reliance on human operators. Coupling AI-enabled accelerator software with its clinical counterpart could also optimise the interface between accelerator and patient. Over the long term, this may reduce operating and maintenance costs enough to transform the particle-therapy business model.

Compact collaboration

A primary challenge in designing particle-therapy accelerators is to make them compact, yet able to integrate emerging treatment modalities. A promising example is the next generation of electron linacs, built to deliver the ultra-high dose that FLASH requires. Compact linac designs are being developed in collaboration with industry by several European laboratories, including CERN, which has adapted the Compact Linear Collider (CLIC) X-band technology for this purpose. These designs operate at different frequencies, reflecting a trade-off between compactness, cost and reliability.

Synchrotrons are also being redesigned at CERN, together with partners interested in ion-therapy accelerators, under the Next Ion Medical Machine Study (NIMMS). Initially, NIMMS contributed to improving the design of a conventional carbon-ion synchrotron-based facility for SEEIIST (South East Europe International Institute for Sustainable Technologies), a planned cancer therapy and research centre in South East Europe. The next step was a simpler and more cost-effective accelerator: a compact, triangular synchrotron accelerating helium ions to treatment energies, with a total circumference of 18 metres (see "Ring of helium" figure). Helium is increasingly viewed as a natural evolution of particle therapy. Relative to protons, it scatters less in tissue, which sharpens the dose distribution, and has a higher linear energy transfer, while its nuclei fragment less than those of carbon. The proposed accelerator can treat deep-seated tumours using helium or protons, and head and neck cancers – which require less penetration – with carbon. Multiple-energy extraction and FLASH-type irradiation are possible, as well as the use of multiple beams for particle radiography.

Defining magnets

In parallel with synchrotron studies, NIMMS has also promoted the development of superconducting magnets for compact particle-therapy synchrotrons within the European projects HITRIplus and I.FAST. Three demonstrators of canted-cosine-theta (CCT) dipole magnets will soon be tested. In a CCT magnet, two layers of solenoid-like windings are tilted in opposite directions, so that their fields along the beam axis cancel while their transverse fields add to form the dipole. One demonstrator combines dipole and quadrupole functions, one is strongly curved, and one uses high-temperature superconductors (HTSs). The goal is to define a magnet that could be the basis of a compact superconducting synchrotron for carbon–ion therapy with a similar lattice and dimensions to the helium synchrotron equipped with conventional magnets. In a similar direction, Japan's National Institutes for Quantum Science and Technology (QST), home of the HIMAC facility, is constructing a small superconducting synchrotron for carbon ions with a 30-metre circumference.

Superconductivity remains the principal route to further size reduction of ion-therapy accelerators, and here HTSs are particularly promising. The cost of HTS tapes is decreasing rapidly, and their higher operating temperature offers the opportunity to reduce both the capital cost and the electricity consumption of the cryogenic system (*CERN Courier* March/April 2026 p30). Teams at CERN are also considering the development of superferric magnets for medical applications, with an iron core and HTS windings. This relatively simple approach could enable low-cost, high-performance magnets whose field can be ramped as quickly as those of conventional synchrotrons, overcoming the slow cycling of traditional superconducting magnets that would limit the number of patients treated per day.

Every technology starts from a dream, and medical accelerators embody one of the oldest: to look inside the human body and cure disease without bloodshed. This fascinating and rapidly evolving field, which stands at the interface between medicine, biology, biophysics, physics and engineering, offers considerable prospects and opportunities to make that dream a reality. ●

Superconductivity remains the principal route to further size reduction of ion-therapy accelerators

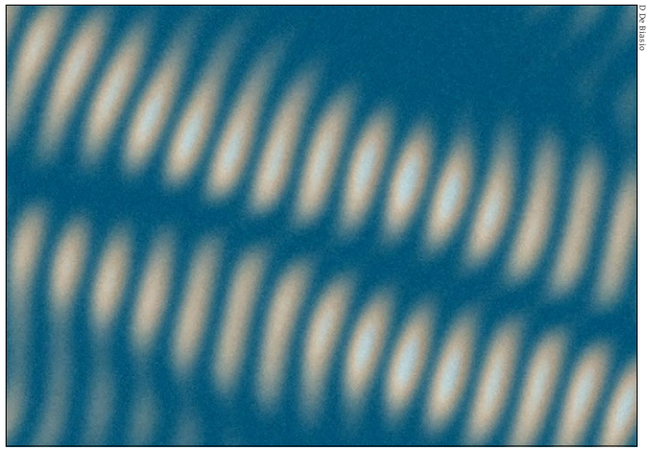


A CENTURY ALONG THE FIFTH DIMENSION

A hundred years ago, Oskar Klein closed a fifth dimension into a circle no instrument could resolve. Jeroen van Dongen and Robert van Leeuwen trace how the proposal emerged, faded and then resurfaced in the quest for unification.

When doing physics, Oskar Klein could feel like Odysseus. Perhaps the most adventurous of his voyages came a century ago this year, when he proposed to merge the nascent quantum theory with an expanded, five-dimensional version of the general theory of relativity. Speculation, he explained, "drags many of us into a mental whirlpool not unlike the hydrodynamical one of Charybdis, from which the escape feels like a miracle. On the other hand, sticking too closely to [Scylla's] facts […] may be equally deadly when using them as building stones for a theory."

The tension between metaphysical speculation, beyond the observable, and a focus on hard empirical facts was already part of Klein's earliest youth. He was born in 1894 near Stockholm, where his father, Gottlieb Klein, served as the rabbi of the city's small Jewish community. Among his acquaintances was Svante Arrhenius – Nobel laureate and leading chemist – who asked Oskar to join his laboratory when he was still a teenager. A fellowship next offered him the opportunity to study in Copenhagen with Hans Kramers and Niels Bohr, who equally wavered between the concrete and the speculative (see "Quantum company" image). Klein defended his PhD thesis, "On the statistical theory of suspensions and solutions", in Stockholm in 1921.



D De Biasio

Round trip *Artistic impression of a particle's wavefunction winding around a compact dimension. In 1926, Oskar Klein employed such a geometry in an attempt to unify gravity, electromagnetism and quantum theory.*

The unification problem

Klein's 1926 publication studied Erwin Schrödinger's successful novel wave equation – arrived at ultimately by foremost expanding on the empirical attainments of atomic spectroscopy – in the five-dimensional theory originally due to German mathematician Theodor Kaluza. Kaluza had seen that introducing an extra dimension could fit electromagnetism and gravity into a single mathematical object, encoding the geometry of a five-dimensional space–time, and thereby "unified" them: he could thus solve the "Unitätsproblem" that had recently begun preoccupying some of the vanguard of theoretical physicists. In his work, Klein pointed out that if that fifth dimension was curled up in a tiny circle (see "Close up" figure), this would account for both its unobserved status and the discrete nature of the electric charge (see "A circle and a tower" panel).

The most prominent member of that vanguard was Albert Einstein. Kaluza had already asked him to present his idea to the Berlin Academy in 1919, and have it published in its proceedings. A problem, however, gave both men pause. The force law for a charged particle contained, alongside the familiar gravitational and electromagnetic interactions, an additional term from a scalar field. In the case of the electron, this would be the leading term, which contradicted its observed behaviour. This convinced Einstein not to forward the work to the Academy, but by 1921 he had changed his mind.

Now deeply involved in unification himself, Einstein sought "non-singular" particle models: smooth field configurations rather than points where the equations break down. His ultimate goal was to offer an alternative route to explain quantum phenomena – top down from the mathematics of unification, so to speak, instead of bottom up from the empirical. In 1927, he repeated elements of Klein's work in a paper of his own (and said as much), except for its quantum aspects. Likely, that was the material he wished to derive, rather than simply posit by incorporating a Schrödinger equation.

Einstein returned to five-dimensional unification a number of times, including to the question of whether this offered any non-singular particle solutions, and invariably with the intention to come up with an alternative to quantum mechanics. His case against the latter remained wedded to his agenda for unification, as expressed in a 1927 letter to Hendrik Antoon Lorentz (Vladimir Fock had presented ideas similar to Klein's): "The quantum theory is completely Schrödingerized and has a lot of practical success because of it. But this cannot be the description of what really happens. It is a mystery. It turns out that the unification of gravity and Maxwell theory is achieved in a completely satisfactory manner by the five dimensional theory (Kaluza–Klein–Fock). I am curious what you have to say about that."

After the 1920s, Einstein remained fully devoted to his attempts at a unified field theory – one reason why his later boss Robert Oppenheimer in 1935 privately called him "completely cuckoo", forcefully expressing the dislike of many (see "Hidden dimension" image). Unlike in 1919, mathematical speculation was now leading Einstein's way, rather than the latest empirical result on quantum particles. As he would say in 1933, in "looking for the mathematically simplest concepts, and the link between them […] lies the theorist's hope of grasping the real in all its depth." In a sense, his relation to the five-dimensional theory, from his first rejection to his later persistent and continued elaborations, illustrates his larger philosophical development, in his words of 1938, from "skeptical empiricism" into "someone who seeks the only trustworthy source of truth in mathematical simplicity."

While in the following decades physicists did occasionally take up the Kaluza–Klein idea, it was only in the 1980s that it would again gain significant traction (*CERN Courier* July/August 2026 p22). Unlike those of Einstein, these proposals were fully on board with quantum theory. The tension between mathematical speculation and the empirical would, however, remain. The scientific context was different: in the preceding decade, an extensive communal effort had led to the formulation of the Standard Model (SM) of particle physics, and the revived interest in extra dimensions was part of attempts to unify it with gravity. Crucially, the novel higher-dimensional proposals incorporated supersymmetry, a new type of symmetry linking bosons and fermions introduced in the early 1970s.

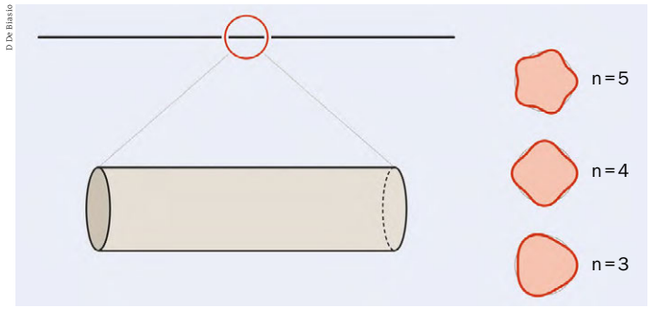
THE AUTHORS

Jeroen van Dongen *University of Amsterdam and* **Robert van Leeuwen** *Aix-Marseille University.*



Niels Bohr Archive, B32

Quantum company *From left to right, bottom row: George Gamow, Niels Bohr, Chandrasekhara Venkata Raman and Oskar Klein; top row: Svend Lauritzen and Ebbe Rasmussen, at the University of Copenhagen's Institute for Theoretical Physics in 1930.*



D De Biasio

Close up *Four-dimensional space–time is represented by a line, and a tiny fifth dimension by a circle attached to each of its points, shown magnified below (left). A particle's wavefunction must contain a whole number of wavelengths around the fifth dimension, so its momentum along it is discrete (right).*

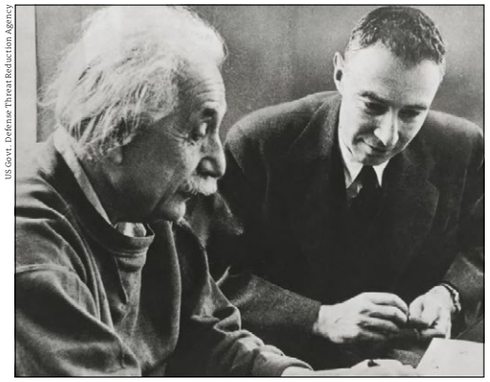
A circle and a tower

In general relativity, the gravitational field is described by the metric of space–time – the mathematical object that encodes its geometry. In 1919 Theodor Kaluza extended this from four to five dimensions, assuming that no physical quantity varies along the fifth coordinate. Seen from four dimensions, the five-dimensional metric then separates into three parts: the familiar space–time metric, an electromagnetic potential and a scalar field. Gravity and electromagnetism can therefore emerge from a single, higher-dimensional geometry.

Oskar Klein closed the fifth dimension into a circle, with a circumference of 0.8×10^{-30} cm. In quantum theory, a particle's momentum is inversely proportional to its wavelength. Since a whole number of wavelengths must fit around the circle, momentum in the fifth direction can take only discrete values. Kaluza had conjectured that electric charge is related to motion in the fifth direction. In Klein's construction, charge is quantised for geometric reasons.

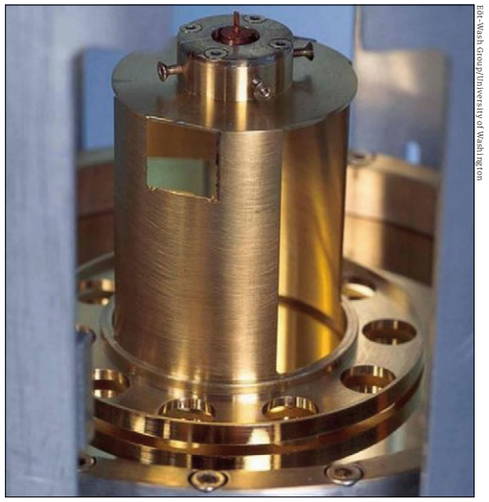
To an observer in four dimensions, momentum in the fifth contributes to a particle's mass. In the modern reading of Klein's construction, every particle therefore acquires a "Kaluza–Klein tower" of ever heavier copies, one for each allowed integer momentum along the circle. Producing the lightest copy would require an energy inversely proportional to its size. For Klein's tiny circumference, this is of order 10^{17} GeV, far beyond the reach of present experiments.

Smallness, however, is not the only way to hide dimensions. In 1998, for instance, Nima Arkani-Hamed, Savas Dimopoulos and Gia Dvali (ADD) proposed confining the SM particles to four dimensions, leaving gravity alone to spread, and dilute, through the extra ones. This would explain its apparent weakness and allow much larger extra dimensions, with possible signatures at the LHC. A year later, Lisa Randall and Raman Sundrum achieved a similar effect by warping space–time along a much smaller extra dimension. In the simple ADD model with two equal-sized extra dimensions, ATLAS and CMS at CERN have so far excluded radii above a few thousandths of a millimetre.



US Govt. Defense Threat Reduction Agency

Hidden dimension *Einstein with Robert Oppenheimer at the Institute for Advanced Study, Princeton, around 1950.*



Eöt-Wash Group/University of Washington

Short measure *A torsion pendulum used by the Eöt-Wash group at the University of Washington to test gravity at sub-millimetre distances. The experiment found no departure from Newton's inverse-square law, and so constrained models with large extra dimensions.*

The comeback of extra dimensions had started with what would become superstring theory, a supersymmetric framework whose basic entities are strings, rather than point particles. The mathematical structure of superstring theory had originated in attempts to model strong nuclear interactions in the late 1960s – notably at CERN, for instance in the work of Gabriele Veneziano – and was reinterpreted as a potential unified theory of particle physics and gravity in 1973 and 1974. Early on in this development, British physicist Claud Lovelace had demonstrated that superstring theory's purely bosonic, non-supersymmetric predecessor could only be rendered consistent in 26 space–time dimensions – a result he referred to as "obviously unworldly." Adding fermions and supersymmetry later brought the number down to 10. For a theory of nuclear interactions, situated in four-dimensional space–time, this was still in blatant disagreement with observation.

Compact thinking

For a unified theory with gravity, however, this was no longer necessarily the case. As elaborated in the mid-1970s by Joël Scherk, Eugène Cremmer and John Schwarz, if one conceived of the extra dimensions as real but unobservable – in the spirit of Oskar Klein's idea – one could make sense of a 10-dimensional theory. Moreover, by making the extra dimensions of space close in upon themselves, the mechanism dubbed compactification, one could generate new gauge symmetries, and thus particles, in the resulting four-dimensional theory.

These and other scholars, including Bernard Julia, also began to use hidden extra dimensions in the study of supergravity, a supersymmetric extension of general relativity that was closely related to superstring theory; they formulated its 11-dimensional version in 1978. For some physicists, extra dimensions changed from a theoretical curiosity in conflict with experience to an opportunity for constructing a fully unified quantum theory of the fundamental interactions that could supersede the SM. Perhaps, these extra dimensions could be "real" after all.

The recent developments had led to a different attitude to extra dimensions

A central figure in further advancing this perspective was Edward Witten (*CERN Courier* January/February 2022 p45), who was appointed professor at Princeton University in 1980. The following year, he published an attempt to construct a supersymmetric higher-dimensional theory unifying gauge theory and gravity, under the title "Search for a realistic Kaluza–Klein theory". Witten, who had majored as an undergraduate in history in 1971 before turning to physics, devoted his paper's first two pages to a brief historical introduction to what was then called "Kaluza–Klein theory", including references to some of Einstein's contributions.

Different attitudes

Witten argued that the recent developments had led to a different attitude to extra dimensions. Some considered them now "true, physical dimensions", because the quantum field perspective offered solutions to some of the problems that had confronted those who had worked, like Einstein, in the "classical period" of unified field theories. For example, the scalar field that had initially frustrated both Kaluza and Einstein no longer stood in the way as its associated particle turned out to be practically undetectable when taking quantum corrections to its mass into account. Any motivation to introduce a fifth dimension to produce an alternative to quantum theory was also absent in the new work.

An important reason why interest in the original Kaluza–Klein theory had waned according to Witten had been its inability to produce a realistic model with testable predictions. Yet, the success of the SM made the goal to unify gauge theory and gravity so urgent that it was now warranted to revisit the idea. Moreover, the rise of new particles since the 1950s had tentatively increased Witten's willingness to consider the additional – actually, infinite – new states that the proposal would entail. When considering the extra dimensions as real, compactification could then arise through spontaneous symmetry breaking, producing the observed four-dimensional theory – in line with the ideas of Cremmer, Scherk and Schwarz.

Witten's brief historical observations on the changing attitude toward Kaluza–Klein theory illustrated a broader change in the outlook of some theoretical particle physicists in the 1970s and 1980s. That is, with the rise of the SM, the immediate objective guiding their efforts was no longer primarily to account for new data, but instead to mathematically unify and thereby "explain" the accepted empirical descriptions. In that sense, their efforts echoed Einstein's philosophical reorientation – and perhaps they had been equally persuaded by the temptation that Charybdis had presented to Klein.

In the mid-1980s, the theoretical work combining Kaluza–Klein theory and supersymmetry culminated in an increased popularity of superstring theory, supergravity, and the accompanying ideas of extra dimensions and compactification. Their actual existence has remained hypothetical, however. Searches for extra dimensions, from probes at sub-millimetre scales (see "Short measure" image) to recent results by the IceCube Neutrino Observatory (p8), have so far come up empty-handed, constraining their possible size. In any case, the number of physicists working with extra dimensions has increased quite considerably since the 1980s, and has remained substantial. Does this perhaps indicate a change in the attitude of part of the theory community toward the role of experimental knowledge? Does the growth in the effort to attain explanation by unification reflect an increase in its stature as a scientific value, at the expense of striving for novel empirical fact? Or is it simply a reflection of the intrinsically limited possibilities for experiment beyond the SM, into the realm of quantum gravity? One century on, the verdict on the fifth dimension is still out. Klein's ideas, however, continue to provoke the minds of scientists and, increasingly, of the public at large. ●

Klein's ideas continue to provoke the minds of scientists

Further reading

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OPINION
VIEWPOINT

Ukraine's place in particle physics

Ukraine became an Associate Member State of CERN 10 years ago. Its physicists, Tetiana Hryn'ova argues, have been contributing to the field for far longer.



T Hryn'ova

Tetiana Hryn'ova *is a CNRS researcher at the Laboratoire d'Annecy de Physique des Particules and a member of the ATLAS collaboration.*

In 1877, Ivan Pulyui published "About a radiometer or a light mill" in the Lviv journal *Pravda* – the earliest known physics article in Ukrainian. Nearly 150 years later, the 10th anniversary of Ukraine's associate membership of CERN coincides with the 35th of its declaration of independence. These milestones – overshadowed by daily Russian attacks, among them one on the National Academy of Sciences of Ukraine on 28 September – provide an occasion to reflect on the contributions of scientists born in Ukraine to the field of particle physics.

The opening sentence of Georges Charpak's autobiography is "Born in 1924, in a small town on the Ukrainian plain I was deeply marked by wanderings imposed upon me by geographical, political and cultural events." These words also apply to many Ukrainians who became scientists despite wars, the Holodomor, the Holocaust, repeated purges of Ukrainian elites and at least six mass emigration waves – the most recent of which is still ongoing. At the same time, scientists from Ukraine helped to establish or led major particle-physics laboratories, with Edward Ginzton at SLAC, Maurice Goldhaber at BNL, Gersh Budker at the Institute of Nuclear Physics in Novosibirsk, Volodymyr Veksler at JINR, and Abram Joffe at the institutes of physics and technology in Kharkiv, Dnipropetrovsk and Leningrad. Through Gleb Wataghin and Marcos Moshinsky, they also played an instrumental role in the development of particle-physics communities in Brazil and Mexico, while Gregory Breit and George Kistiakowsky contributed to the Manhattan Project. George Gamow, who explained alpha decay as quantum tunnelling and laid the foundations of the hot Big Bang model, brought science to the wider public through his popular books. Matvei Bronstein, Moïse Haïssinsky and Stephen Timoshenko were pioneers of quantum gravity, modern radiation chemistry and engineering mechanics, respectively.



Ukrainian community at CERN

Heritage *Participants in the January 2026 workshop on Ukrainian contributions to particle physics, gathered at CERN on the street named after the Ukrainian-born accelerator physicist Volodymyr Veksler.*

A major milestone for particle physics in Ukraine was the establishment of the Ukrainian Institute of Physics and Technology in Kharkiv (UIPT, now KIPT) in 1928. It was there that Dmytro Ivanenko and Lev Landau – and later their students Oleksandr Akhiezer, Isaak Pomeranchuk, and Evgeniy and Ilya Lifshitz – laid the foundation of their schools of theoretical physics. Victor Weisskopf worked in Kharkiv, while Niels Bohr, Robert Van de Graaff and Paul Dirac came for visits. Type II superconductors were discovered in 1935 at UIPT's cryogenic laboratory by Lev Shubnikov with colleagues Volodymyr Khotkevych, Georgy Shepelev and Yuri Rjabinin (*CERN Courier* November 2011 p17). Their success, however, led to a downfall. In the second half of the 1930s, at UIPT alone, 16 members of personnel were arrested for espionage, sabotage and "Ukrainian bourgeois nationalism"; seven were executed and one died in prison. Although Kharkiv was home to a 2 GeV electron accelerator between 1965 and 1990, a CERN delegation visiting in 1992 noted that "Few people we have met had had the opportunity to go abroad and our visit was for many the first direct contact with CERN." For those who did make it to CERN, the experience was life-changing. Among them was Dmitry Volkov, who played a crucial role in the development of supersymmetry and supergravity with his KIPT colleagues Volodymyr Akulov and Vyacheslav Soroka.

Although Kyiv hosted the International Conference on High Energy Physics (ICHEP) in both 1959 and 1970, research carried out by Ukrainian scientists and institutions was rarely recognised internationally as such. Ukrainian-language scientific journals were closed, scientific institutions were systematically Russified, and many of their graduates were prevented from remaining in Ukraine to pursue their careers. Only a few scientists, most notably Mykola Bogolyubov, dared publish their research in Ukrainian. It is therefore hardly surprising that, writing in 1972, Weisskopf described Kharkiv, where he worked in 1933 and which was then the capital of Soviet Ukraine, as being in Russia. More troubling, in my opinion, is that, as recently as 2025, at the 4th International Symposium on the History of Particle Physics at CERN, research from scientific institutions in Kharkiv and Kyiv was presented under the title "Post-1980s Diaspora of Russian Particle Physicists".

Strong foundations

Following the disintegration of the Soviet Union, one of the priorities of the government of independent Ukraine was to join CERN. This effort was driven by Ukrainian scientists and research institutes, whose achievements provided a strong foundation for the collaboration. Ludmyla Nagorna, from the Institute for Single Crystals in Kharkiv, introduced new techniques for growing large $PbWO_4$ crystals, which are now used in the CMS and ALICE calorimeters. The advanced ultralight interconnection technologies, championed by Gennady Zinovjev from the Bogolyubov Institute for Theoretical Physics in Kyiv, found applications in the tracker of the ALICE experiment. Since the 1990s, Ukrainian scientists have contributed to a wide range of particle-physics experiments, in particular at B-factories, Fermilab, DESY and CERN.

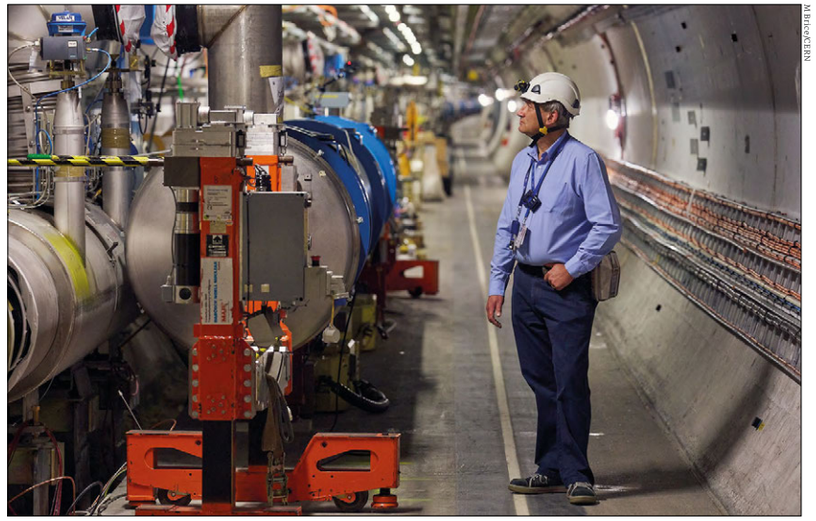
As discussed extensively at the "Ukrainian contributions to particle physics: history and prospects" workshop held at CERN and in Kharkiv in January 2026, Ukraine's associate membership of CERN marked not a beginning, but a continuation of a century-and-a-half-long scientific journey, reaffirming the role of its researchers in shaping the future of particle physics.

For those who did make it to CERN, the experience was life-changing

OPINION
INTERVIEW

A shutdown in name only

The LHC will see no beam until 2030, yet its tunnel has not been this busy since the machine was installed in the 2000s. Jean-Philippe Tock, who leads the coordination of CERN's third long shutdown, explains how four years of interventions on the LHC were fitted into a schedule with no margin to spare, alongside an intense programme of work across the rest of the accelerator complex.



M Brice/CERN

Critical point *Jean-Philippe Tock, head of CERN's LS3 Coordination Team, at Point 1 of the LHC. He previously led the interventions on the collider's superconducting magnets after its first and second runs.*

The LHC completed its third run at the end of June. Is that when Long Shutdown 3 (LS3) began?

For the LHC, it was. It entered LS3 on 29 June, at exactly 6 a.m. But for some parts of the CERN complex, LS3 had started a year earlier. The first large activity, the removal of the target area of the former CERN Neutrinos to Gran Sasso (CNGS) beam facility, began in June 2025. ISOLDE then stopped in December 2025 for a complete renewal and upgrade of equipment several decades old and will take beam again in 2028. Starting early makes it possible to use the beam as soon as it returns, spreads the load on our resources and gives teams time to ramp up and train.

As with the other facilities, the LHC electrical circuits were locked out, so that people could access the equipment safely. Then its superconducting magnets, which operate at 2 K, had to be warmed up before the interventions could start. Bringing some 36,000 tonnes of metal to room temperature, one sector after another, took two and a half months. In parallel, we tested the machine's mechanical and electrical integrity, looking for any non-conformity to fix for reliable operation in Run 4. Once the warm-up was complete, in September, the intensive removal of components began, to make room for the High-Luminosity LHC (HL-LHC).

What exactly is being removed, and what will replace it?

About 1.2 km of the LHC will be renewed, 300 m on each side of ATLAS and CMS. Along that stretch, the focusing magnets close to the experiments, which make the size of the beams as small as possible at the collision point to maximise the luminosity, will be removed together with other beamline equipment, such as collimators, valves and other magnets. The removal of the cables, cable trays and piping will follow, so that at some point this section of the tunnel will be completely empty. The magnets will then be replaced by new, higher-performing ones, or upgraded and put back in place in the last phase of LS3. The cryogenic line feeding them will also give way to one dedicated to the HL-LHC equipment, providing more cooling power.

That is a massive technical challenge. What about the people involved?

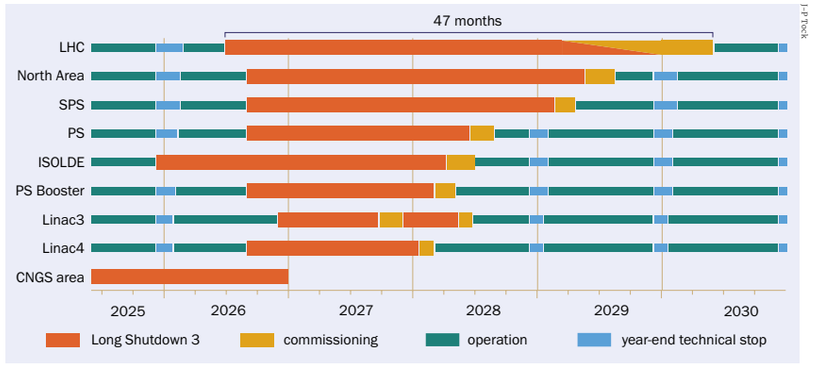
This huge effort covers the LHC and its experiments, the injector complex and its experimental areas, and a large part of the technical infrastructure, so literally every CERN site is touched. It involves CERN staff, collaborators and contractors, with more than a thousand extra people coming just for LS3. Those who operated the accelerators are now carrying out interventions or already preparing for the restart. And since the work will last years, with many people joining as students, graduates or new staff, we must also guarantee the continuity of expertise.

How does LS3 compare in scale with the two previous long shutdowns?

The first, in 2013 and 2014, was triggered by the need to consolidate the electrical splices, the connections between the LHC's superconducting magnets. The second was mainly dedicated to upgrading the injectors'

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chain, to prepare the beams needed for high-luminosity operation of the LHC, but it also covered the upgrades of ALICE and LHCb, the consolidation of the insulation of the diodes that protect the LHC dipoles and much of the underground civil engineering for the HL-LHC, which could not be done during LHC operation because of the vibrations. It started at the end of 2018 and was supposed to end in 2020, but it lasted longer than expected because of the COVID-19 pandemic. LS3 is larger than either, in volume and in extent, both in time and geographically. How much larger depends on the group, but for some the work is two or three times greater.



Out of phase *CERN's accelerators do not all stop, or start again, at the same time. Each row of the expected timeline shows one accelerator or facility being upgraded during LS3 (orange), returning to operation (yellow), running (teal) and on its winter break (blue).*

When did the planning start, and what did it involve?
The trigger for this third multi-year shutdown was the HL-LHC, with the upgrade of the LHC and of its detectors, mainly ATLAS and CMS, so that they can digest the increased luminosity. The installation has been under study for more than 15 years. Since the machines would stop anyway, it was the opportunity for other upgrades, like the complete renovation of the North Area, where some equipment is as much as 40 years old. Drawing on the first two long shutdowns, a coordination team was set up in 2021. It now has about 15 people, experts in planning, logistics and safety – which is our first priority – and representatives of the HL-LHC. We checked that every planned intervention was ready and that all were compatible, first for safety, minimising co-activity between teams working in the same place, and then for resources, which are limited.

Let's talk about the schedule. The first estimate for the work in the LHC came to a little over 51 months, and it was brought down to 47. How did you manage that?
It came from the LS3 Readiness Review in 2024, where a bottom-up evaluation of all the activities in the LHC exceeded the allocated time. And that figure was already optimised. A reasonable target of 47 months was then set, and we switched to a top-down approach, with the hard objective of fitting into that window.

To achieve that, we reviewed in detail every single activity on the critical path, the sequence of tasks where any delay pushes back the end of the shutdown, and on the near-critical paths. We went to a very fine granularity, both geographically and in time, to maximise parallelism, which was one of the keys to gaining time. Another knob was double-shift work, used at an unprecedented level for key activities on the critical path, such as cabling and de-cabling. We will even use the night shift for transport, which restricts access, and for inspections such as radiography. Shift work, parallelism and the removal of any margin mean that the schedule is highly optimised. The adverse effect is that we have less flexibility to face unexpected events.

The trigger for this third multi-year shutdown was the HL-LHC

How fine did that granularity get? Can you give us an example?
I will give two. One important activity is drilling 28 vertical cores, 1m wide and 8m high, to connect the LHC tunnel with the new underground galleries built for the HL-LHC. The galleries were excavated during the second long shutdown, but the final connection has to be drilled during LS3. In the original schedule, drilling was supposed to be the only activity in that part of the tunnel. We divided the 250m of tunnel into several smaller portions of a few tens of metres, to allow other civil-engineering or infrastructure work in parallel with the drilling.

The other example is in time. The critical path passes through Point 1 and Point 5, where ATLAS and CMS sit and where most of the HL-LHC work takes place. For some activities there, like the electrical lock-out at the start of LS3, we planned down to the day, or even the half-day. We did not do that for all activities, but that was the level of detail. Altogether, with the flexibility, commitment and experience of all the teams involved, and the support of CERN's management, we just managed to fit into these 47 months.

Forty-seven months is still a long stretch…
It will be a marathon for the team [chuckles], that's for sure, and far from plain sailing, hopefully with not too many hurdles. But it breaks down into phases common to most facilities. The first is testing, to identify any non-conformity or weakness that we must fix, followed by removal campaigns, to clear space for the improved or new equipment. For the LHC specifically, the drilling of the vertical cores connecting the LHC and HL-LHC worlds will be a key phase. After that, the new technical infrastructure will be installed, then the accelerator or experimental equipment, and finally all the superconducting systems will be cooled down. The last phase before operation is the hardware and beam (re)commissioning (see "Out of phase" figure).

You mentioned that ISOLDE will take beam again in 2028, and some of the people now working on LS3 will be back operating accelerators. How will that work?
It will be a real challenge for managing resources, because the same groups will be supporting operation and carrying out LS3 interventions. The accelerators always restart in order, from the source to the LHC, but after a winter break that takes a few weeks. This time the restart will span two years, from mid-2028 to 2030, which will be a first at CERN on such a scale. So there will be priorities to define, and arbitration. The HL-LHC comes first. It's a must. By that I mean the project itself, the upgrade of the experiments and all the other projects needed for the LHC to enter the high-luminosity era efficiently and safely.

One of them is the access and alarm system, which dates from the LHC's installation. The new one has to be ready by the end of 2028, because in the first part of 2029 we will start cooling down some LHC sectors to commission all the new equipment, and for that we will need a safe access system.

Another is the beam-screen treatment, which will deposit a thin layer of amorphous carbon on 12km of beam screens, to keep the heat load from the beams within what the cryogenic system can handle.

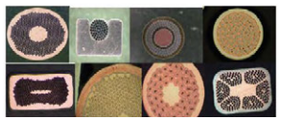
Is it your team that sets those priorities?
We aim to optimise the schedule for efficient resource allocation, aligned with CERN's priorities as defined by top management. In addition, I see our role as one of support and service for the groups and projects. They manage their resources and set their objectives, and we are there to give them the best conditions to reach those objectives safely. We also help with logistics, managing more than 40,000 square metres of requests for storage and site compounds – including underground, where space is scarcest. And we foster discussion between the people working on site, because teamwork, flexibility and understanding each other's constraints are key to solving the everyday issues we encounter.

I see our role as one of support and service for the groups and projects

What is your typical day, if there is one?
That's an interesting question. The great thing about this work is that it's not routine, and we face very different issues. Sometimes we have to adapt and reshuffle work because we have discovered a non-conformity that needs fixing. Sometimes unexpected interventions have to be studied and integrated into the already heavy schedule, because we judge them important for the machines' long-term robustness. If there is a *fil rouge*, it is the many meetings, presentations and exchanges with all the stakeholders, to understand their needs, their constraints and where there is room for flexibility. People at CERN are committed to their own work, but they also understand the global picture and the interest of the Organization.

How is the mood among the teams, now that the work has started?
For every machine, when operation stops, it is the end of an adventure for the physicists gathering data, and it can be a bit sad. But it is for the best, since it will bring improved machines. On our side, the team has prepared LS3 for years. In this first phase the feeling is that people are eager to start the actual interventions in the field. Seeing this become concrete makes for a nice atmosphere on – and under – the ground. Of course, there will be difficulties to overcome, but I am confident in the team spirit and the commitment of everyone, at all levels. LS3 has to be a success, to boost performance, improve reliability and broaden the physics programme. Everyone contributing to it is paving the way for the discoveries of the decades to come.

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

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OPINION REVIEWS

Where the action is

Top Ten Ideas of Physics: Foundations for Understanding the Universe

By Anthony Zee

Princeton University Press

Reading a book is like swimming. The first lengths are the worst: the water is cold, the shoulders stiff, every stroke a negotiation. Then, somewhere around the fourth or fifth length, the muscles warm, water simply becomes the medium you are in, and the resistance turns into something that carries you. All swimmers count their lengths, but all lose count at some point, when the mind slips its moorings and you surface two or three lengths later with no idea how you got there. *Top Ten Ideas of Physics* by Anthony Zee, of the Kavli Institute for Theoretical Physics in Santa Barbara, is like that. You come to it stiff and for a page or two you feel the cold. Then the prose warms around you and you stop counting.

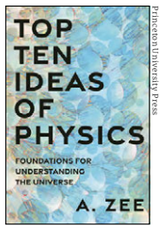
In the prologue, Zee declares an aim different from that of most books of this kind. Readers looking for the latest results, he says, should go to the web. While the market might ask for black holes and whatever anomaly is at three sigma, Zee has written about ideas that have long stopped being news. What earns an idea a chapter is not novelty, nor even beauty, but that people have leaned on it very hard for very long and it has not given way. The author has evidently been pondering for many years which 10 ideas in physics to include and how to describe them.

The order of the top 10 is neither historical nor pedagogical. It is an argument. The first two entries, that the world is comprehensible and that the laws are the same across space and time, are not laws at all, but the conditions under which physics is possible. Zee is right to give them the two shortest chapters, since one cannot derive the fact that the world is comprehensible. One notices, with Einstein, that it inexplicably is, and gets to work. Ontology follows, in the chapters on quantum mechanics and fields, and then structure, in those on symmetry, space–time and unification. A chapter on why mathematics works sits comfortably only because it arrives after seven chapters of evidence. The book then turns to entropy and, last of all, the action.



ESA/Webb, NASA & CSA, I. Furtak, S. Fujimoto

Same rules, far away *The galaxy cluster MACS J0454.1−0300, seen as it was some 8 billion years after the Big Bang, bends the light of galaxies behind it into arcs. The interpretation of such images rests on applying the same gravitational physics across cosmic distances, an assumption repeatedly tested by observations.*



Princeton University Press

Ending on the action is the boldest decision in the book and, in my opinion, the correct one. Most accounts treat the principle of least action as a third-year undergraduate technicality. Zee makes it the climax, and opens the chapter by admitting that he finds it astonishing and mysterious. That gives the reader permission to be astonished too, and it implies a serious claim: the deepest thing we know is not what the world is made of, but the form in which its laws are written.

Quantum mechanics gets 44 pages, Einstein 42, fields 35, while the two opening principles get 14 and 13. Two-fifths of the book is quantum mechanics, field theory and general relativity. The imbalance tells the reader where Zee's own work has been, and is itself a good reason to read the book. Chapters four and six are built on two of his earlier textbooks, *Quantum Field Theory in a Nutshell* and *Einstein Gravity in a Nutshell*, and there the writing stops being exposition and becomes testimony. When Zee describes the quantum fields as murmuring and telling one another how to dance, he is not decorating. That is the picture he himself works with.

On a practical note, chapters one and two work better as a retrospective frame than as an introduction. I would therefore suggest reading the prologue, jumping to chapter three, then coming back. And there is nothing on holography, on the information problem, on cosmological tensions. Zee warned us at the beginning, and the exclusion is likely to keep the book readable in 20 years.

At the end one holds 10 sentences, each short enough to remember and general enough to use. A reader who finishes with those in place has learnt more physics than one who finishes a fatter book with a head full of analogies.

What keeps swimmers swimming is neither the first length nor the last. It is the middle, the part one cannot account for afterwards, when the counting has failed and something in the mind has gone off duty. A book that induces that state is doing something that has nothing to do with the transfer of information, and Zee's does. Through the long central stretch, the counting stops, and one is in the company of somebody who has thought about this for 40 years and has finally decided which 10 things matter.

Antonio Riotto *University of Geneva.*

Facing Infinity: Black Holes and Our Place on Earth

By Jonas Enander

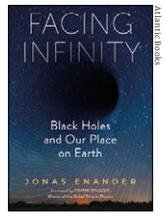
Atlantic Books

It is hard to imagine the abyss of a black hole without being drawn in. Its interior represents an absolute limit on human knowledge that cannot be overcome by technology. And at its edge the great pillars of quantum theory and general relativity come crashing together.

Fresh insight into how black holes have a very real impact here on Earth

In *Facing Infinity*, Jonas Enander (translated by Nichola Smalley) gives a compelling and accessible account of how black holes went from an extreme interpretation of Newtonian gravity to a pivotal field of research. Alongside this, Enander provides fresh insight into how black holes exist in the public imagination and how, even though they are thousands of light-years away from us, they have a very real impact here on Earth.

In the 18th century, British clergyman John Michell took Newton's work to its logical conclusion and imagined an ▷ object with gravity so strong that light could not escape. Enander begins his tale here and then recounts how, in the early 20th century, these Newtonian black holes were transformed through war and relativity.



Atlantic Books

This era is well-trodden ground in popular physics writing, but Enander manages to delve deeper and show the human side of these scientific developments. A rich and complex story of scientific discovery is laid bare, with details such as how John Michell, isolated in his Yorkshire rectory, felt nervous about sharing his bold ideas with the Royal Society, or how Karl Schwarzschild found the solution of Einstein's equations that describes a black hole while immersed in one of the most violent episodes of the First World War.

What these examples also highlight is that Einstein could not have developed his theories of gravity and relativity alone. Although the lone genius is a popular image, Enander consciously counters it to illustrate the necessity of collaboration in science. As the narrative moves into the 21st century, the teams become necessarily global. Scientific feats such as the discovery of gravitational waves and the first ever images of the black holes M87* and Sagittarius A* could only have been achieved through significant international collaboration.

Through conversations with a wide array of researchers and his own experience in science, Enander explores both the latest physics of black holes and what motivates those who want to gaze into the abyss. The book really hits its stride in the third and final section: having established the sheer amount of work required to reach our current understanding of black holes, Enander then provides numerous examples of what it is all for.

Our understanding of relativity allows the Global Positioning System to function, and the advances required to study black holes spurred the development of another now vital technology: Wi-Fi. Additionally, black holes themselves, as the engines of distant quasars, provide the firmest anchors in our night sky, allowing extremely precise measurements of the Earth and its moving tectonic plates, data that is becoming ever more pertinent as sea levels rise.

These concrete examples of real-world benefits run alongside the more abstract, but no less valuable, ones that black hole research brings to humanity, including a better grasp of where we come from and our place in the universe. He writes captivatingly, for instance, about the idea that black holes may be an integral part of the creation of the heavy elements that make up our bodies. Enander is also not afraid to point out where scientists clash with wider society, something that is seldom mentioned in popular science. Many such stories are discussed in the book, including that of the resistance to the proposed Thirty Meter Telescope on Mauna Kea, in Hawaii.

By the end, I felt moved by the strength of human collaboration that has allowed us to study such elusive and distant objects. And throughout this book, the author makes a very convincing argument for not just the beauty of blue-skies research but also its necessity. He shows how even black holes – which seem so removed from our daily life – can have a profound impact on society.

Rory Harris *CERN.*



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PEOPLE
CAREERS

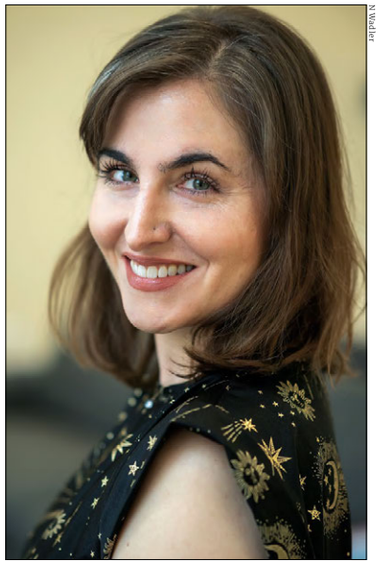
Follow the spiral

Former astrophysicist Jess Kirkpatrick reflects on moving into data science, and on the detector that brought her back to physics.

For much of her early career, Jess Kirkpatrick imagined scientific success as a straight line. Graduate school would lead to postdoctoral positions, then a faculty role and, eventually, a life spent exploring the universe. "As a student, I assumed careers were linear," she says. "My experience is that a career is more like a spiral."

Growing up in a family of social scientists, she found herself drawn instead to mathematics. "When I took physics in high school, I was so excited to learn it was about applying mathematics to understand the world," she recalls. "Is there anything cooler to study than how the universe works?"

As an undergraduate, she also learned to program, a skill that would later prove useful in her transition to data science. "Some students grew up programming, but I had never been exposed to it before. It felt like magic that a computer could do all this work for me and then visualise the results."



N Waldie

New coordinates *Jess Kirkpatrick, a data scientist at the online resale company ThredUp, moved from astrophysics into industry after her PhD at the University of California, Berkeley.*

Measures of success

When Kirkpatrick arrived at the University of California, Berkeley, for a PhD in astrophysics, she expected the next steps to follow naturally. But watching the faculty around her, she saw a different reality. "I realised people were mostly administering grants and going to conferences," she says. "They didn't seem to have the time or bandwidth to do actual research."

Kirkpatrick also wanted to build a life in the San Francisco Bay Area with her partner, and the uncertainty and geographical constraints of the academic job market made that especially difficult. "I started thinking about what else I could do with my skills that would let me stay here and work in the same city as my partner."

Data science had not been part of her original plan, and breaking in was hard. Some 60 applications brought her two interviews. Once she was in, though, the work itself felt familiar. "I'm still trying to solve problems that no one has solved before," she says. "I read academic papers about what people have tried in other settings and then see how I can adapt those methods."

There's no single right way to do things. If someone needs more time or a different approach, that's okay

What stood out most was the speed. "I could put my work into practice right away and see results, without the overhead of huge collaborations or peer review. The pace of industry is a better match for me."

Professionally, the move made sense. Personally, it meant letting go of an identity she had spent years building. "For 15 years I had been studying physics and thinking I was going to do physics research," she says. "It was a shift in my self-identity." She initially worried about letting down friends and mentors still in academia. "I never felt judged by anyone else. That pressure came from inside me."

Those doubts faded as she began to see the impact of her work and recognised how much happier she was. "Change is hard, but looking back, becoming a data scientist was one of the best decisions I've ever made."

Her own experience has also shaped how she leads teams. Living with a learning disability has taught her that people tackle challenges differently. "There's no single right way to do things. If someone needs more time or a different approach, that's okay."

Second pass

Leaving academia, it turned out, did not mean leaving physics. Later, while working in mineral exploration at KoBold Metals, Kirkpatrick came across the idea of using cosmic-ray muons to image underground structures. She contacted her undergraduate research advisor, Daniel Snowden-Ifft of Occidental College, with whom she had worked on a dark-matter experiment. "We ended up building a detector together and filing a patent."

Kirkpatrick is now at the online resale company ThredUp. She has recently stepped back from management to return to hands-on research, drawn by the rapid changes in artificial intelligence. Her work on computer vision and image processing uses the same skills that she applied to telescope images during her PhD. "What once felt like leaving a path behind doesn't feel that way anymore," she says.

For researchers considering careers beyond academia, Kirkpatrick's advice is not to decide in advance that they are unqualified for an opportunity. "It's not your job to reject yourself," she says. "It's the employer's job to evaluate you."

And if she could speak to her younger self, newly out of her PhD, her message would be equally direct. "Trust yourself," she says. "You know more than you think, and it's going to be okay."

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

Appointments and awards



KEK

Asai set for second term
On 3 September 2026, the Director General Selection Committee of KEK, Japan's High Energy Accelerator Research Organization, selected Shoji Asai as its candidate for a second term as director general, running from 1 April 2027 to 31 March 2030. Asai became the laboratory's fifth director general on 1 April 2024, after having directed the International Center for Elementary Particle Physics at the University of Tokyo (*CERN Courier* November/December 2023 p58). His research career began with a doctoral thesis on the lifetime of positronium. In 1995 he joined the OPAL experiment at LEP and then ATLAS at the LHC, searching for supersymmetry at both, and he led the Japanese ATLAS team during the discovery of the Higgs boson.

DOE honours RHIC team
On 28 September 2026, the Discovery and Innovation Team of Brookhaven's Relativistic Heavy Ion Collider (RHIC), represented by 11 physicists, received a Secretary of Energy Achievement Award at the US Department of Energy's headquarters in Washington, DC. The award recognises 25 years of exploring quantum chromodynamics at extreme temperatures and densities, during which RHIC characterised the quark–gluon plasma as a strongly coupled fluid and found that gluons and antiquarks contribute to the proton's spin (p25). It also recognises the accelerator innovations behind this work, including collisions across a wide range of ion species and energies, and the first demonstration of electron cooling based on radio-frequency acceleration. RHIC delivered its final collisions on 6 February.

Carini to lead CHESS
Cornell University has appointed Gabriella Carini director of the Cornell High Energy Synchrotron Source (CHESS), the only high-energy synchrotron in the US that a university hosts and operates, from 1 October. Carini received a PhD in electronics engineering from the University of Palermo, and has long worked on radiation detectors and scientific instrumentation. She started her career at Brookhaven National Laboratory (BNL) and held several positions before moving to SLAC, where she headed the detectors department of the Linac Coherent Light Source. In 2018 she went



SLAC National Accelerator Laboratory

back to BNL, where she directed the Instrumentation Division and, from 2024, the Discovery Technologies Directorate. She will oversee the expansion of CHESS, including the commissioning of the High Magnetic Field Beamline, which combines powerful X-rays with magnetic fields of up to 20 T, and XLEAP, a beamline for the life and environmental sciences due to open to users in 2028.

Muggli wins AAC prize
Patric Muggli has been awarded the 2026 Advanced Accelerator Concepts (AAC) Prize "for seminal contributions to plasma wakefield acceleration with electron, positron, and proton beams, and for exceptional service to the advanced accelerator community". One prize is given at each of the biennial AAC workshops, the latest of which was held at the University of California, Los Angeles, from 26 to 31 July. A senior scientist in the AWAKE group of the Max Planck Institute for Physics, Muggli works on proton-driven plasma wakefield acceleration at CERN. There, protons from the Super Proton



A Goksu

Synchrotron are injected into 10 m of plasma, where they drive wakefields that accelerate a trailing electron beam. In 2018, AWAKE demonstrated the acceleration of electrons to multi-GeV energies in these wakefields for the first time.

Faraday Cup for gas curtain
The Faraday Cup Award, which recognises outstanding innovation in beam diagnostics and instrumentation, has gone to the Beam Gas Curtain collaboration of the University of Liverpool, CERN and the GSI Helmholtz Centre for Heavy Ion Research. Carsten Welsch (Liverpool), who began the research some two decades ago, Peter Forck (GSI), Ray Venness and Daniele Butti (CERN), accepted the award at the 15th International Beam Instrumentation Conference in Whistler, Canada. The collaboration's monitor sends a thin curtain of supersonic gas across an accelerator beam and images the fluorescence induced by the passing particles, revealing the beam profile with minimal disturbance. After a prototype was evaluated in the LHC, the device was approved for full operational use there in October 2025 and adopted as baseline equipment for the High-Luminosity LHC in February 2026.

Bassi prize to Fantoni
The Italian Physical Society has awarded its 2026 Laura Bassi Prize for Women in Physics to Alessandra Fantoni, a senior researcher at the INFN Frascati National Laboratories. The prize recognises her contributions to high-energy nuclear and hadronic physics, and her scientific coordination roles, particularly in the ALICE experiment at the LHC. Fantoni worked on HERMES at DESY from 1992, first as a PhD student building the electromagnetic calorimeter, later as deputy spokesperson. In ALICE she was deputy project leader for the electromagnetic calorimeters from 2012 to 2022 and oversaw the construction of staves for the upgraded Inner Tracking System. She chairs the ALICE Collaboration Board and the Nuclear Physics Division of the European Physical Society.

Two academies for Rubbia
In August 2026, Carlo Rubbia, CERN Director-General from 1989 to 1993, was appointed a member of the European



C Rubbia

Academy of Engineering and of the Luxembourg Academy of Sciences and Arts, a scholarly association founded in 2024, in recognition of his contribution to modern physics and international scientific cooperation. Rubbia shared the 1984 Nobel Prize in Physics with Simon van der Meer, for their decisive contributions to the project that led to the discovery of the W and Z bosons at CERN's proton–antiproton collider in 1983.

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PEOPLE OBITUARIES

Daniele Amati 1931–2026

An inspiring catalyst

On 4 August, a week before his 95th birthday, Daniele Amati, one of the most charismatic and influential figures of modern theoretical physics, passed away in Trieste. Born in Rome on 11 August 1931, Amati was just eight when his Jewish family fled from fascist Italy for Argentina.

Studying in Buenos Aires, he developed a keen interest in theoretical physics, completing his studies in 1952. Soon after, together with his schoolmate Alberto Sirlin, he attended a course – in Portuguese – by Richard Feynman in Rio de Janeiro. It deeply influenced him. Amati occasionally boasted having been, with Sirlin, the first physicist to hear about the path-integral formulation of quantum mechanics from Feynman himself.



Giulia Arnoni – SISSA Archive

Daniele Amati had an exceptional intuition for formulating interesting questions and for assembling the right people to pursue them.

Strong interactions

In 1954 Amati returned to Italy as an assistant professor in Rome and attended a school, in Les Houches, where he met Enrico Fermi, who was lecturing there just a few months before his premature death. In this Roman period, his main interest was in the dynamics of strong interactions.

In 1959 Amati joined the newly formed Theory Division of CERN, which he later led from 1973 to 1975. Early in his CERN period (1959 to 1986), he was also a professor at the University of Trieste (1965 to 1967) – establishing very strong and long-lasting ties there. His research at CERN touched on many subjects at the cutting edge: in the early 1960s, he was part of the famous Amati–Fubini–Stanghellini collaboration, inventing the multi-peripheral model of multi-particle production and predicting what later became known as Feynman scaling. He also worked on Regge-pole theory and the analytic S-matrix approach to strong interactions.

A sudden jump in Amati's line of research came around 1968–1969, with the advent of the dual-resonance model, later understood as a model of hadrons as strings. Amati worked enthusiastically in this new branch of theoretical physics, performing ground-breaking work within a group at CERN with David Olive, Victor Alessandrini and others, and influencing the research of many young theorists, until roughly 1973–1974. His famous qualification of string theory as "a piece of 21st-century physics that fell, by accident, into the 20th" goes back to those days.

> **String theory is a piece of 21st-century physics that fell, by accident, into the 20th**

After the formulation of the Standard Model in the early 1970s, Amati, like many other string theorists of the time, turned his attention to quantum chromodynamics (QCD), justifying the QCD parton model and introducing the concept of pre-confinement in QCD jets, an important ingredient for current numerical jet simulators. In the mid-1980s, Amati and several colleagues investigated the non-perturbative properties of supersymmetric extensions of QCD, co-authoring a well-known review article on the subject. During those two decades Amati also had a leading role in the CERN Staff Association, where he helped to establish a tripartite structure in which the Association sits alongside the CERN Management and the Member States in personnel-related discussions.

The last turn in Amati's interests in theoretical physics came with the so-called first string revolution of 1984, when string theory made a comeback as a "theory of everything" – quantum gravity included. Around that time, his plans to continue his career as director of the International School for Advanced Studies (SISSA) in Trieste were consolidating. Just as he was preparing for it, in 1986, Amati began a collaboration with Marcello Ciafaloni and myself on what became known as the ACV (Amati–Ciafaloni–Veneziano) approach to string scattering at trans-Planckian energies. Although its original motivation was purely theoretical, as a kind of thought experiment for quantum string gravity, this work found an application to the physics of coalescing black holes and the ensuing gravitational-wave emission some 30 years later.

As director of SISSA from 1986 to 2001, Amati brought about what a physicist would call a phase transition, a change not only quantitative but qualitative, broadening SISSA's areas of research considerably to include, for instance, neuroscience and cognitive science. He also pioneered, with Loriano Bonora and Hector Rubinstein, the idea of open-access scientific publishing, launching in 1997 the entirely digital *Journal of High Energy Physics* (JHEP). Run "by scientists for scientists", JHEP quickly became the most widely used journal in theoretical high-energy physics, disrupting the traditional academic-publishing industry. It was soon followed by its offspring, the *Journal of Cosmology and Astroparticle Physics* (JCAP), dedicated to (mostly theoretical) astrophysics and cosmology.

Amati had a many-sided personality, with interests that went far beyond physics and even science. If one had to summarise in two words the skill in which he most clearly excelled, he was an inspiring catalyst. He had an exceptional physical intuition for formulating interesting questions and a great ability to motivate and assemble the right people to carry the research through. A research project, he used to say, may or may not succeed, but even in the latter case there is much to learn from the failure. Above all, his motto was that having fun is the most important signature of good research.

Amati left an indelible mark on all those who had the opportunity and privilege of interacting closely with him. We all now feel orphans of the man often and affectionately referred to as "Babbo Daniele".

Gabriele Veneziano *CERN.*

Fred James 1939–2026

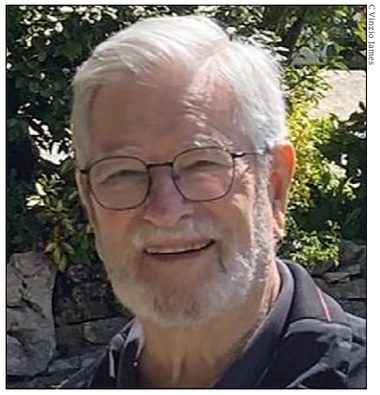
A guide to statistical rigour

Fred James, a CERN expert on data analysis and statistics, a pioneer of numerical methods in particle physics and co-author of the popular text *Statistical Methods in Experimental Physics*, passed away on 31 July. For several decades, Fred served as a widely sought guide to experimentalists seeking statistical rigour, leaving a legacy that includes the optimisation tool MINUIT and notable contributions to pseudo-random number generation.

Fred was born in Detroit, in the United States, on 28 May 1939. He graduated from Princeton University in 1960 with a degree in physics and earned his PhD from Yale University in 1965 under the supervision of Henry Kraybill, researching strangeness production in pion–proton reactions at Brookhaven National Laboratory. In 1967 he joined CERN, where his deep affinity for mathematics placed him at the vanguard of numerical analysis in high-energy physics.

By the late 1960s, Fred was already deeply involved in simulation techniques. His early notes evolved into his definitive review article, "Monte Carlo theory and practice", published in *Reports on Progress in Physics* in 1980. Meanwhile, Fred authored several mathematical algorithms in the CERN Program Library, CERNLIB.

Fred recognised the need for robust numerical methods for function minimisation, particularly for chi-square and negative log-likelihood evaluations. Together with Matts Roos, he developed MINUIT, first written in the era of punch cards and Fortran. MINUIT quickly became a standard function-minimisation package across particle physics and beyond. It has evolved over the decades, with a translation into C++ and integration in the ROOT data-analysis framework, and it remains a fundamental tool for negative log-likelihood minimisation in particle physics, used today for most of the results published by the LHC experiments. Among them is the discovery of the Higgs boson, for which it was the backbone of the significance computation. With MINUIT, Fred also provided MINOS, an essential tool for interpreting the negative log-likelihood function near its minimum and for computing confidence intervals and regions.



C Vinzio James

Fred James's insistence on statistical precision shaped the toolsets of generations of researchers.

> **His computational tools and textbooks will continue to guide scientific discovery for years to come**

In 1971, Fred joined William Eadie, Daniel Drijard, Matts Roos and Bernard Sadoulet to write *Statistical Methods in Experimental Physics*, a graduate-level treatise covering both theory and practice. After it had served generations of young physicists, Fred gave it new life by single-handedly publishing a thoroughly revised and updated second edition in 2006 (*CERN Courier* November 2007 p49). In January 2000, Fred, Louis Lyons and Yves Perrin organised a landmark Workshop on Confidence Limits at CERN. The event filled the Council Chamber with physicists and statisticians diving deep into contentious methodological questions, and sparked the PHYSTAT workshop series, which continues to flourish.

Philosophically, Fred was a strong advocate of the frequentist interpretation of probability. While *Statistical Methods in Experimental Physics* included Bayesian statistics, Fred firmly maintained that scientific inference is driven not by Bayesian decision theory, with its subjective degrees of belief, but by objective inferences rooted in the frequentist tradition. He championed this principle vigorously throughout his career and into retirement.

Fred's work on Monte Carlo methods naturally extended to the mathematics of pseudo-random number generation. In the 1990s, with Martin Lüscher, he developed and promoted RANLUX, an influential implementation of Lüscher's high-quality random-number algorithm, which has seen 30 years of intensive use in different branches of science. Fred continued this research after his retirement from CERN in 2004. He frequently came to CERN and collaborated with Lorenzo Moneta on pseudo-random number generators based on chaotic dynamical systems, culminating in a comprehensive review published in 2020.

Fred James was always available for discussion, and many of us enjoyed his friendship and his generosity. He was an accomplished cellist, and with his late wife Christa raised two daughters in Geneva, enjoying life with them and their families, as well as fine wines and leisure time at their solar-powered chalet in the rural French pre-Alps. He also had a passion for teaching, and for many years following his retirement he taught statistics to physics students at EPFL. His computational tools, textbooks and insistence on statistical precision have shaped the analytical toolsets of generations of researchers, and will continue to guide scientific discovery for years to come. He will be dearly missed, and our thoughts are with his daughters, grandchildren, friends and colleagues at this difficult time.

His friends and colleagues.

Vasily Parkhomchuk 1946–2026

A trailblazer of beam cooling

Vasily Vasilievich Parkhomchuk, who passed away on 23 July 2026 at the age of 79, was among the most gifted accelerator physicists of his generation, an experimentalist of rare physical intuition whose influence stretched across continents and decades, and whose warmth and generosity shaped the careers of countless scientists around the world.

Born on 1 September 1946 in the Ukrainian village of Torchyn, he grew up in the remote Altai village of Rodino and came of age at a moment of extraordinary intellectual ferment in Siberia. In 1963 he joined the inaugural class of Novosibirsk State University's celebrated physics-and-mathematics boarding school, and was admitted to the university itself the following year. After graduating from its physics department, he joined the Budker Institute of Nuclear Physics (BINP). He would remain there for the rest of his life, becoming one of the truest embodiments of the scientific culture ▷

CERN COURIER
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that Gersh Budker had created – bold, inventive and rigorous.

The central achievement of Vasily's career was electron cooling. In the early 1970s he joined the experiments at the NAP-M storage ring, a model for antiproton accumulation, and played a decisive role in the world's first demonstration of electron cooling of ion beams in 1974, establishing the physical foundations of the magnetised cooling regime. His semi-empirical formula for cooling rates, which distils complex beam physics into practical, reliable engineering guidance, became an international standard and remains in use today.

Under his leadership, BINP grew into the world's leading centre for electron-cooling technology, and Parkhomchuk personally guided its transfer to laboratories across the globe, at Uppsala, GSI in Darmstadt, COSY in Jülich, CERN's Low Energy Ion Ring (LEIR) and the Institute of Modern Physics in Lanzhou. The applications that followed were far-reaching, from high-current heavy-ion accumulation and proton cooling to heavy-ion cancer therapy and the heavy-ion programme of the LHC. Late in his career, he helped bring Russia's first heavy-ion electron-cooling systems into operation at the NICA complex in Dubna.

Vasily had an extraordinary talent for elegant, unconventional solutions. He devised a compass-based system capable of measuring the inclination of magnetic field lines to a precision of one microradian. Once, he needed a quartz fibre of micron-scale diameter – invisible to the naked eye – for a flying-wire beam-profile monitor. His team made one by firing molten quartz from a bow into a tube



BINP SB RAS

Vasily Parkhomchuk played a decisive role in the first demonstration of electron cooling.

One of the truest embodiments of the scientific culture of the Budker Institute

lined with black velvet from his wife's dress, so that the fibre would catch the light and could be seen. It worked.

His physical instincts ranged well beyond cooling. Leading a team that analysed the effects of diffusive ground motion on beam dynamics in the VLEPP linear electron–positron collider project and the Superconducting Super Collider in the early 1990s, he coined the term "ATL law", which has since become a widely accepted concept in accelerator alignment and stability. His studies of magnetised electron beams helped lay the groundwork for the electron lenses used in beam–beam compensation, and his kinetic theory of ionisation cooling contributed to the theoretical basis for muon colliders. He also founded Russia's first accelerator mass spectrometry centre, in Novosibirsk, which today serves researchers in radiocarbon dating and biomedical science.

Elected a full member of the Russian Academy of Sciences in 2016, Parkhomchuk was honoured with the Chinese Government Friendship Award (2004), the Dieter Möhl Medal (2013), the Robert R Wilson Prize of the American Physical Society (2016) and the Budker Gold Medal of the Russian Academy of Sciences (2023). He wore these distinctions lightly. Colleagues remember him not for the awards but for his presence in the accelerator control room, working side by side with colleagues and students until the very end, patient and curious and always ready to laugh.

Vasily's ideas live on in many of the world's most advanced accelerators. His humanity lives on in everyone who had the privilege of knowing him.

Yuan He *Institute of Modern Physics, Lanzhou,* **Igor Meshkov** *Joint Institute for Nuclear Research,* **Sergei Nagaitsev** *Brookhaven National Laboratory,* **Vladimir Shiltsev** *Northern Illinois University and* **Alexander Skrinsky** *Budker Institute of Nuclear Physics.*

Niels Doble 1938–2026

An authority on secondary beams

Niels Doble, born on 2 May 1938 in Denmark, passed away on 8 August 2026 after a short illness. Niels was best known for his pivotal contributions to the initial design and subsequent operation of the North Area of the Super Proton Synchrotron (SPS).

At a young age, Niels moved from Denmark to England. Though he initially intended to become a watchmaker, he studied physics at the University of Bristol. After a year at the Niels Bohr Institute, he joined CERN as a staff member in September 1962, working in Bill Lock's emulsion group on hyperon polarisation. In 1968 he earned his PhD at Bristol, on measurements of the magnetic moments of the hyperons, under the supervision of Don Perkins. He then moved to the Max Planck Institute for Physics in Munich for five years, working on the HYBUC bubble-chamber experiment and, when visiting CERN, on a 15 T normal-conducting magnet. It was in Munich, too, that he met his wife Gunilde, whom he married in 1966.



L Gatignon

Niels Doble shaped the layout of the SPS North Area and designed the kaon beams of three generations of CP-violation experiments.

Niels then came back to CERN, in 1972, to join Giorgio Brianti's group in the 300 GeV project, focusing on the design and construction of the North Area. Niels did many of the lattice calculations and essentially shaped the North Area layout. He had the ability to understand an experiment as a whole and found creative solutions when needed. As early as 1974, he wrote a conceptual design paper with Roger Clifft for the M2 muon beam, which was commissioned in 1978. Niels was leader of the Experimental Areas group from 1979 until the end of 1991. From 1979 to 1991, he was a member of the SPS Committee.

Once the North Area started operation, Niels took part in several important experiments, including NA20 (1980) on particle production, which is still a reference for secondary beamline design at CERN, and NA30 (1985), for measuring the neutral-pion lifetime. The users of the North Area remember the exceptional support that he provided over the years. Through his advice, written notes and willingness to ▷ listen and explain, Niels mentored the next generation of beam physicists.

While ensuring excellent support across all beamlines, Niels focused his scientific experience on beams for the kaon programme, starting with NA31 in the EHN1 hall. He designed and implemented the specialised K_L and K_S beamlines for the experiment. This ambitious design featured a 20 m-long train that moved the K_S production target, flanked by two 5 m dipole magnets, across 41 stations inside a 2 m-diameter vacuum tank, ending in a 1 mm-thick Kevlar window. Niels had a deep appreciation for mechanics and thoroughly enjoyed collaborating with engineers on every detail. His precise drawings by hand, always to scale, were much appreciated. The experiment showed the first evidence for direct CP violation in 1988.

In the follow-up experiment, NA48, Niels was instrumental in providing simultaneous, almost collinear K_L and K_S beams. This was made possible by the pioneering use of a bent

Pivotal contributions to the North Area of the Super Proton Synchrotron

crystal to transport a small fraction of the protons traversing the K_L production target to a second target, which produced the K_S beam. Niels set up a collaboration with several outside institutes and organised, with colleagues in Aarhus, the production of the crystal, along with its bending mechanism and goniometer. Naturally, Niels coordinated the overall design and construction of the beamlines. The experiment was a great success, leading to a 7σ observation of direct CP violation in the neutral-kaon system in 2002.

Kaon beams remained a passion for Niels throughout his life. After his retirement, he continued to make vital contributions to the K12 beamline for the NA62 experiment, particularly on beam optics and muon sweeping. He remained actively involved in beam operation and in the experiment until the very end.

Niels was well known for solving complex issues over informal coffee meetings. In his free time, he loved music, skiing, snowshoeing, hiking in the mountains and swimming in the lake. Niels was a calm, thoughtful colleague and a good friend to many. He was a genuinely nice, approachable and generous person, and a gentleman. He earned widespread respect through his thorough, deep approach to every topic. We benefited continuously from his quiet wisdom, calmness and authority on secondary beamlines and experiments alike. Niels was a key figure for the kaon programme and the North Area as a whole, and he will be deeply missed.

Our thoughts are with his son, Michael, and his daughter, Karin.

His colleagues and friends.

Paolo Emilio Strolin 1939–2026

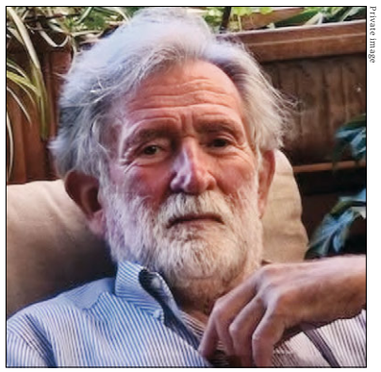
An advocate of science without barriers

Paolo Strolin, emeritus professor of physics at the University of Naples Federico II and a significant contributor to many CERN experiments, passed away on 28 June 2026 at the age of 87.

Born in Reggio Emilia in 1939, Paolo graduated from the University of Bologna in electronic engineering in 1963 and in physics in 1968. From 1964 to 1975 he worked at CERN, first in the Accelerator Division and then in the Particle Physics Division as a research physicist. In the second half of the 1970s he moved to ETH Zurich as an associate professor. He was then appointed full professor of experimental physics in Naples in 1980, where he spent the rest of his career and eventually became emeritus professor.

In Naples, Paolo founded a neutrino-physics group, which contributed significantly to CHARM II (1983–1994), a CERN experiment that made precision measurements of neutrinos to test the Standard Model. In 1989, theorist Haim Harari proposed that neutrinos could account for dark matter and urged the experimental community to test the idea. This was the origin of the CHORUS experiment, which Paolo and his group helped to design, build and operate, with Paolo serving as spokesperson from 1996 to 1999. When the atmospheric-neutrino results of 1998 showed that neutrinos do oscillate, but with mass splittings far below the reach of CHORUS, the collaboration turned to measuring neutrino-induced processes with charmed hadrons.

Around this time, Paolo, Antonio Ereditato and Kimio Niwa proposed the OPERA experiment, with Paolo as its first spokesperson. CERN directed a muon–neutrino beam towards the Gran Sasso National Laboratory of the Italian National Institute for Nuclear Physics (INFN), where the OPERA collaboration built and operated a 4000-tonne detector containing 110,000 m² of nuclear-emulsion films. After five years of data collection and several years of painstaking analysis, the experiment published the first observation of muon neutrinos oscillating into tau neutrinos in appearance mode, with a significance of 5σ, in 2015.



Private image

Paolo Strolin advocated science without barriers, geographical or disciplinary.

A significant contributor to many CERN experiments

At CERN, Paolo was a member of the Scientific Policy Committee and of the experiments committees for the Intersecting Storage Rings, LEP and the SPS. In Italy he was director of the physics department in Naples, director of the Naples section of INFN and chair of the INFN's National Scientific Committee 2, for astroparticle physics. He also served as vice-president of the Réseau Méditerranéen des Écoles d'Ingénieurs.

In retirement, Paolo focused on wider applications of physics research, such as muon radiography for the study of volcanoes and archaeology. He pursued these activities with great passion, encouraging young colleagues to take responsibility and lead new endeavours. He also worked hard to promote science in secondary schools and founded the association *Scienza e Scuola*, engaging dozens of schools and teachers in projects, some of them international in scope.

Paolo advocated science without barriers, geographical or disciplinary. He possessed a sometimes-disarming simplicity in his human relationships, and a personal and scientific charisma that left its mark. He had many friends both inside and outside work. Paolo leaves behind an impressive scientific legacy and a profound human and professional imprint on our community.

Giovanni De Lellis *CERN.*

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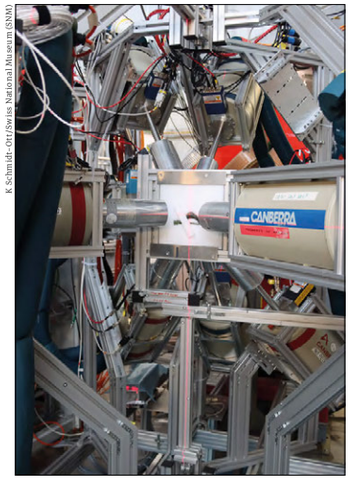
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BACKGROUND

Notes and observations from the high-energy physics community

A μseum piece

The smiths of Iron Age Ticino could hardly have pictured their brooches, 2400 years on, in the experimental hall of a 590 MeV proton cyclotron. Yet this summer, researchers at the Paul Scherrer Institute bathed some of them in the world's most powerful continuous muon beam. Inside the metal, negative muons are captured by atoms, which then emit X-rays that identify each element. Since a muon's momentum sets how far it penetrates, tuning the beam let the team compare the composition near the surface with that deeper inside.



K Schmidt-Ott/Swiss National Museum (SNM)

In the crosshairs *An Iron Age fibula ringed by X-ray detectors.*

890

Metres of beam vacuum components removed from the LHC in August and September to prepare for its high-luminosity upgrade

Media corner

"For me the main pleasure of it, besides winning the Nobel Prize, is that I hope this reflects on the really courageous people who joined me in the beginning of this project."
Francis Halzen (University of Wisconsin–Madison), speaking by telephone to the press conference announcing his Nobel Prize in Physics (Nobel Prize *YouTube* channel, 6 October).

"We need to remember our skepticism and be careful about the hype that we're hearing. Human physics is not over."
Sarah Demers (Yale University), on the growing use of artificial intelligence in physics (*Quanta Magazine*, 3 September).

"With this star we hope to measure, within the next 10 years, the spin of the black hole."
Felix Mang (Max Planck Institute for Extraterrestrial Physics), on S301, which passes roughly as close to the Milky Way's central black hole as Saturn is to the Sun (*The Guardian*, 19 August).

"Helping people grasp how extraordinary it is that the universe obeys a handful of fundamental laws is the best way to explain why a new accelerator is worth building."
Gino Isidori (University of Zurich), on explaining fundamental physics to the public (*la Repubblica*, 3 October).

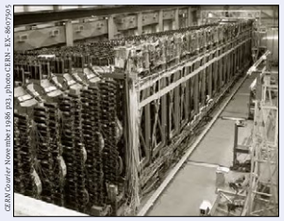
From the archive: November/December 1986

Heavy-ion research begins at the AGS

On 20 October, oxygen ions from the Brookhaven Tandem Van de Graaff were transferred to the Alternating Gradient Synchrotron (AGS) and for the first time accelerated to the full design energy of 14.6 GeV per nucleon. Four days later, ions were extracted and the first AGS heavy-ion experiment was completed during the weekend. The beam intensity was about 4×10^8 ions per pulse.

In the first experiment with the beam of oxygen-16, targets of various elements were exposed for periods from 10 minutes to 36 hours. For the longest run, this amounted to an accumulated exposure of 10^{13} ions.

Efforts to accelerate and extract silicon or sulphur ions will begin soon. Ion species up to gold will be available when the booster ring, now approved for construction, is completed.



CERN Courier November 1986 p331, photo CERN-SX-8607001

CERN neutrinos back in town
SPS neutrinos were back in business in September, with CHARM II taking its first data.

Proton synchrotron for cancer therapy

Fermilab has collaborated with the Loma Linda University Medical Center (LLUMC) in California to design a small proton synchrotron for use in cancer therapy. The conceptual design for a 250 MeV synchrotron has been published and it is hoped that industry will pick up the technology and that many such facilities will eventually be built.

Fermilab has agreed to design, construct and commission the accelerator then to move it to Loma Linda and put it into operation. The associated treatment facility is the responsibility of the Loma Linda staff. It is intended to complete the design early next year and to put the accelerator into operation at Fermilab early in 1988.

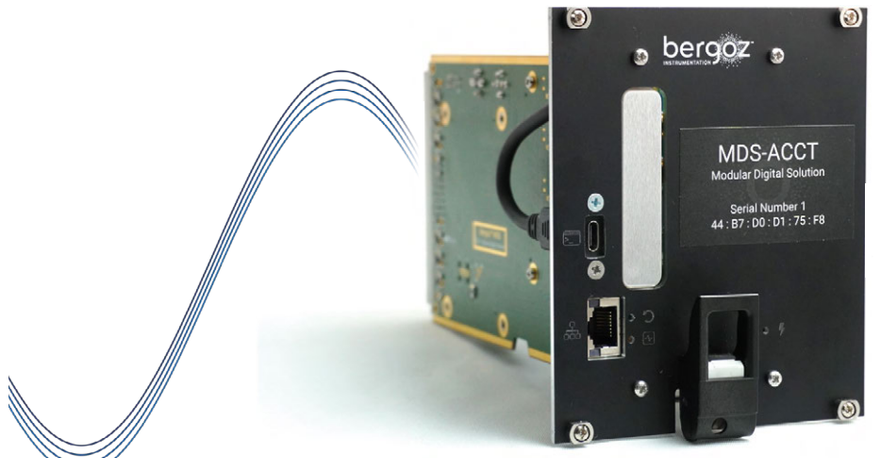
● Text adapted from *CERN Courier* December 1986 pp 5–7 and p17.

Compiler's note

Brookhaven National Laboratory began to explore relativistic heavy-ion physics with the acceleration of oxygen ions in the AGS in 1986, and went on to produce beams of gold ions in 1992. The Relativistic Heavy Ion Collider (RHIC) started up in 2000. Fed by the AGS, it often used beams of gold ions in research that opened a window onto a new state of matter, the quark–gluon plasma, and more (p25). The use of protons for cancer therapy was first proposed by Robert Wilson in 1946. While accelerators built for physics were later adapted for particle therapy, no machine was built specifically for proton therapy until the collaboration between LLUMC and Fermilab, appropriately the laboratory where, as its first director, Wilson was a guiding force. Proton-therapy centres now operate in many countries, but the technology remains complex and expensive. Conventional radiotherapy with X-rays is much more widespread, although limited in availability in low- and middle-income countries (p37).

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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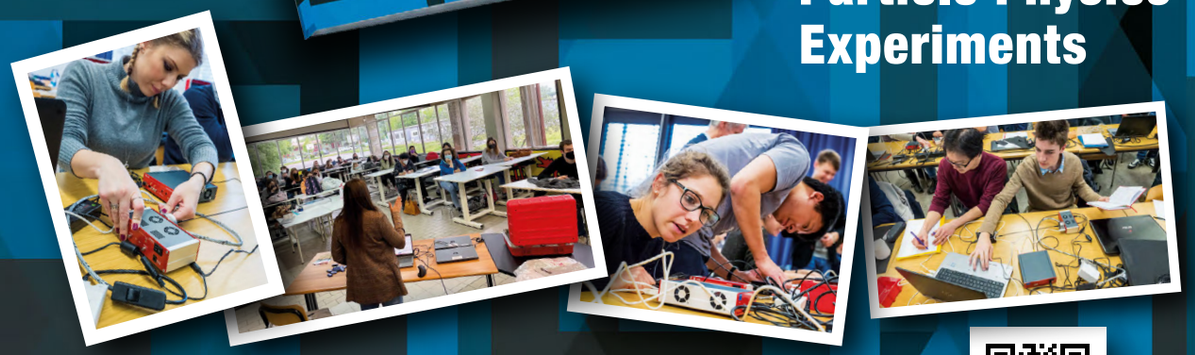
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