WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the January/February 2026 issue of *CERN Courier*.

Physicists can be allies, wrote Wassily Kandinsky, "who test matter again and again, who tremble before no problem, and who finally cast doubt on that very matter which was yesterday the foundation of everything, so that the whole universe is shaken."

This edition of *CERN Courier* offers two examples of physics to shake the universe. Each spontaneously breaks the symmetry of a field, plunging the vacuum into a potential well shaped like the rim of a hat, releasing a torrent of energy into the universe.

Peccei–Quinn symmetry breaking would explain the fine tuning of the Standard Model to produce no CP violation in the strong interaction, while also yielding a dark-matter candidate, the QCD axion (p21). Two ingenious experiments are smashing the limits of cavity haloscopes to search for the QCD axion over the next 10 years (p26).

Electroweak symmetry breaking is thought to have given mass to elementary particles. Its smoking gun was the Higgs boson, but very little is known about how it took place in the early universe. Much depends on the shape of the Higgs potential, which we have barely even begun to probe. In this issue, Valentina Cairo and Steven Lowette explore what can be learnt at the High-Luminosity LHC (p31).

These projections provide an important input to the 2026 update to the European Strategy for Particle Physics. The biggest decision concerns seven large-scale collider projects that the community has proposed as possible successors to the High-Luminosity LHC. Like Kandinsky's geometric constructivism at the Bauhaus, they are a harmony of lines, arcs and circles (p35).

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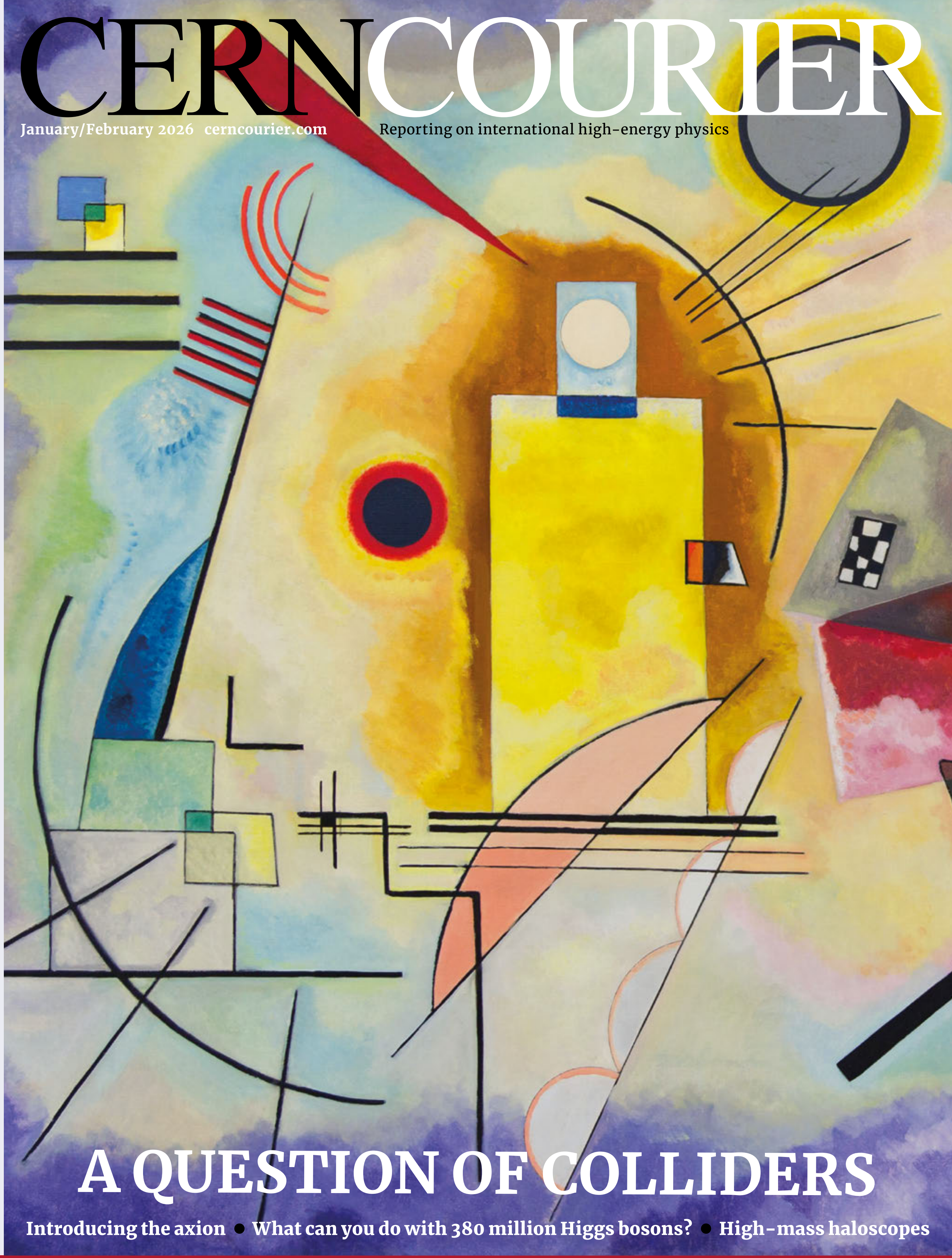
EDITOR: MARK RAYNER



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FROM THE EDITOR

Physics to shake the universe

Mark Rayner
Editor

Wassily Kandinsky was the prophet of abstract art. He valued those who question conventional wisdom and see beyond the external. Physicists can be allies, he wrote in 1911, "who test matter again and again, who tremble before no problem, and who finally cast doubt on that very matter which was yesterday the foundation of everything, so that the whole universe is shaken," to borrow Sadleir's translation.

In the same year, at the Solvay conference, Einstein argued for the quantisation of energy exchanges. By 1925, when Kandinsky painted this month's cover image, Heisenberg was putting the finishing touches to quantum mechanics.

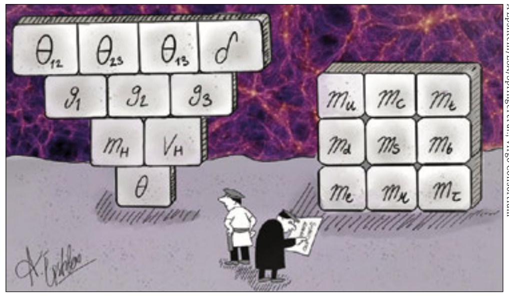
This edition of *CERN Courier* offers two contemporary examples of physics to shake the universe. Literally. Each spontaneously breaks a symmetry, plunging the vacuum into a potential well shaped like the rim of a hat, pouring energy into the universe. The rotational symmetry of the rim is important. For electroweak symmetry breaking, this gives mass to the W and Z bosons. For Peccei–Quinn symmetry breaking, it yields a dark-matter candidate, the QCD axion. The radial excitations of the two fields are the Higgs boson and an inaccessibly massive Peccei–Quinn analogue.

Peccei and Quinn's mechanism allowed Wilczek and Weinberg to predict the QCD axion. Other axion-like fields are available, but this one could explain two mysteries at once: the nature of dark matter and the fine tuning of the Standard Model to produce no CP violation in the strong interaction (p21).

A key question is whether Peccei–Quinn symmetry broke before or after the mysterious cosmic inflation by a factor 10^{26} that cosmologists pencil in to make their models fit. If Peccei–Quinn symmetry broke after inflation, we know roughly where to look for the QCD axion. Two ingenious experiments are smashing the limits of cavity haloscopes to search for the post-inflation QCD axion over the next 10 years (p26).

The QCD axion is having a moment

Quite coincidentally, the QCD axion is having a moment. In its original form with massless neutrinos, the Standard Model has 19 free parameters (see "An axion to grind" figure). That's nothing to boast about, and Peccei and Quinn's mechanism trades the QCD vacuum angle θ for a dynamical mechanism, which admittedly comes with additional free parameters. But



An axion to grind *Free parameters of the Standard Model.*

another group garnered significant attention in the theory community in December with their claim that θ arises from a subtle inconsistency in standard treatments of quantum field theory. An online event with more than 800 physicists and research-group watching parties seems to have hardened opinion against them, but Kandinsky might have admired the courage to argue with lattice simulations.

After inflation and Peccei–Quinn symmetry breaking – if they happened – the universe may have been shaken again, by an electroweak phase transition. Much depends on the shape of the Higgs potential, which we have barely even begun to probe. In this issue, Valentina Cairo and Steven Lowette explore what can be learnt at the High-Luminosity LHC (p31).

These projections provide an important input to the 2026 update to the European Strategy for Particle Physics. The biggest decision concerns seven large-scale collider projects that the community has proposed as possible successors to the High-Luminosity LHC. Like Kandinsky's geometric constructivism at the Bauhaus, they are a harmony of lines, arcs and circles. Gianluigi Arduini, Philip Burrows and Jacqueline Keintzel report on a comparative assessment of the seven (p35).

In late breaking news as the *Courier* went to press, one project among them received support from both community deliberations (p7) and private donors (p9).

Reporting on international high-energy physics

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NEWS ANALYSIS

Policy

European Strategy Group recommends FCC-ee

PIXELRISE

Preferred option *Artist's impression of the electron–positron Future Circular Collider.*

The European Strategy Group (ESG) has finalised its recommendations for the 2026 update to the European Strategy for Particle Physics. As required by the CERN Council, the recommendations include a preferred option for the next large-scale collider at CERN and a prioritised alternative option to be pursued if the preferred plan turns out not to be feasible or competitive.

"The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN," explains strategy secretary Karl Jakobs of the University of Freiburg. "A descoped FCC-ee is the preferred alternative option. Descoping scenarios include removing the top-quark run, constructing two rather than four interaction regions and experiments, and decreasing the RF-system power."

The ESG drafted its recommendations in a dedicated meeting at Monte Verità in Ascona, Switzerland. From 1 to 5 December, 62 delegates from across the field built on community inputs and the work of the Physics Preparatory Group to elaborate a proposal for the update to the European Strategy for Particle Physics. The recommendations address a broad range of topics and goals related to research in high-energy physics in Europe and beyond (*CERN Courier* November/December 2025 p23).

Seven large-scale collider projects have been the subject of a comparative assessment: CLIC, FCC-ee, FCC-hh, LCF, LEP3, LHeC and a muon collider (see p35). Following community submissions to the strategy process in March 2025 and at the open symposium in Venice in June 2025, a consensus emerged that an electron–positron Higgs and electroweak factory is the optimal collider to follow the High-Luminosity LHC (HL-LHC), with FCC-ee the favoured machine of a strong majority of the community (*CERN Courier* September/October p24). The identification of a descoped FCC-ee as the preferred alternative option was a new development in Ascona.

"Descoping would reduce the construction cost of FCC-ee by approximately 15%," says Jakobs. "Although this would have a significant impact on the breadth of the physics programme and the precision achieved, the descoped FCC-ee would still provide a very strong physics programme and a viable path towards high energies, compared to the alternative collider options. Should additional resources become available, these descoping scenarios would be reversible."

"The other electron–positron collider options offer substantially reduced precision physics programmes and would not be competitive with a collider like the FCC-ee," continues Jakobs. "Moreover, in themselves, they currently lack a viable path towards energies of 10 TeV."

In preparation for the Ascona meeting, working groups were set up to study national inputs, the physics and technology of the large-scale flagship collider projects, the implementation of the strategy, relations with other fields of physics, sustainability and environmental impact, public engagement, education and communication, as well as social and career aspects, and knowledge and technology transfer.

According to the ESG, the FCC-ee would deliver the world's broadest high-precision particle-physics programme, with an outstanding discovery potential through the Higgs, electroweak, flavour and top-quark sectors, as well as advances in QCD. Its technical feasibility, scope and cost are defined by the FCC Feasibility Study (*CERN Courier* May/June 2025 p9). The FCC-ee would maintain European leadership in high-energy particle physics, says the ESG, as well as advancing technology and providing significant societal benefits.

The FCC-ee would maintain European leadership in high-energy particle physics

"The FCC-ee or the descoped version would also pave the way towards a hadron collider reusing the tunnel and much of the infrastructure, providing direct discovery reach well beyond the 10 TeV parton energy scale, in line with the community's ambition for exploration at the highest achievable energy," concludes Jakobs. "The overwhelming endorsement of the FCC-ee by the particle-physics communities of CERN's Member and Associate Member States further reinforces it as the preferred path."

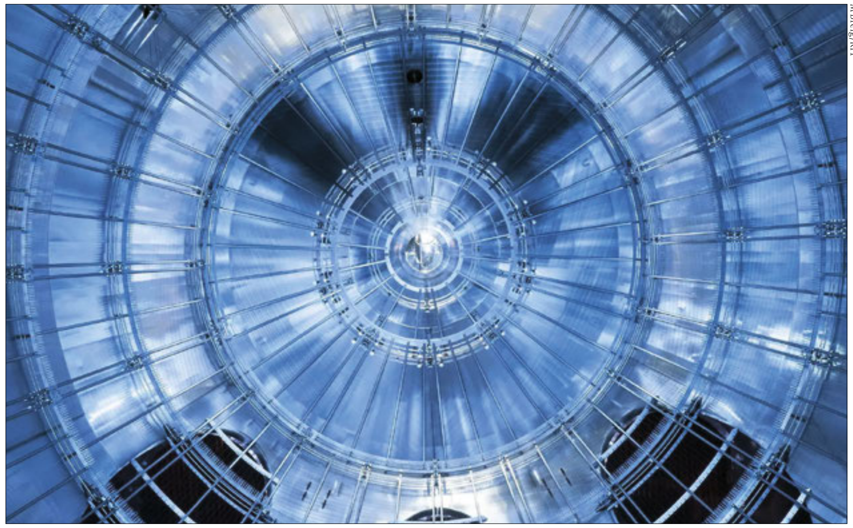
The recommendations of the ESG advise but do not constrain the CERN Council, which is expected to formally deliberate on the official update to the European Strategy for Particle Physics at a dedicated Council Session in Budapest in May 2026.

Further reading

The European Strategy Group 2025 CERN-ESU-2025-002.

NEUTRINOS

Two strikes for the light sterile neutrino


M Breig/KIT

Extreme precision *Inside the KATRIN detector.*

In the 1990s, the GALLEX and SAGE experiments studied solar electron neutrinos using large tanks of gallium. Every few days a neutrino would transform a neutron into a proton, and every few weeks the experimenters would count the resulting germanium atoms using radiochemical techniques. To control systematic uncertainties in these difficult experiments, they also exposed the detectors to well-understood radioactive sources of electron neutrinos. But both experiments reported 20% fewer electron neutrinos from radioactive decay than expected.

Thus was born the gallium anomaly, which was carefully checked and confirmed by SAGE's successor, the BEST experiment, as recently as 2022. The most tempting explanation is the existence of a new particle: a "sterile" neutrino flavour that doesn't interact via any Standard Model interaction. Neutrino oscillations would transform the missing 20% of electron neutrinos into undetectable sterile neutrinos. It would nevertheless have remained invisible to LEP's famous measurement of the number of neutrino flavours as it would not couple to the Z boson.

Out the window

This interpretation has been in tension with neutrino-oscillation fits for some time, but a new measurement at the KATRIN experiment likely excludes a sterile-neutrino explanation of the gallium anomaly, says Patrick Huber (Virginia Tech). "There was a strong hint of that from solar neutrinos, but the KATRIN result really nails this window shut. That is not to say the gallium anomaly went away; the experimental evidence here is firm and stands at more than five sigma significance, even under the most conservative assumptions about nuclear cross sections and systematics. So this still requires an explanation, but due to KATRIN we now know for sure it can't be a vanilla sterile neutrino."

KATRIN's main objective is to measure the mass of the electron neutrino (*CERN Courier* January/February 2020 p28). Though neutrino oscillations imply that the particle is massive, its mass has thus far proved to be below the sensitivity of experiments. The KATRIN experiment, based at the Karlsruhe Institute of Technology in Germany, seeks to remedy this with precise observations of the beta decay of tritium. The heavier the electron neutrino, the lower the maximum energy of the beta-decay electrons. Though KATRIN has not yet been able to uncover evidence for the tiny mass of the electron neutrino, the much larger mass of any sterile neutrino able to explain the gallium anomaly would have made itself felt in precise observations of the endpoint of the energy spectrum of beta-decay electrons thanks to mixing between the neutrino flavours.

After the new KATRIN analysis, the best fit of the sterile neutrino from the gallium anomaly is excluded at 96.6% confidence

"A sterile neutrino would manifest itself as a model-independent kink-like distortion in the beta-decay spectrum, rather than as a deficit in the event rate," explains lead analyst Thierry Lasserre of the Max-Planck-Institut für Kernphysik, in Heidelberg, Germany. "After the new KATRIN analysis, including 36 million electrons in the last 40 electron volts below the endpoint, the best fit of the sterile neutrino from the gallium anomaly is excluded at 96.6% confidence."

Though heavy sterile neutrinos remain a well motivated completion of the Standard Model of particle physics with the potential to solve problems in cosmology, light sterile neutrinos struck out a second time in the same volume of *Nature* last month, thanks to a new measurement at the MicroBooNE experiment at Fermilab, near Chicago.

The MicroBooNE collaboration was following up on a persistent anomaly uncovered by their sister experiment, MiniBooNE, which was itself following up on the infamous LSND anomaly of 2001 (*CERN Courier* July/August 2020 p32). Both experiments had reported an excess of electron neutrinos in a beam of muon neutrinos generated using a particle accelerator. Here, the sterile-neutrino explanation would be more subtle: muon neutrinos would have to oscillate twice, once into sterile neutrinos and then into electron neutrinos. Using a bespoke liquid-argon time projection chamber, the MicroBooNE collaboration excludes the single-light-sterile-neutrino interpretation of the LSND and MiniBooNE anomalies at 95% confidence.

Confirmation

"The MicroBooNE result is just confirming what we knew from global fits for a long time," clarifies Huber. "We cannot treat the appearance of electron neutrinos in a muon neutrino beam as a two-flavour problem if a sterile neutrino is involved – if we accept this simple fact of quantum mechanics then LSND and MiniBooNE's excess of electron neutrinos cannot be due to mixing with a sterile neutrino since the corresponding disappearance of electron and muon neutrinos has not been observed."

One sterile-neutrino anomaly remains unmentioned, the reactor anomaly, but it has already evaporated into statistical insignificance thanks to new experiments and careful modelling of the flux of electron antineutrinos from nuclear reactors. The promise of experiments with reactor neutrinos is now exemplified by the rapid progress of the Jiangmen Underground Neutrino Observatory (JUNO) in China, which started data taking on 26 August last year (*CERN Courier* November/December 2025 p9).

Back to the standard paradigm

While the recent KATRIN and MicroBooNE analyses sought evidence for a hypothetical sterile neutrino beyond the standard scenario, JUNO operates within the standard three-flavour framework. Using just 59 days of data, the experiment independently exceeded the precision of previous global fits on two out of six of the parameters governing neutrino oscillations. These are the same mixing angle and mass splitting that govern the oscillations of solar electron neutrinos into other flavours – the very effect that GALLEX and SAGE were initially designed to study in the 1990s. As JUNO gathers data, it will resolve a fine-toothed comb that modulates this oscillation spectrum – the effect of a smaller mass splitting between the three neutrinos. JUNO is designed to resolve these tiny oscillations, revealing a fundamental aspect of nature's design: the hierarchy of the small and large mass splittings.

The JUNO result is exciting because it marks the successful start of an experiment that will deeply change neutrino physics

"The JUNO result is very exciting," says Huber, "not so much because of its immediate impact, but because it marks the very successful start of an experiment that will deeply change neutrino physics."

JUNO is the first of a trio of a new generation of large-scale neutrino-oscillation experiments using controlled sources. Concluding a busy two-month period for neutrinos since the previous edition of *CERN Courier* was published, the launch of the nuSCOPE collaboration now dangles the promise of a valuable boost to the other two. One hundred physicists attended its kick-off workshop at CERN from 13 to 15 October 2025. The collaboration seeks to implement a concept first proposed 50 years ago by Bruno Pontecorvo: nuSCOPE will eliminate systematic uncertainties related to neutrino flux by measuring the energy and flavour of neutrinos as they are created as well as when they interact with a target.

If approved, nuSCOPE will study neutrino–nucleus interactions with a level of accuracy comparable to that in electron–nucleus scattering, and control the sources of uncertainty projected to be dominant in the DUNE experiment under construction in the US and at the Hyper-Kamiokande experiment under construction in Japan. DUNE and Hyper-Kamiokande both plan to study the oscillations of accelerator-produced beams of muon neutrinos. Their most specialised design goal is to observe another fundamental aspect of physics: whether the weak interaction treats neutrinos and antineutrinos symmetrically.

With three ambitious and sharply divergent experimental concepts, DUNE, Hyper-Kamiokande and JUNO promise substantial progress in neutrino physics in the coming decade. But KATRIN and MicroBooNE now leave precious little merit for the once compelling phenomenology of the single light sterile neutrino.

Two strikes, and you're out.

Further reading

The KATRIN Collab. 2025 *Nature* **648** 70.
The MicroBooNE Collab. 2025 *Nature* **648** 64.
A Abusleme *et al.* 2025 arXiv:2511.14593.

POLICY

Private donors pledge support for FCC

For the first time in CERN's history, private donors (individuals and philanthropic foundations) have agreed to support a CERN flagship research project. Recently, a group of friends of CERN, including the Breakthrough Prize Foundation, The Eric and Wendy Schmidt Fund for Strategic Innovation, and the entrepreneurs John Elkann and Xavier Niel, have pledged significant funds towards the construction of the Future Circular Collider (FCC), the potential successor of the Large Hadron Collider. These potential contributions, totalling some 860 million euros and corresponding to 1 billion US dollars, would represent a major private-sector investment in the advancement of research in fundamental physics.

"It's the first time in history that private donors wish to partner with CERN to build an extraordinary research instrument that will allow humanity to take major steps forward in our understanding of fundamental physics and the universe. I am profoundly grateful to them for their generosity, vision and unwavering commitment to knowledge and exploration. Their support is essential to the prospective realisation of the FCC and to enabling future generations of scientists to push the frontiers of scientific discovery and technology," said CERN Director-General Fabiola Gianotti.

Understanding the fundamental nature of our universe is the mission that unites humanity

"Understanding the fundamental nature of our universe is the mission that unites humanity," said Pete Worden, chairman of the Breakthrough Prize Foundation. "We're proud to support the creation of the most powerful scientific instrument in history, that can shed new light on the deepest questions humanity can ask."

"The Future Circular Collider is an instrument that could push the boundaries of human knowledge and deepen our understanding of the fundamental laws of the universe," said Eric Schmidt. "Beyond the science, the technologies emerging from this project could benefit society in profound ways, from medicine to computing to sustainable energy, while training a new generation of innovators and problem-solvers. Wendy and I are inspired by the ambition of this project and by what it could mean for the future of humanity."

"CERN's Member States are extremely grateful for the interest expressed by our donors in contributing to the funding of the Laboratory's next flagship project. This once again demonstrates CERN's relevance and positive impact on society, and the strong interest in CERN's future that exists well beyond our own particle-physics community," said the president of the CERN Council Costas Fountas.

The FCC has also been included among 11 proposed "Moonshot" projects in the draft Multiannual Financial Framework for the years 2028–2034, released by the European Commission in July.

Based on strong input from the international particle-physics community, the FCC has been recommended as the preferred option for the next flagship collider at CERN in the ongoing process to update the European Strategy for Particle Physics, which will be concluded by the CERN Council in May 2026 (see p7). A decision by the CERN Council on the construction of the FCC is expected around 2028.

MATERIALS SCIENCE

Asteroid tests challenge nuclear-deflection models

Millions of asteroids orbit the Sun. Smaller fragments often brush the Earth's atmosphere to light up the sky as meteors. Once every few centuries, a meteoroid has sufficient size to cause regional damage, most recently the Chelyabinsk explosion that injured thousands of people in 2013, and the Tunguska event that flattened thousands of square kilometres of Siberian forest in 1908. Asteroid impacts with global consequences are vastly rarer, especially compared to the frequency with which they appear in the movies. But popular portrayals do carry a grain of truth: in case of an impending collision with Earth, nuclear deflection would be a last-resort option, with fragmentation posing the principal risk. The most important uncertainty in such a mission would be the materials properties of the asteroid – a question recently studied at CERN's Super Proton Synchrotron (SPS), where experiments revealed that some asteroid materials may be stronger under extreme energy deposition than current models assume.

E Halwax

Stronger than expected *The Campo del Cielo meteorite.*

Planetary defence

"Planetary defence represents a scientific challenge," says Karl-Georg Schlesinger, co-founder of OuSoCo, a start-up developing advanced material-response models used to benchmark large-scale nuclear deflection simulations. "The world must be able to execute a nuclear deflection mission with high confidence, yet cannot conduct a real-world test in advance. This places extraordinary demands on material and physics data."

Accelerator facilities play a key role in understanding how asteroid material behaves under extreme conditions, providing controlled environments where impact-relevant pressures and shock conditions can be reproduced. To probe the material response directly, the team conducted experiments at CERN's HiRadMat facility in 2024 and 2025, as a part of the Fireball collaboration with the University of Oxford. A sample of the Campo del Cielo meteorite, a metal-rich iron-nickel body, was exposed to 27 successive short, intense pulses of the 440 GeV SPS proton beam, reproducing impact-relevant shock conditions that cannot be achieved with conventional laboratory techniques.

"The material became stronger, exhibiting an increase in yield strength, and displayed a self-stabilising damping behaviour," explains Melanie Bochmann, co-founder and co-team lead alongside Schlesinger. "Our experiments indicate that – at least for metal-rich asteroid material – a larger device than previously thought can be used without catastrophically breaking the asteroid. This keeps open an emergency option for situations involving very large objects or very short warning times, where non-nuclear methods are insufficient and where current models might assume fragmentation would limit the usable device size."

Throughout the experiments at the SPS, the team monitored each pulse using laser Doppler vibrometry alongside temperature sensors, capturing in real time how the meteorite softened, flexed and then unexpectedly re-strengthened without breaking. This represents the first experimental evidence that metal-rich asteroid material may behave far more robustly under extreme, sudden energy loading than predicted.

After the SPS campaign, initial post-irradiation measurements were performed at CERN. These revealed that magnesium inclusions had been activated to produce sodium-22, a radioactive isotope that decays to produce a positron, allowing diagnostics similar to those used in medical imaging. Following these initial measurements, the irradiated meteorite has been transferred to the ISIS Neutron and Muon Source at the Rutherford Appleton Laboratory in the UK, where neutron diffraction and positron annihilation lifetime spectroscopy measurements are planned.

The experiments could also provide valuable insights into planetary formation processes

"These analyses are intended to examine changes in the meteorite's internal structure caused by the irradiation and to confirm, at a microscopic level, the increase in material strength by a factor of 2.5 indicated by the experimental results," explains Bochmann.

Complementary information can be gathered by space missions. Since NASA's NEAR Shoemaker spacecraft successfully landed on asteroid Eros in 2001, two Japanese missions and a further US mission have visited asteroids, collecting samples and providing evidence that some asteroids are loosely bound rocky aggregates. In the next mission, NASA and ESA plan to study Apophis, an asteroid several hundreds of metres in size in each dimension that will safely pass closer to Earth than many satellites in geosynchronous orbit on 13 April 2029 – a close encounter expected only once every few thousand years.

The missions will observe how Apophis is twisted, stretched and squeezed by Earth's gravity, providing a rare opportunity to observe asteroid-scale material response under natural tidal stresses. Bochmann and Schlesinger's team now plan to study asteroids with a similar rocky composition.

Real-time data

"In our first experimental campaign, we focused on a metal-rich asteroid material because its more homogeneous structure is easier to control and model, and it met all the safety requirements of the experimental facility," they explain. "This allowed us to collect, for the first time, non-destructive, real-time data on how such material responds to high-energy deposition."

"As a next step, we plan to study more complex and rocky asteroid materials. One example is a class of meteorites called pallasites, which consist of a metal matrix similar to the meteorite material we have already studied, with up to centimetre-sized magnesium-rich crystals embedded inside. Because these objects are thought to originate from the core–mantle boundary of early planetesimals, such experiments could also provide valuable insights into planetary formation processes."

Further reading

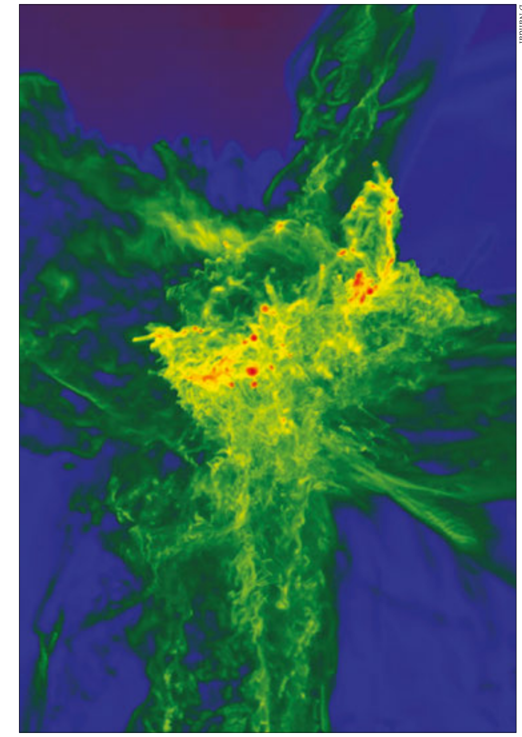
M Bochmann *et al.* 2025 *Nat. Commun.* doi:10.1038/s41467-025-66912-4.

ASTROWATCH

First indirect evidence for primordial monsters

Cosmology has long predicted that the first generation of stars should differ strongly from those forming today. Born out of pristine gas of only hydrogen and helium, they could have reached masses between a thousand and ten thousand times that of the Sun, before collapsing after only a few million years. Such "primordial monsters" have been proposed as the seeds of the first quasars (see "Collapsing monster" image), but clear observations had until now been lacking.

An analysis of the galaxy GS 3073 using the James Webb Space Telescope (JWST) now carries an unexpectedly loud message from the first generation of stars: there is far too much nitrogen to be explained by known stellar populations. This mismatch suggests a different kind of stellar ancestor, one no longer present in our universe. It is the first indirect evidence for the long-sought primordial monsters, first proposed in the early 1960s by Fred Hoyle and William Fowler in the US, and independently by Yakov Zel'dovich and Igor Novikov in the Soviet Union, in attempts to explain the newly discovered quasars.



D Nandal

Collapsing monster *Simulation of a primordial monster star giving birth to a quasar – an extremely luminous active galactic nucleus powered by a supermassive black hole that is actively accreting matter.*

Black-hole powered

JWST's near-infrared spectroscopy of GS 3073 reveals the highest nitrogen-to-oxygen ratio yet measured while surveying the universe's first billion years. Its dense central gas contains almost as many nitrogen atoms as oxygen, while carbon and neon are comparatively modest. In addition, the galaxy has an active nucleus powered by a black hole that is already millions to hundreds of millions of times the mass of the Sun, despite the galaxy's low metallicity.

Could a primordial monster explain GS 3073? The answer lies in how these huge stars mix and burn their fuel.

Simulations reveal that after an initial phase of hydrogen burning in the core, these stars ignite helium, producing large amounts of carbon and oxygen. Because the stars are so luminous and extended, their interiors are strongly convective. Hot material rises, cool material sinks and chemical elements are constantly stirred. Freshly made carbon from the helium-burning core leaks outward into a surrounding shell where hydrogen is still burning. There, a sequence of reactions known as the CNO cycle converts hydrogen into helium while steadily turning carbon into nitrogen. Over time, this process loads the outer parts of the star with nitrogen, while also moderately enhancing oxygen and neon. The heaviest elements produced in the final burning stages remain trapped in the core and never reach the surface before the star collapses.

GS 3073 could offer the first chemical evidence for the largest stars the universe ever formed and to the early production of massive black holes

Mass loss from such primordial stars is uncertain. Without metals, they cannot generate the strong line-driven winds familiar from massive stars today. Instead, mass may be lost through pulsations, eruptions or interactions in dense environments. But simulations allow a robust conclusion: supermassive primordial stars between roughly one thousand and ten thousand solar masses naturally produce gas with nitrogen-to-oxygen, carbon-to-oxygen and neon-to-oxygen ratios that match those measured in the dense regions of GS 3073. Stars significantly lighter or heavier than this range cannot reproduce the extreme nitrogen-to-oxygen ratio, even before carbon and neon are taken into account.

Under pressure

Radiation pressure could have supported these primordial monsters for no more than a few million years. As their cores contract and heat, photons become energetic enough to convert into electron–positron pairs, reducing the radiation pressure. For classical massive stars with masses in the range of nine to 120 times the mass of the sun, this instability leads to a thermonuclear explosion that we refer to as a supernova. By contrast, supermassive stars are so dominated by gravity due to their much larger mass that they collapse directly into black holes, without undergoing a supernova explosion.

This provides a natural path from supermassive primordial stars to the over-massive black hole now seen in GS 3073's nucleus. In this scenario, one or a few such giants enrich the surrounding gas with nitrogen-rich material through mass loss during their lives, and leave behind black-hole seeds that later grow by accretion. If this picture is correct, GS 3073 offers the first chemical evidence for the largest stars the universe ever formed and ties them directly to the early production of massive black holes. Future JWST observations, together with next-generation ground-based telescopes, will search for more nitrogen-loud galaxies and map their chemical structures in greater detail.

Further reading

D Nandal *et al.* 2025 *ApJL* **994** L11.

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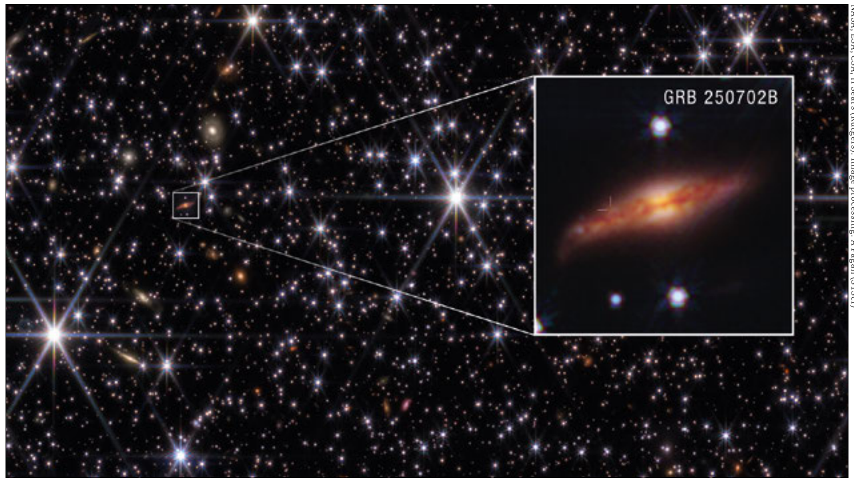
ASTROWATCH

Longest gamma-ray burst confounds astrophysicists



NASA, ESA, CSA, H Sears (Rutgers). Image processing: A Pagan (STScI)

Not from the nucleus *GRB 250702B emerged from the top edge of its host galaxy's dark dust lane (see inset).*

On 2 July 2025, NASA's Fermi Gamma-ray Space Telescope observed a gamma-ray burst (GRB 250702B) of a record seven hours in duration. Intriguingly, high-resolution images from the Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST) revealed that the burst emerged nearly 1900 light-years from the centre of its host galaxy, near the edge of its disc. But its most unusual feature is that it was seen in X-rays a full day before any gamma rays arrived.

The high-energy transient sky is filled with a cacophony of exotic explosions produced by stellar death. Short GRBs of less than two seconds are produced by the merging of compact objects such as black holes and neutron stars. Longer GRBs are produced by the death of massive stars, with "ultralong" GRBs most often hypothesised to originate in the collapse of massive blue supergiants, as they would allow for accretion onto their central black-hole engines over a period from tens of minutes to hours.

Peculiar observations

GRB 250702B lasted for at least 25,000 seconds (7 hours), superseding the previous longest GRB 111209A by over 10,000 seconds. However, the duration alone was not enough to identify this event as a different class of GRB or as an extreme outlier. Two other observations immediately marked GRB 250702B as peculiar: the multiple gamma-ray episodes seen by Fermi and other high-energy satellites; and the soft X-rays from 0.5 to 4 keV seen by China's Einstein Probe over a period extending a full day before gamma rays were detected.

No previous GRB is known to have been preceded by X-ray emission over such a period. Nor is it an expectation of standard GRB models, even those invoking a blue supergiant. Instead, these X-rays suggest a relativistic tidal disruption event (TDE) – the shredding of a star by a massive black hole, launching a jet that moves near the speed of light. All known relativistic TDE systems are produced by supermassive black holes weighing a million times the mass of our Sun, or more. Such black holes are found at the centre of their host galaxies, but the HST and JWST observations revealed that the transient had occurred near the edge of its host galaxy's disc (see "Not from the nucleus" image).

This peripheral origin opens the door to a more exotic scenario involving an intermediate-mass black hole (IMBH) weighing hundreds to thousands of solar masses. IMBHs are a missing link in black-hole evolution between the stellar-mass black holes that gravitational-wave detectors frequently see merging and the supermassive black holes found at the centre of most galaxies. Alternative scenarios reduce the black-hole mass even further, and include a micro-TDE, where a star is shredded by a stellar-mass black hole, or a helium star being eaten by a stellar-mass black hole.

There is little consensus on the origin of GRB 250702B, beyond that it involved an accreting black hole

The rapid gamma-ray variability observed by Fermi and other high-energy satellites is an important clue. The time variability of relativistic jets is thought to be orders of magnitude slower than the characteristic scale set by a black hole's Schwarzschild radius. While an intermediate-mass black hole of a few hundred solar masses is not incompatible, the observed variability is nearly 100 times faster than that seen in relativistic TDEs. By contrast, with characteristic physical scales smaller in proportion to the smaller masses of their black holes, micro-TDEs and helium-star black-hole mergers have no difficulty accommodating such short-timescale variability.

The environment of the transient also provides crucial clues into its origin. JWST spectroscopy revealed that the light from the transient and its host galaxy was emitted 8 billion years ago, when the universe was just a teenager. The galaxy is among the largest and most massive at that age in the universe, and – unusually for galaxies hosting GRBs – a massive dust lane splits its disc in half. Ongoing star formation at the transient's location suggests a stellar-mass progenitor, as opposed to an IMBH.

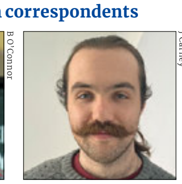
Despite numerous studies, there is little consensus on the origin of GRB 250702B, beyond that it involved an accreting black hole. Its exceptional duration and early X-ray emission initially suggested a supermassive black hole, but its rapid variability and location in its host galaxy instead point to a stellar-mass black hole, with a far rarer IMBH potentially splitting the difference. Given that it is a notably rare once-every-50-years event, the wait for the next ultralong GRB may be long, but astrophysicists are optimistic that theoretical advances will disentangle the different progenitor scenarios and reveal the origin of this extraordinary transient.

Further reading

B O'Connor *et al.* 2025 *ApJL* **994** L17.
J Carney *et al.* 2025 *ApJL* **994** L46.

Guest Astrowatch correspondents

B O'Connor



J Carney

Brendan O'Connor *Carnegie Mellon University.*

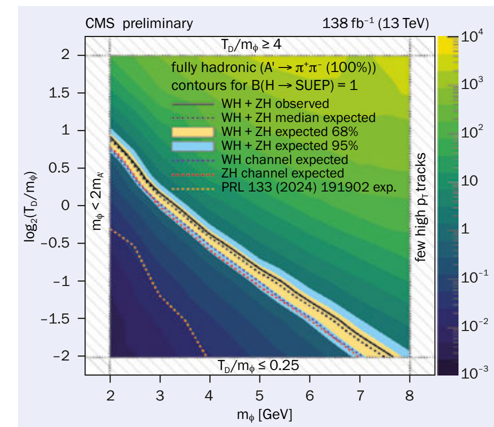
Jonathan Carney *University of North Carolina at Chapel Hill.*

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

Soft clouds probe dark QCD



CMS Collab. CMS-PAS-EXO-25-007

Fig. 1. *Limits on the branching ratio of the decay of the 125 GeV Higgs-boson mediator to a fully hadronic SUEP shower are shown as a function of the SUEP particle mass and the relative dark-sector energy scale. The colour map represents the upper limits for different model parameters, with the contour at which the observed (expected) limit reaches 100% shown as a solid (dotted) black line. Previous best limits from the gluon-fusion channel are shown as the orange dotted line.*

Despite decades of searches, experiments have yet to find evidence for a new particle that could account for dark matter on its own. This has strengthened interest in richer "dark-sector" scenarios featuring multiple new states and interactions, potentially analogous to those of the Standard Model (SM). The CMS collaboration targeted one of the most distinctive possible signatures of a dark strong force in proton–proton collisions: a dense, nearly isotropic cloud of low-momentum particles known as a soft unclustered energy pattern (SUEP).

Searches in the LHC proton–proton collision data for events with many low-momentum particles are plagued by overwhelming backgrounds from pileup and soft QCD interactions. The CMS collaboration has recently overcome this challenge by using large-radius clusters of charged particle tracks and relying on quantities that characterise the expected isotropy of SUEP decays.

The 125 GeV Higgs boson serves in many theoretical models as a natural mediator between the SM and a hidden sector, and current experimental constraints still leave room for exotic decays. Motivated by this possibility, CMS focused on Higgs-boson production in association with a vector (W or Z) boson that decays into leptons. While these modes account for < 1% of Higgs bosons produced at the LHC, the leptons provide significant handles for triggering and background suppression.

Rather than relying on SM simulations, which face modelling and statistical challenges for such soft interactions, the background was extrapolated from events with low isotropy or relatively few charged-particle tracks per cluster, using a method that accounts for small correlations between the quantities used in the extrapolation. To validate the approach, an orthogonal sample of events with a high-momentum photon was studied, taking advantage of the Higgs boson's minuscule coupling to photons and the similarity of background processes in W/Z + jet and photon + jet events that could mimic a SUEP signal.

The data in the search region, consisting of events with a W or Z boson candidate and many isotropically distributed charged particles, was found to be consistent with the SM expectation. Stringent limits were placed on the branching ratio of the 125 GeV Higgs boson decaying to a SUEP shower for a wide range of parameters (see figure 1).

This analysis complements a previous CMS search that primarily targeted much heavier mediators produced via gluon fusion, improving limits on the H → SUEP branching ratio by two orders of magnitude. It additionally provides model-agnostic limits and detailed reinterpretation recipes, maximising the usability of this data for testing alternative theoretical frameworks.

SUEP signatures are not unique to the benchmark scenarios under scrutiny. They naturally emerge in hidden-valley models, where mediators connect the SM to a new, otherwise isolated sector. If the hidden states interact through a "dark QCD", proton–proton collisions would trigger a crowded cascade of dark partons rather than the familiar collimated showers.

Crucially, unlike in ordinary QCD – where the coupling quickly weakens at energies above confinement – the dark coupling could remain large well beyond its typically low confinement scale. This sustained strong coupling would drive frequent interactions and efficiently redistribute momentum, producing an almost isotropic radiation pattern. As the system cooled, it would then hadronise into numerous soft dark hadrons whose decays back to SM particles would retain this softness and isotropy – yielding the characteristic SUEP probed by CMS.

Further reading

CMS Collab. CMS-PAS-EXO-25-007.

ATLAS

Trigger-level search for dijet resonances

The LHC's increased collision energies have opened new territory for TeV-scale searches, but its vast datasets also provide unparalleled opportunities to thoroughly explore the electroweak scale. A new ATLAS result uses an unconventional trigger-level analysis (TLA) of the full Run 2 dataset to achieve record sensitivity to low-mass particles decaying into quarks or gluons. ATLAS employs a two-stage trigger system, with a fast hardware-based first-level trigger selecting about 100 kHz of events from the 40 MHz bunch-crossing rate, followed by a software high-level trigger (HLT) that performs detailed event reconstruction and further reduces the accepted event rate by about two orders of magnitude. By recording a much reduced event format at the trigger level, TLA preserves a substantially larger fraction of events than would normally be output by the HLT.

The new result achieves record sensitivity to low-mass particles decaying into quarks or gluons

New particles that decay with a two-jet final state feature in many Standard Model (SM) extensions. For example, the properties of "dark mediators" that couple to both quarks and dark matter could explain the present abundance of ▷

dark matter by controlling how much of it remains after falling out of equilibrium with normal matter in the early universe. At the LHC, the coupling of dark mediators to quarks would enable both production and decay into quark–antiquark pairs. This should appear as resonances in the dijet mass distribution.

Searching for dijet resonances at low mass is challenging. Dijet production from strong interactions is one of the LHC's most abundant signatures. Beyond requiring a precise understanding of these enormous backgrounds and the detector response, the low-mass dijet rate far exceeds what ATLAS can record. Only the most energetic dijet events can be kept, limiting conventional dijet searches to masses above approximately 1 TeV.

To access the low-mass region, ATLAS used TLA to record multi-jet events throughout Run 2. By dropping the raw detector data from the readout, these TLA events were ~200 times smaller than standard events while retaining all high-level jet and calorimeter-based variables reconstructed in real-time by the HLT.

The size reduction allowed ATLAS to record TLA events at rates of up to 27 kHz – compared to an average 1.2 kHz for the full detector readout. This rate was achieved in conjunction with the additional trigger bandwidth allocated to TLA at the end of LHC fills and a more efficient use of this bandwidth for dijet events. In Run 2, this was aided by ATLAS's L1Topo trigger processor, which applies simple topological selections – such as angular correlations between jets – already at first level. The new result uses 1 billion dijet events, or up to 75 times the data sample available to the equivalent conventional search, achieving unprecedented statistical precision.

This enormous dataset demands excellent control of systematic uncertainties. ATLAS developed a dedicated multi-step calibration for trigger-level jets, achieving a jet energy scale precision of 1 to 4%, comparable to calibrations using full detector readout. The overwhelming SM background was modelled using a data-driven fitting technique, reaching a relative precision better than 1 part in 10^4.

The search has found the dijet invariant-mass distribution to be consistent with the background expectation. The analysis provides numerical results that can be used to constrain any of the numerous models of dijet resonances, as well as explicit constraints on a specific dark mediator model used as a common benchmark for many ATLAS and CMS searches. The result sets ATLAS's most stringent exclusion limits to date on the potential coupling of such a mediator to quarks, across a broad range of mediator masses reaching as low as 375 GeV (see figure 1).

The dijet TLA during Run 2 has established a foundation for an expanded trigger-level physics programme. In Run 3, trigger-level jets incorporate tracking information, allowing flavour tagging and improving jet energy resolution and robustness against pile-up. ATLAS also records trigger-level photons and uses them in combination with partial detector readout at full granularity. These and other advances in TLA should enable future ATLAS searches to probe a wider variety of signatures at the electroweak scale.

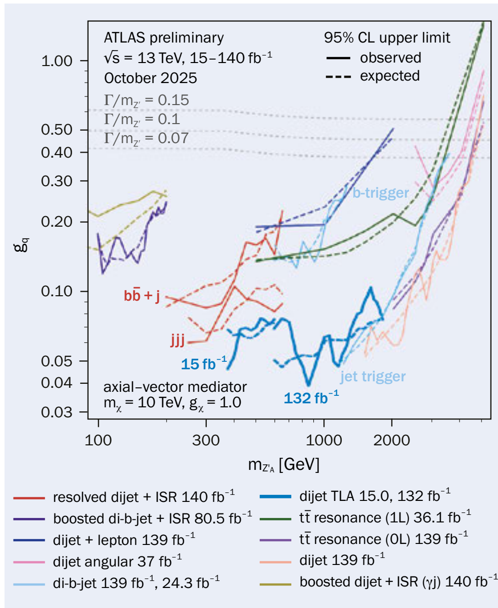


Fig. 1. *Observed (solid lines) and expected (dashed lines) 95% confidence upper limits on the coupling between quarks and an axial-vector mediator to the dark sector, as a function of the mass of the mediator. The TLA (thick blue line) places the strictest limits across a wide mass range. (Analysis references can be found in ATL-PHYS-PUB-2025-041.)*

ATLAS Collab 2025 ATL-PHYS-PUB-2025-041

Further reading

ATLAS Collab. 2025 *Phys. Rev. D* **112** 092015.
ATLAS Collab. 2024 *JINST* **19** P06029.
CMS Collab. 2025 arXiv:2510.21641.

LHCb

Tau leptons join the hunt

As the Standard Model (SM) withstands increasingly stringent experimental tests, rare decays remain a prime hunting ground for new physics. In a recent paper, the LHCb collaboration reports its first dedicated searches for the decays $B^0 \to K^+\pi^-\tau^+\tau^-$ and $B^0_s \to K^+K^-\tau^+\tau^-$, pushing hadron–collider flavour physics further into tau-rich territory.

At the quark level, the $B^0 \to K^+\pi^-\tau^+\tau^-$ and $B^0_s \to K^+K^-\tau^+\tau^-$ decays happen via the flavour-changing process $b \to s\tau^+\tau^-$, which is highly suppressed in the SM. The expected branching fractions of around 10^{-7} would place these decays well below the current experimental sensitivity.

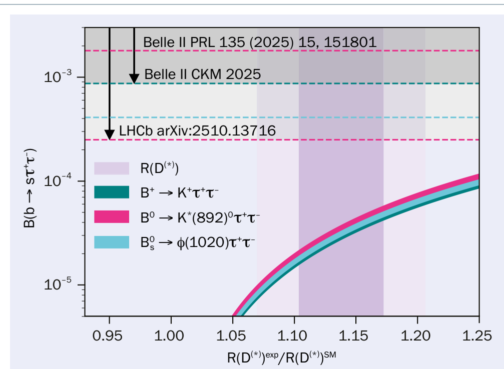


Fig. 1. *The curves show the predicted branching fractions for three rare $b \to s\tau^+\tau^-$ decays as functions of the possible deviation in the ratios of semileptonic branching fractions $R(D^{(*)})$ from the SM, based on the model proposed in PRL 120 (2018) 18180 and compared to the latest results from The Heavy Flavor Averaging Group (vertical bands). The horizontal lines indicate the upper limits at 90% confidence level from the LHCb and Belle II collaborations.*

LHCb Collab. 2025 arXiv:2510.13716

However, many new-physics scenarios, such as those involving leptoquarks or additional Z′ bosons, predict mediators that couple preferentially to third-generation leptons.

The tensions with the SM observed in the ratios of semileptonic branching fractions $R(D^{(*)})$ and in $b \to s\mu^+\mu^-$ processes could, for example, result in an enhancement of $b \to s\tau^+\tau^-$ decays. Yet despite its potential to yield signs of new physics, the tau sector remains largely unexplored.

The LHCb analysis only considered tau decays to muons, in order to exploit the detector's excellent muon identification systems. Reconstructing decays to final states with tau leptons at a hadron collider is notoriously challenging, particularly when relying on leptonic decays such as $\tau^+ \to \mu^+\nu_\tau\bar{\nu}_\mu$, which result in multiple unreconstructed neutrinos. Using the Run 2 data set of about 5.4 fb^{-1} of proton–proton collisions, the ▷

collaboration applied machine-learning techniques to extract the topological and isolation features of suppressed tau-pair signals from the background.

Due to the large amount of missing energy in the final state, the B-meson mass cannot be fully reconstructed and the output of the machine-learning algorithm was instead fitted to search for a $b \to s\tau^+\tau^-$ component. The search was primarily limited by the size of the control samples used to constrain the background shapes – a limitation that will be alleviated by the larger datasets expected in future LHC runs.

No significant signal excess was observed in either the $K^+\pi^-\tau^+\tau^-$ or the $K^+K^-\tau^+\tau^-$ final states. Upper limits on the branching fractions were then established in bins of the dihadron invariant masses, allowing separate exploration of regions dominated by dihadron resonances and those expected to be primarily non-resonant.

When interpreted in terms of resonant modes, the limits are $B(B^0 \to K^*(892)^0\tau^+\tau^-) < 2.8 \times 10^{-4}$ and $B(B^0_s \to \phi(1020)\tau^+\tau^-) < 4.7 \times 10^{-4}$ at the 95% confidence level. The $B^0 \to K^*(892)^0\tau^+\tau^-$ limit improves on previous bounds by approximately an order of magnitude, while the limit on $B^0_s \to \phi(1020)\tau^+\tau^-$ is the first ever established.

These results represent the world's most stringent limits on $b \to s\tau^+\tau^-$ transitions

These results represent the world's most stringent limits on $b \to s\tau^+\tau^-$ transitions. The analysis lays essential groundwork for future searches, as the larger LHCb datasets from LHC Run 3 and beyond are expected to open a new frontier in measurements of rare b-hadron transitions involving heavy leptons.

With the upgraded detector and the novel fully software-based trigger, the efficiency in selecting low-p_T muons – and consequently the tau leptons from which they originate – will be much improved. Sensitivity to $b \to s\tau^+\tau^-$ transitions is therefore expected to increase substantially in the coming years.

Further reading

LHCb Collab. 2025 arXiv:2510.13716.

ALICE

Strangeness at its extremes

Strangeness production in high-energy hadron collisions is a powerful tool for exploring quantum chromodynamics (QCD). Unlike up and down, strange quarks are not present as valence quarks in colliding protons and neutrons, and must therefore appear through interactions. They are, however, still light enough to be abundantly produced at the LHC.

Over the past 15 years, the ALICE collaboration has shown that the abundance of strange over non-strange hadrons grows with event multiplicity in all collision systems. In particular, high-multiplicity proton–proton (pp) collisions display a significant strangeness enhancement, reaching saturation levels similar to those in heavy-ion collisions. In one of the most precise studies of strange-to-non-strange hadron production to date, the ALICE collaboration has reported its recent results from pp and lead–lead collisions at the LHC.

Strange hadrons (K^0_S, Λ, Ξ, Ω) were reconstructed from their weak-decay topologies. Candidates were then selected by applying geometrical and kinematic cuts, estimating and subtracting backgrounds, and correcting the resulting distributions using detector-response simulations. The analyses were carried out at a centre-of-mass energy per nucleon pair of 5.02 TeV and span a wide multiplicity range, from 2 to 2000 charged particles at mid-rapidity.

To better understand how strangeness is produced, the collaboration has taken a significant step by measuring the probability distribution of forming a specific number of strange particles of the same species per event. This study, based on event-by-event strange-particle counting, moves beyond average yields and probes higher orders in the strange-particle production probability distribution. To account for the response of the detector, each candidate is assigned a probability of being genuine rather than background, and a Bayesian unfolding method iteratively corrects for particles that were missed or misidentified to reconstruct the true counts. This provides a novel technique for testing theoretical strangeness-production mechanisms, particularly in events characterised by a significant imbalance between strange and non-strange particles.

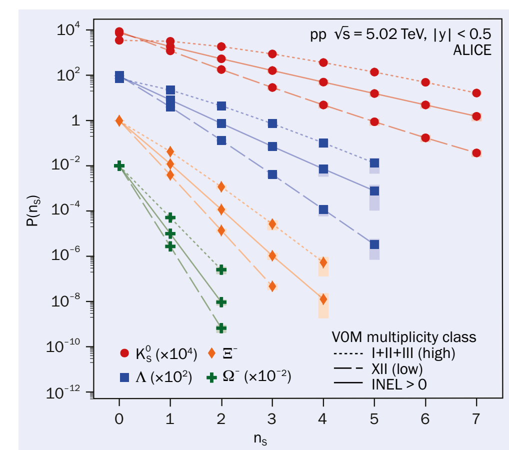


Fig. 1. *(Multi-)strange-particle-multiplicity distributions, $P(n_S)$, for K^0_S (red), Λ (blue), Ξ^- (orange) and Ω^- (green) in three multiplicity classes in pp collisions at 5.02 TeV: minimum bias (INEL > 0), low (dashed) and high (dotted) charged-particle multiplicity. The progression from dashed to dotted lines illustrates the rise of $P(n_S)$ with multiplicity.*

ALICE Collab. 2025 arXiv:2511.10413

Exploiting a large dataset of pp collisions, the probability of producing n particles of a given species S ($S = K^0_S$, Λ, Ξ^- or Ω^-) per event, $P(n_S)$, could be determined up to a maximum of $n_S = 7$ for K^0_S, $n_S = 5$ for Λ, $n_S = 4$ for Ξ and $n_S = 2$ for Ω (see figure 1). An increase of $P(n_S)$ with charged-particle multiplicity is observed, becoming more pronounced for larger n, as reflected by the growing separation between the curves corresponding to low- and high-multiplicity classes in the high-n tail of the distributions.

The average production yield of n particles per event can be calculated from the $P(n_S)$ distributions, taking into account all possible combinations that result in a given multiplet. This makes it possible to compare events with the same or a different overall strange quark content that hadronise into various combinations of hadrons in the final state. While the ratio between Ω triplets to single K^0_S shows an extreme strangeness-enhancement pattern up to two orders of magnitude across multiplicity, comparing hadron combinations that differ in up- and down-quark content but share the same total s-quark content (for instance, Ω singlets compared to Λ triplets) helps isolate the part of the enhancement unrelated to strangeness.

Comparisons with state-of-the-art phenomenological models show that this new approach greatly enhances sensitivity to the underlying physics mechanisms implemented in different event generators. Together with the traditional strange-to-pion observables, the multiplicity-differential probability distributions of strange hadrons provide a more detailed picture of how strange quarks are produced and hadronise in high-energy collisions, offering a stringent benchmark for the phenomenological description of non-perturbative QCD.

Further reading

ALICE Collab. 2025 arXiv:2511.10306.
ALICE Collab. 2025 arXiv:2511.10360.
ALICE Collab. 2025 arXiv:2511.10413.

FIELD NOTES

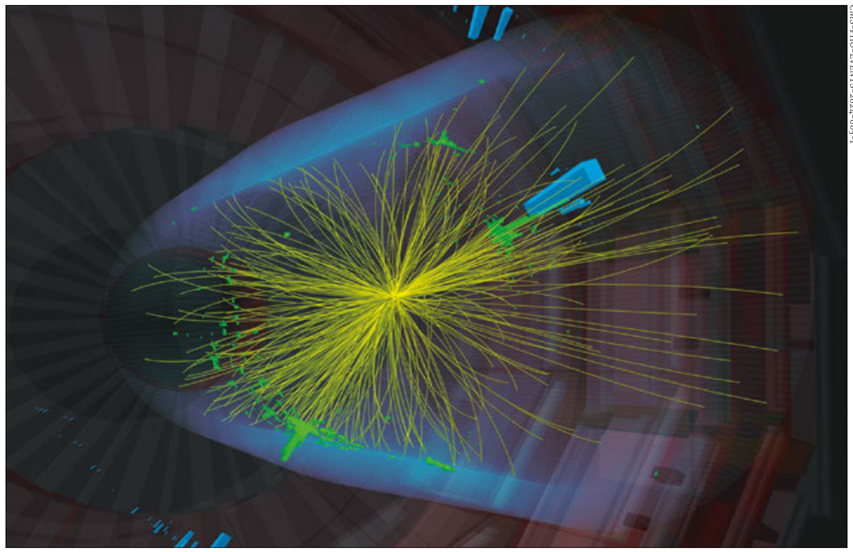
Reports from events, conferences and meetings

SEARCH 2025

From theories to signals

Over the past decade, many theoretical and experimental landscapes have shifted substantially. Traditional paradigms such as supersymmetry and extra dimensions – once the dominant drivers of LHC search strategies – have gradually given way to a more flexible, signature-oriented approach. The modern search programme is increasingly motivated by signals rather than full theories, providing an interesting backdrop for the return of the SEARCH conference series, which last took place in 2016. The larger and more ambitious 2025 edition attracted hundreds of participants to CERN from 20 to 24 October.

The workshop highlighted how much progress ATLAS and CMS have made in searches for long-lived particles, hidden-valley scenarios (see "Soft cloud" figure) and a host of other unconventional possibilities that now occupy centre stage. Although these ideas were once considered exotic, they have become natural extensions of models connected to cosmology, dark matter and electroweak symmetry breaking. Their experimental signatures are equally rich: displaced vertices, delayed showers, emerging jets or unusual track topologies that demand a rethinking of reconstruction strategies from the ground up.



CMS-PHO-EVENTS-2024-005-1

Soft cloud *Soft, unclustered energy patterns such as the one seen in this CMS event are a possible signature of hidden-valley dark-matter models (see p13).*

Deep learning

The most transformative change since previous editions of SEARCH is the integration of AI-based algorithms into every layer of analysis. Deep-learning-driven b-tagging has dramatically increased sensitivity to final states involving heavy flavour, while machine learning is being embedded directly into hardware trigger systems to identify complex event features in real time. This is not technological novelty for its own sake: these tools directly expand the discovery reach of the experiments.

Novel ideas in reconstruction also stood out. Talks showcased how muon detectors can be repurposed as calorimeters to detect late-developing showers, and how tracking frameworks can be adapted to capture extremely displaced tracks that were once discarded as outliers. Such techniques illustrate a broader cultural shift: expanding the search frontier now often comes from reinterpreting detector capabilities in creative ways.

Anomaly detection – the use of unsupervised or semi-supervised deep-learning models to identify data that deviate from learned patterns – was another major focus. These methods, used both offline and in level-one triggers, enable model-agnostic searches that do not rely on an explicit beyond-the-Standard-Model target. Participants noted that this is especially valuable for scenarios like quirks in dark-sector models, where realistic event-generation tools still do not exist. In these cases, anomaly detection may be the only feasible path to discovery.

The rising importance of precision was another theme threading through the discussions. The detailed understanding of detector performance achieved in recent years is unprecedented for a hadron collider. CMS's muon calibration, which is crucial for its W-mass analysis, and ATLAS's record-breaking jet-calibration accuracy exemplify the progress. This maturity opens the possibility that new physics could first appear as subtle deviations rather than as striking anomalies. As the era of the High-Luminosity LHC approaches, the upcoming additions of precision timing layers and advanced early-tracking capabilities will further strengthen this dimension of the search programme.

The most transformative change since previous editions of SEARCH is the integration of AI-based algorithms into every layer of analysis

The workshop also provided a platform to explore connections between collider searches and other experimental efforts across particle physics. Strong first-order phase transitions, relevant to electroweak baryogenesis, motivated renewed interest in an additional scalar that would modify the Higgs potential. Such a particle could lie anywhere from the MeV scale up to hundreds of GeV – often below the mass ranges targeted by standard resonance searches. Alternative data-taking strategies such as data scouting and data parking offer new opportunities to probe this wide mass window systematically. ▷

Complementarity with flavour physics at LHCb, long-lived particle searches at FASER, and precision experiments seeking electric dipole moments, axion-like particles and other ultralight states, was also highlighted. In a moment without an obvious theoretical favourite, this diversification of experimental approaches is a key strategic strength.

A recurring sentiment was that the LHC remains a formidable discovery machine, but the community must continue pushing its tools beyond their traditional boundaries. Many discussions at SEARCH 2025 echoed a famous remark by Freeman Dyson: "New directions in science are launched by new tools much more often than by new concepts." The upcoming upgrades to ATLAS and CMS – precision timing, enhanced tracking earlier in the trigger chain and high-granularity readout – exemplify the kinds of new tools that can reshape the search landscape.

New directions in science are launched by new tools much more often than by new concepts

If SEARCH 2025 underscored the need to explore new signatures, technologies and experimental ideas, it also highlighted an equally important message: we must not lose sight of the physics questions that originally motivated the LHC programme. The hierarchy problem, the apparent fine tuning of quantum corrections to the Higgs mass that prevent it rising to the Planck scale, remains unresolved, and supersymmetry continues to offer its most compelling and robust solution by stabilising it through partner particles. With the dramatic advances in reconstruction, triggering and analysis techniques, and with the enormous increase in recorded data from Run 1 through Run 3, the time is ripe to revitalise the inclusive SUSY search programme. A comprehensive, modernised SUSY effort should be a defining element of the combined ATLAS and CMS legacy physics programme, ensuring that the field fully exploits the discovery potential of the LHC dataset accumulated so far.

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INTERNATIONAL CONFERENCE ON PHYSICS OF THE TWO INFINITIES

Tokyo targets the two infinities

From 17 to 23 November, the second International Conference on Physics of the Two Infinities (P2I) gathered nearly 200 participants on the historic Hongo campus of the University of Tokyo. Organised by the ILANCE laboratory, a joint initiative by CNRS and the University of Tokyo, the P2I series aims to bridge the largest and smallest scales of the universe. In this spirit, the 2025 programme drew together results from cosmological surveys, particle colliders and neutrino detectors.

ILANCE

Across the universe *About 200 researchers gathered in Tokyo to discuss physics at the largest and smallest scales.*

Two cosmological tensions will play a key role in the coming decades. One concerns how strongly matter clumps together to form structures such as galaxy clusters and filaments. The other involves the universe's expansion rate, H_0. In both cases, measurements based on early-universe data differ from those conducted in the local universe. The discrepancy on H_0 has now reached about 6σ (*CERN Courier* March/April 2025 p28). Independent methods, such as strong lensing, lensed supernovae and gravitational-wave standard sirens, are essential to confirm or resolve this discrepancy. Several of these techniques are expected to reach 1% precision in the near future. More broadly, upcoming large-scale cosmological missions, including Euclid, DESI, LiteBIRD and the Legacy Survey of Space and Time (LSST) – which released its world-leading camera's first images in June – are set to deliver important insights into inflation, dark energy and the cosmological effects of neutrino masses.

The dark universe featured prominently. Participants discussed an excess of gamma rays from the galactic centre detected by the Fermi telescope, which is consistent with the self-annihilation of weakly interacting massive particles (WIMPs) and may represent one of the strongest experimental hints for dark matter. Recent analyses on more than 40 million galaxies and quasars in DESI's Data Release 2 show that fits to baryon acoustic oscillation distances deviate from the standard ΛCDM model at the 2.8 to 4.2σ level, with a dynamical dark energy providing a better match. Euclid, having identified approximately 26 million galaxies out to over 10.5 billion light-years, is poised to constrain the nature of dark matter by combining measurements of large-scale structure, gravitational-lensing statistics, small-scale substructure, dwarf-galaxy populations and stellar streams. Experiments such as XENONnT and PandaX-4T are instead pursuing a mature direct-detection programme.

Future colliders were a central topic at P2I. While new physics has long been expected to emerge near the TeV scale to stabilise the Higgs mass, the Standard Model remains in excellent agreement with current data, and precision flavour measurements constrain many possible new particles to lie at much higher energies. The LHC collaborations presented a flurry of new results and superb prospects for its high-luminosity phase, alongside new results from Belle II and NA64. Looking ahead, a major future collider will ▷

CERNCOURIER
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be essential for exploring and probing the laws connecting particle physics with the earliest moments of the universe.

The conference hosted the first-ever public presentation of JUNO's experimental results, only a few hours after their appearance on arXiv. Despite relying on only 59.1 days of data, the experiment has already demonstrated excellent detector performance and produced competitive measurements on solar-neutrino oscillation that are fully consistent with previous results. This level of precision is remarkable, after barely two months of data collection. Three major questions in neutrino physics remain unresolved: the ordering of neutrino masses, the value of the CP-violating parameter and the octant of the mixing angle θ_{32}. The next generation of experiments, including JUNO, DUNE, Hyper-K and upgraded neutrino telescopes, are specifically designed to answer these questions. Meanwhile, DESI has reported a new, stringent upper limit of 0.064 eV on the sum of neutrino masses, within a flat ΛCDM framework. It is the tightest cosmological constraint to date.

New data from the JWST, Subaru and ALMA telescopes revealed an unexpectedly rich population of galaxies only 200–300 million years after the Big Bang. Many of these early systems appear to grow far more rapidly than predicted by the ΛCDM model, raising questions such as whether star formation efficiency was significantly higher in the early universe or whether we currently underestimate the growth of dark-matter halos (*CERN Courier* November/December 2025 p11). These data also highlighted a surprisingly abundant population of high-redshift active galactic nuclei, with important implications for black-hole seeding and early supermassive black-hole formation. A comprehensive review of the rapidly evolving field of supernova and transient astronomy was also presented. The mechanisms behind core-collapse supernovae remain only partially understood, and the thermonuclear explosions of white dwarfs continue to pose open questions. At the same time, observations keep identifying new transient classes, whose physical origins are still under investigation. Important insights into protostars, discs and planet formation were also discussed. Observations show that interstellar bubbles and molecular filaments shape the formation of stars and planets across a vast range of physical scales. More than 6000 exoplanets have today been detected, from hot Jupiters to super Earths and ocean planets, many without counterparts in our Solar System.

The LHC collaborations presented a flurry of new results and superb prospects for its high-luminosity phase

With more than 150 new gravitational-wave (GW) candidates now identified, including extreme ones with rapid spins and highly asymmetric component masses, GW astronomy offers outstanding opportunities to investigate gravity in the strong-field regime. Notably, the GW250114 event was shown to obey Hawking's area law, which states that the total horizon area cannot decrease during a black-hole merger, providing strong confirmation of general relativity in the most nonlinear regime. Next-generation observatories such as the Einstein Telescope, Cosmic Explorer and LISA will allow detailed black-hole spectroscopy and impose tighter constraints on alternative theories of gravity.

Even if the transition to multi-messenger astronomy began in the late 20th century, the first binary neutron-star merger, GW170817, remains its landmark event. An extraordinary global effort – more than 70 teams and 100 instruments pointed at the event for years – highlighted several historic firsts: the first gravitational-wave "standard siren" measurement of the Hubble constant, the first association between a neutron-star merger and a short gamma-ray burst, the first observed kilonova confirming the astrophysical site of heavy-element production, and the first direct test comparing the speed of gravity and light. Very-high-energy gamma-ray astronomy (HESS, MAGIC and VERITAS) also reported impressive results, with more than 300 sources above 100 GeV observed, and bright prospects, as the Cherenkov Telescope Array Observatory (CTAO) is about to start operations.

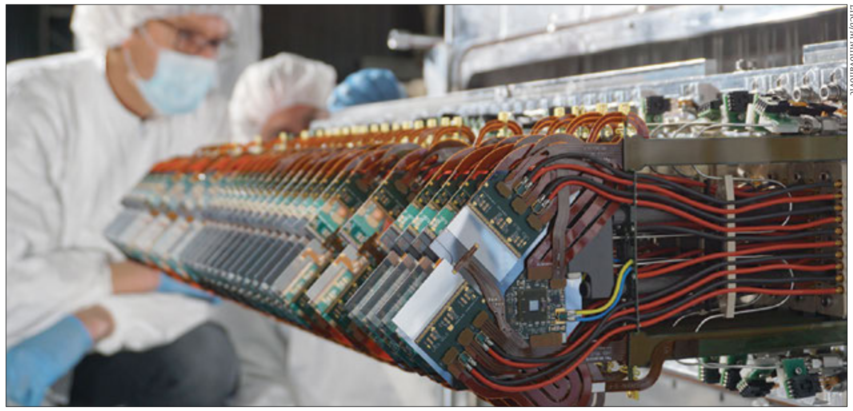
Michel Gonin *ILANCE and*
Marumi Kado *MPI.*

IMPLICATIONS OF LHCb MEASUREMENTS AND FUTURE PROSPECTS

The many flavours of LHCb

The 15th edition of the Implications of LHCb Measurements and Future Prospects annual workshop took place at CERN from 4 to 7 November 2025, attracting more than 180 participants from the LHCb experiment and the theoretical physics community.

Peilian Li (UCAS) described how, thanks to an upgraded trigger that is fully software-based, the dataset gathered in 2025 alone already exceeded the total one from Run 1 and Run 2 combined. The future of LHCb was discussed, with prospects for an upgrade targeting the high-luminosity phase of the LHC, where timing information will be introduced. Theorist Monika Blanke (KIT) concluded the workshop with a keynote on the status of B-decay anomalies, highlighting the importance of LHCb measurements ▷



LHCb/M Milovanovic

Thinking implications *Thanks to its upgraded software trigger, LHCb collected more data in 2025 than in Runs 1 and 2 combined.*

on constraining new physics models.

Much attention went to the long-standing discrepancies between data and theory on lepton-flavour-universality tests – such as the measurement of the R(D) and R(D*) ratios in semileptonic B-meson decays. Marzia Bordone (UZH) gave a theoretical overview of the determination of the form factors describing B→D* transitions, highlighting discrepancies in the determination of some form-factor shapes, both among different lattice-QCD determinations and within extractions from different experimental datasets.

A new combination of all LHCb measurements of the CKM angle γ, which quantifies a key CP-violating phase in b-hadron decays, yielded an overall value of (62.8 ± 2.6)°. The collaboration reported flagship electroweak precision measurements of the effective weak mixing angle and the W-boson mass, as well as the first dedicated measurement of the Z-boson mass at the LHC.

An exciting focus for 2026 will be the search for the double open-beauty tetraquark $T_{bb}(bb\bar{u}\bar{d})$ – the first accessible exotic hadron expected to be stable against strong decay (*CERN Courier* November/December 2024 p34). Saša Prelovšek (UL) presented the first lattice-QCD calculation of the state's electromagnetic form factors, allowing her to rule out an interpretation of the tetraquark as a loosely-bound B–B^* molecule.

An exciting focus for 2026 will be the search for the double open-beauty tetraquark $T_{bb}(bb\bar{u}\bar{d})$

The legacy Run 1+2 $B \to K^* \mu^+ \mu^-$ angular analysis, based on a dataset roughly twice as large as that used in previous ones, was presented. Previously seen tensions were confirmed with much increased precision and new observables are reported for the first time. Theorists Arianna Tinari (UZH), Giuseppe Gagliardi (INFN Rome3) and Nazila Mahmoudi (IP2I, CERN) reviewed the status of the non-local hadronic contributions that could affect this channel, discussing how the use of different theoretical approaches can be employed to determine these contributions and how compatible the current results are with the theoretical expectations.

Zhengchen Lian (THU, INFN Firenze) showed the characteristic "bowling-pin" deformation of neon nuclei as it was recently observed using the SMOG2 apparatus, which allows collisions of LHC protons with a variety of fixed-target light nuclei injected into the beampipe (*CERN Courier* November/December 2025 p8).

Marco Fedele *University of Mainz and* **Mary Richardson-Slipper** *University of Cambridge.*

25TH ZIMÁNYI WINTER SCHOOL

Budapest brims with heavy ions

HUN-REN Wigner Research Centre for Physics

Expanding systems *The 25th Zimányi Winter School was jointly organised by the Institute for Particle and Nuclear Physics of the HUN-REN Wigner Research Centre for Physics and the Institute of Physics at Eötvös Loránd University.*

The 25th Zimányi Winter School gathered 120 researchers in Budapest to discuss recent advances in medium- and high-energy nuclear physics. The programme focused on the properties of strongly-interacting matter produced in heavy-ion collisions – little bangs that recreate conditions a few microseconds after the Big Bang.

József Zimányi was a pioneer of Hungarian and international heavy-ion physics, playing a central role in establishing relativistic heavy-ion research in Hungary and contributing key developments to hydrodynamic descriptions of nuclear collisions. Much of the week's programme revisited the problems that occupied his career, including how the hot, dense system created in a collision evolves and how it converts its energy into the observed hadrons.

Giuseppe Verde (INFN Catania) and Máté Csanád (ELTE) emphasised the role of femtoscopic methods, rooted in the Hanbury Brown–Twiss interferometry originally developed for stellar measurements, in understanding the system that emerges from heavy-ion collisions. Quantum entanglement in high-energy nuclear collisions – a subject closely connected to the 2025 Nobel Prize in Physics – was also explored in a dedicated, invited lecture by Dmitri Kharzeev (Stony Brook University), who described the approach and the results of his team that suggest the origin of the observed thermodynamic properties is quantum entanglement itself.

The NA61/SHINE collaboration reported ongoing studies of isospin-symmetry breaking, including a recent result where the charged-to-neutral kaon ratio in argon–scandium collisions deviates at 4.7σ from expectations based on approximate isospin symmetry (*CERN Courier* March/April 2025 p9). Further detailed studies are planned, with potential implications for improving the understanding of antimatter production.

Hydrodynamic modelling remains one of the most successful tools in heavy-ion physics. Tetsufumi Hirano (Sophia University, Japan), the first recipient of the Zimányi Medal, discussed how the collision system behaves like an expanding relativistic fluid, whose collective motion encodes its initial conditions and transport properties. Hydrodynamic approaches incorporating spin effects – and the resulting polarisation effects in heavy-ion collisions – were discussed by Wojciech Florkowski (Jagiellonian University) and Victor E Ambrus (West University of Timisoara).

Péter Kovács *HUN-REN Wigner FK,* **Dániel Kincses** *ELTE and* **Sandor Lokos** *IFJ PAN and MATE Institute of Technology.*

NEUTRON LIFETIME PUZZLE

The beam–bottle debate at PSI

Free neutrons have a lifetime of about 880 seconds, yet a longstanding tension between two measurement techniques continues to puzzle the neutron-physics community. The most precise averages from beam experiments and magnetic-bottle traps yield 888.1 ± 2.0 s and 877.8 ± 0.3 s, respectively – roughly corresponding to a 5σ discrepancy.

B Lauss/PSI

On 13 September 2025, 40 representatives of all currently operating neutron-lifetime experiments came together at the Paul Scherrer Institute (PSI) to discuss the current status of the tension and the path forward. Geoffrey Greene (University of Tennessee) opened the workshop by reflecting on five decades of neutron-lifetime measurements from the 1960s to the present.

The beam method employs cold-neutron beams, with protons from neutron beta-decays collected in a magnetic trap and counted. The lifetime is then inferred from the ratio of proton counts to neutron flux. Fred Wietfeldt (Tulane University) highlighted the huge efforts undertaken at the National Institute of Standards and Technology (NIST) in Gaithersburg, most importantly on the absolute calibration of the neutron detector.

A lifetime disagreement *The neutron-lifetime community assembled at PSI to discuss a stubborn 5σ tension.*

Susan Seestrom (Los Alamos National Laboratory) described today's most precise experiment, the UCNτ experiment at Los Alamos National Laboratory, which uses the magnetic-bottle trap method. It confines ultracold neutrons (UCNs) via their magnetic and gravitational interaction and counts the surviving ones at different times. She also provided an outlook on its next phase, UCNτ+, with increased statistics goals. The τSPECT experiment at PSI's UCN facility is also based on magnetic confinement of neutrons and has recently started data taking, but has distinct differences. As explained by Martin Fertl from Johannes Gutenberg-University Mainz, τSPECT uses a double-spin-flip method to increase the UCN filling of the purely magnetic trap, and a detector moving in and out of the storage volume to first remove slightly higher-energetic neutrons before storage, and then measures the surviving neutrons *in situ* after storage.

Kenji Mishima (University of Osaka) presented the neutron-lifetime experiment at J-PARC, based on a new principle: the detection of the charged decay products in an active time-projection-chamber, where the neutrons are captured on a small ³He admixture. This experiment's systematics are entirely different from those of previous efforts and may offer a unique contribution to the field. Other studies largely excluded the possibility that the beam–bottle discrepancy could be explained by hypothetical exotic decay channels or other non-standard processes.

New results from LANL, NIST, J-PARC and PSI should clarify the currently puzzling situation in the coming years.

Bernhard Lauss *and* **Dieter Ries** *PSI.*

INAUGURATION OF THE MARIETTA BLAU INSTITUTE

Vienna's new hub for particle physics

On 7 November 2025, the Austrian Academy of Sciences inaugurated the Marietta Blau Institute for Particle Physics (MBI). The new centre brings together the former Stefan Meyer Institute for Subatomic Physics and the Institute of High Energy Physics (HEPHY), creating Austria's largest hub for particle-physics research. In total, about 130 researchers with broad expertise across the discipline now work under the MBI umbrella.

Marietta Blau was one of the first women to study physics at the University of Vienna. As recalled by Brigitte Strohmaier (University of Vienna), who summarised Blau's biography, she became best known for her work at the Institute for Radium Research between 1923 and 1938, where she developed the nuclear-emulsion technique for detecting charged particles with micrometre-scale precision.

Together with Hertha Wambacher, Blau exposed nuclear emulsions to cosmic rays at Victor Hess's observatory near Innsbruck, producing photographic evidence of the interactions between high-energy particles and matter.

Staying in Scandinavia when Nazi Germany annexed Austria in 1938, Blau could not return to Vienna. She secured a position at the Polytechnic Institute of Mexico City on the recommendation of Albert Einstein, but found herself isolated from colleagues. From 1944 on, she worked in the US before returning to Vienna in 1960, where she supervised the evaluation of photographic plates from CERN.

Her method of nuclear emulsions was further advanced by Cecil Powell in Bristol, who was awarded the Nobel Prize in Physics in 1950 for discoveries regarding mesons made with this method. On this and other occasions, Marietta Blau was also nominated, but never recognised for her groundbreaking research.

Legacy *The Marietta Blau Institute is named after a pioneer of nuclear-emulsion techniques.*

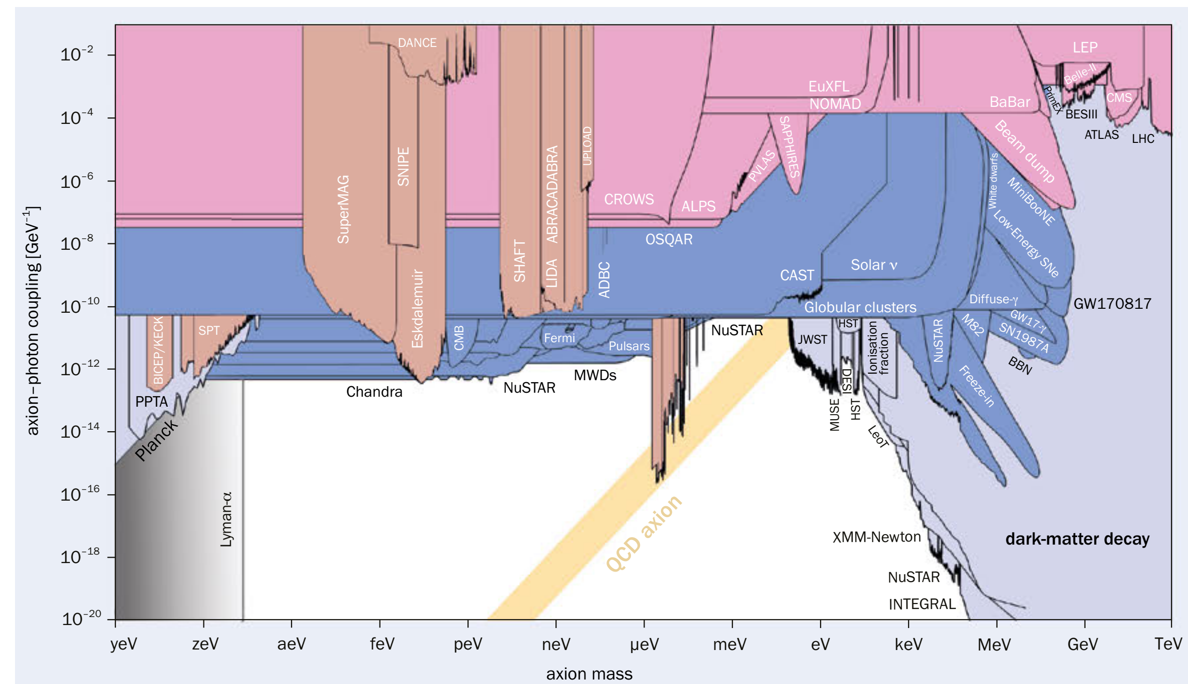
Joachim Kopp, chair of the Scientific Advisory Board of HEPHY, introduced the institute's scientific outlook. He highlighted the breadth of MBI's programme, which includes major contributions to CERN experiments such as CMS and ALICE at the LHC, and ASACUSA at the AD/ELENA facility, where antimatter is studied using low-energy antiprotons.

Groups at MBI are also involved in the Belle II experiment at KEK, as well as the dark-matter experiments CRESST and COSINUS at the LNGS underground lab. Neutrino physics, gravitational-wave studies at the Einstein Telescope, as well as tests of fundamental symmetries using ultra-cold hydrogen and deuterium beams, are also part of the research programme. The MBI also builds on the long tradition of detector development and construction for future experiments, complemented by a dedicated theory group.

Jochen Schieck *MBI.*

INTRODUCING THE AXION

Astrophysical constraints stake out 90 orders of magnitude for the mass of dark-matter particles. Clara Murgui surveys this vast terrain before zooming in on a particularly interesting region of parameter space: the post-inflation QCD axion.



In pursuit of the QCD axion *The vast parameter space explored by axion experiments. Axion–photon couplings are excluded as a function of axion mass by: collider and accelerator experiments (pink); pure astrophysical constraints (blue); astrophysical constraints that assume axions constitute all of the dark matter in the universe (light blue); and table-top experiments known as haloscopes that also assume axions account for the full dark-matter abundance (light brown). The yellow band indicates the region predicted for the QCD axion.*

There is an overwhelming amount of evidence for the existence of dark matter in our universe. This type of matter is approximately five times more abundant than the matter that makes up everything we observe: ourselves, the Earth, the Milky Way, all galaxies, neutron stars, black holes and any other imaginable structure.

We call it dark because it has not yet been probed through electroweak or strong interactions. We know it exists because it experiences and exerts gravity. That gravity may be the only bridge between dark matter and our own "baryonic" matter, is a scenario that is as plausible as it is intimidating, since gravitational interactions are too weak to produce detectable signals in laboratory-scale experiments, all of which are made of baryonic matter.

However, dark matter may interact with ordinary matter through non-gravitational forces as well, possibly mediated by new particles. Our optimism is rooted in the need for new physics. We also require new mechanisms to generate neutrino masses and the matter–antimatter asymmetry of the universe, and these new mechanisms may be inti-

THE AUTHOR
Clara Murgui *CERN.*

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NASA, ESA, CSA, K McQuinn (STScI), J DePasquale (STScI)

Leo P *The size of dwarf galaxies such as Leo P stakes out 90 orders of magnitude for the mass of dark-matter particles. This recent image from the James Webb Space Telescope's Near-Infrared Camera shows the galaxy's stars in blue at the lower right of the image.*

mately connected to the physics of dark matter. This view is reinforced by a surprising coincidence: the abundances of baryonic and dark matter are of the same order of magnitude, a fact that is difficult to explain without invoking a non-gravitational connection between the two sectors.

It may be that we have not yet detected dark matter simply because we are not looking in the right place. Like good sailors, the first question we ask is how far the boundaries of the territory to be explored extend. Cosmological and astrophysical observations allow dark-matter masses ranging from ultralight values of order 10^{-22} eV up to masses of the order of thousands of solar masses. The lower bound arises from the requirement that the dark-matter de Broglie wavelength not exceed the size of the smallest gravitationally bound structures, dwarf galaxies, such that quantum pressure does not suppress their formation (see "Leo P" image). The upper limit can be understood from the requirement that dark matter behave as a smooth, effectively collision-less medium on these small astrophysical structures. This leaves us with a range of possibilities spanning about 90 orders of magnitude, a truly overwhelming landscape. Given that our resources, and our own lifetimes, are finite, we guide our expedition both by theoretical motivation and the capabilities of our experiments to explore this vast territory.

Dark matter could be connected to the Standard Model in alternative ways

The canonical dark-matter candidate where theoretical motivation and experimental capability coincides is the weakly interacting massive particle. "WIMPs" are among the most theoretically economical dark-matter candidates, as they naturally arise in theories with new physics at the electroweak scale and can achieve the observed relic abundance through weak-scale interactions. The latter requirement implies that the mass of thermal WIMPs must lie above the GeV scale – approximately a nucleon mass. This "Lee–Weinberg" bound arises because lighter particles would not have annihilated fast enough in the early universe, leaving behind far more dark matter than we observe today.

WIMPs can be probed using a wide range of experimental strategies. At high-energy colliders, searches rely on missing transverse energy, providing sensitivity to the production of dark-matter particles or to the mediators that connect the dark and visible sectors. Beam dump and fixed-target experiments offer complementary sensitivity to light mediators and portal states. Direct-detection experiments measure nuclear recoils of heavy and stable targets, such as noble liquids like xenon or argon, which are sensitive to energy depositions at the keV scale, allowing us to probe dark-matter masses in the light end of the typical WIMP range with extraordinary sensitivity.

Light dark matter

So far, no conclusive signal has been observed, and the simplest realisations of the WIMP paradigm are becoming increasingly constrained. However, dark matter could be connected to the Standard Model in alternative ways, for example through new force carriers, allowing its mass to fall below the Lee–Weinberg bound. This sub-GeV dark matter, also referred to as light dark matter, appears in highly motivated theoretical frameworks such as asymmetric dark matter, in which an asymmetry between dark-matter particles and antiparticles sets the relic abundance, analogously to the baryon asymmetry that determines the visible matter abundance. In some of the best motivated realisations of this scenario, the dark-matter candidate resides in a confining "hidden sector" (see, for example, p13). A dark-baryon symmetry may guarantee the stability of such composite dark-matter states, with the baryonic and dark asymmetries being generated by related mechanisms.

Dark matter could be even lighter and behave as a wave. This occurs when its mass is below the eV-to-10 eV scale, comparable to the ionisation energy of hydrogen. In this case, its de Broglie wavelength exceeds the typical separation between particles, allowing it to be described as a coherent, classical field. In the ultralight dark-matter regime, the leading candidate is the axion. This particle is a prediction of theories beyond the Standard Model that provide a solution to the strong charge-parity (CP) problem.

In the Standard Model, there is no fundamental reason for CP to be conserved by strong interactions. In fact, two terms in the Lagrangian, of very different origin, contribute to an effective CP-violating angle, which would generically induce an electric dipole moment of hadrons, corresponding phenomenologically to a misalignment of their electromagnetic charge distributions. But remarkably – and this is at the heart of the puzzle – high-precision experiments measuring the neutron electric dipole moment show that this angle cannot be larger than 10^{-10} radians.

Why is this? To quote Murray Gell-Mann, what is not forbidden tends to occur. This unnaturally precise alignment in the strong sector strongly suggests the presence of a symmetry that forces this angle to vanish.

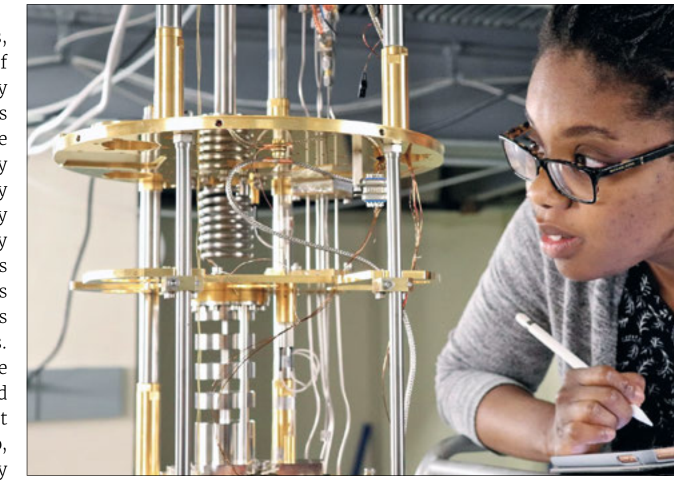
One of the most elegant and widely studied solutions, proposed by Roberto Peccei and Helen Quinn, consists of extending the Standard Model with a new global symmetry that appears at very high energies and is later broken as the universe cools. Whenever such a symmetry breaks, the theory predicts the appearance of one or more new, extremely light particles. If the symmetry is not perfect, but is slightly disturbed by other effects, this particle is no longer exactly massless and instead acquires a small mass controlled by the symmetry-breaking effects. A familiar example comes from ordinary nuclear physics: pions are light particles because the symmetry that would make them massless is slightly broken by the tiny masses of its constituent quarks.

In this framework, the new light particle is called the axion, independently proposed by Steven Weinberg and Frank Wilczek. The axion has remarkable properties: it naturally drives the unwanted CP-violating angle to zero, and its interactions with ordinary matter are not arbitrary but tightly controlled by the same underlying physics that gives it its tiny mass. Strong-interaction effects predict a narrow, well-defined "target band" relating how heavy the axion is to how strongly it interacts with matter, providing a clear roadmap for current experimental searches (the yellow band in the "In pursuit of the QCD axion" figure).

An excellent candidate

Axions also emerge as excellent dark-matter candidates. They can account for the observed cosmic dark matter through a purely dynamical mechanism in which the axion field begins to oscillate around the minimum of its potential in the early universe, and the resulting oscillations redshift as non-relativistic dark matter. Inflation is a little understood rapid expansion of the early universe by more than 26 orders of magnitude in scale factor that cosmologists invoke to explain large-scale correlations in the cosmic microwave background and cosmic structure. If the Peccei–Quinn symmetry was broken after inflation, the axion field would take random initial values in different regions of space, leading to domains with uncorrelated phases and the formation of cosmic strings. Averaging over these regions removes the freedom to tune the initial angle and makes the axion relic density highly predictive. When the additional axions from cosmic strings and domain walls are included, this scenario points to a well defined axion mass in the tens to few-hundreds of µeV range.

There is now a wide array of ingenious experiments, the result of the work of large international collaborations and decades of technological development, that aim to probe the QCD-axion band in parameter space. Despite the many experimental proposals, so far only ADMX, CAPP and HAYSTAC have reached sensitivities close to this target (see "Cavity haloscope" image). These experiments, known as haloscopes, operate under the assumption that axions constitute the dark matter in our universe. In these setups, a high-quality-factor electromagnetic cavity is placed inside a strong magnetic field in which axions from the dark-matter halo of the Milky Way are expected to convert into photons. The resonant frequency of the cavity is tuned like a radio scanning axion masses. This technique allows experiments to probe couplings many orders of magnitude weaker than typical Standard Model interactions. However, scaling these resonant experiments to significantly different axion masses is challenging as a cavity's resonant frequency is tied to its size. Moving away from its optimal axion-mass range either forces the cavity volume to become very small, reducing the signal power, or requires geometries that are difficult to realise in a laboratory environment.



S Cahn

Cavity haloscope *Danielle Speller (Johns Hopkins University) at work on the HAYSTAC haloscope. The HAYSTAC collaboration is beginning to exclude parameter space for QCD axions with masses just below 20 µeV, at the lower end of the mass range for post-inflation QCD axions.*

Other experimental approaches, such as helioscopes, focus on searching for axions produced in the Sun. These experiments mainly probe the higher-mass region of the QCD-axion band and also place strong constraints on axion-like particles (ALPs). ALPs are also light fields that arise from the breaking of an almost exact global symmetry, but unlike the QCD axion, the symmetry is not explicitly broken by strong-interaction effects, so their masses and couplings are not fixedly related. While such particles do not solve the strong CP problem, they can be viable dark-matter candidates that naturally arise in many extensions of the Standard Model, especially in theories with additional global symmetries and in quantum-gravity frameworks.

Among the proposed experimental efforts to observe post-inflation QCD axions, two stand out as especially promising: MADMAX and ALPHA. Both are haloscopes, designed to detect QCD axions in the galactic dark-matter halo. Neither is traditional. Each uses a novel detector concept to target higher axion masses – a regime that is especially well motivated if the Peccei–Quinn symmetry is broken after inflation (see p26).

We are living in an exciting era for dark-matter research. Experimental efforts continue and remain highly promising. A large and well-motivated region of parameter space is likely to become accessible in the near future, and upcoming experiments are projected to probe a significant fraction of the QCD axion parameter space over the coming decades. Clear communication, creativity, open-mindedness in exploring new ideas, and strong coordination and sharing of expertise across different physics communities, will be more important than ever. ●

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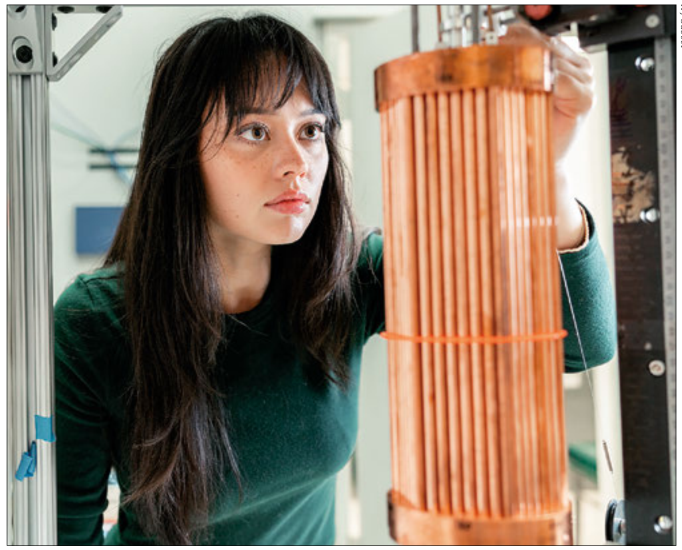
IN PURSUIT OF THE POST-INFLATION AXION

Breaking with decades of haloscope design, the ALPHA and MADMAX collaborations are pushing the search for dark matter into a promising new niche.



A J Gubser

High-mass haloscope *Graduate student Heather Jackson at work on a prototype metamaterial plasma resonator for the ALPHA collaboration at UC Berkeley. Novel designs such as ALPHA's plasma haloscopes and the MADMAX collaboration's dielectric haloscopes are pushing axion searches into parameter space inaccessible to traditional designs.*

One hundred μeV. 25 GHz. 10 m. This is the mass, frequency and de Broglie wavelength of a typical post-inflation axion. Though well motivated as a potential explanation for both the nature of dark matter and the absence of CP violation in the strong interaction, such axions subvert the "particle gas" picture of dark matter familiar to many high-energy physicists, and pose distinct challenges for experimentalists.

Axions could occupy countless orders of magnitude in mass, but those that result from symmetry breaking after cosmic inflation are a particularly interesting target, as their mass is predicted to lie within a narrow window of just one or two orders of magnitude, up to and around 100 μeV (see p21). Assuming a mass of 100 μeV and a local dark-matter density of 0.4 GeV/cm^3 in the Milky Way's dark-matter halo, a back-of-the-envelope calculation indicates that every cubic de Broglie wavelength should contain more than 10^{21} axions. Such a high occupation number means that axion dark matter would act like a classical field. Moving through the Earth at several hundreds of kilometres per second, the Milky Way's axion halo would be nonrelativistic and phase coherent over domains metres in width and tens of microseconds in duration.

Axion haloscopes seek to detect this halo via faint electric-field oscillations. The same couplings that should allow axions to decay to pairs of photons on timescales many orders of magnitude longer than the age of the universe should allow them to "mix" with photons in a strong magnetic field. The magnetic field provides a virtual photon, and the axion oscillates into a real photon. For several decades, the primary detection strategy has been to seek to detect their resonant conversion into an RF signal in a microwave cavity permeated by a magnetic field. The experiment is like a car radio. The cavity is tuned very slowly. At the frequency corresponding to the cosmic axion's mass, a faint signal would be amplified.

The ADMX, CAPP and HAYSTAC experiments have led the search below 25 μeV. These searches are dauntingly difficult, requiring the whole experiment to be cooled down to around 100 mK. Quantum amplifiers must be able to read out signals as weak as 10^{-24} W. The current generation of experiments can tune over about 10% of the resonant frequency, remaining stable at each small frequency step for 15 minutes before moving onto the next frequency. The steps are determined by the expected lineshape of the axion signal. Axion velocities in the Milky Way's dark-matter halo should follow a thermal distribution set by the galaxy's gravitational potential. This produces a spread of kinetic energies that broadens the corresponding photon frequency spectrum into a boosted-Maxwellian shape with a width about 10^{-6} of the frequency. For a mass around 100 μeV, the expected width is about 25 kHz.

The trouble is that the resonance frequency of a cavity is set by its diameter: the larger the cavity, the smaller the accessible frequency. Because the signal power scales with the cavity volume, it is increasingly difficult to achieve a good sensitivity at higher masses. For a 100 μeV axion with frequency 25 GHz that oscillates into a 25 GHz photon, the cavity would have to be of order only a centimetre wide.

Probing this parameter space calls for novel detector concepts that decouple the mass of the axion from the volume where axions convert into radio photons. This realisation has motivated a new generation of haloscopes built around electromagnetic structures that no longer rely on the resonant frequency of a closed cavity, but instead engineer large effective volumes matched to high axion masses.

Two complementary approaches – dielectric haloscopes and plasma haloscopes – exploit this idea in different ways. Each offers the possibility of discovering a post-inflation axion in the coming decade.

The MADMAX dielectric haloscope

J Egge/MADMAX Collab. 2025 *PRL* **134** 151004

A work in progress *A MADMAX prototype setup in the shielded laboratory at DESY/University of Hamburg. Microwaves from the booster (above, top right and enhanced image far right) are reflected from the focusing mirror (left) into a horn antenna (foreground right).*

Thanks to their electromagnetic coupling, a galactic halo of axions would drive a spatially uniform electric field oscillation parallel to an external magnetic field. For 100 μeV axions, it would oscillate at about 25 GHz. In such a field, a dielectric disc will emit photons perpendicular to its surfaces due to an electromagnetic boundary effect: the discontinuity in permittivity forces the axion-induced field to readjust, producing outgoing microwaves.

The Magnetized Disc and Mirror Axion (MADMAX) collaboration seeks to boost this signal through constructive interference. The trick is multiple discs, with tuneable spacing and a mirror to reflect the photons. As the axion halo would be a classical field, each disc should continuously emit radiation in both directions. For multiple dielectric discs, coherent radiation from all disc surfaces leads to constructive interference when the distance between the discs is about half the electromagnetic wavelength, potentially boosting axion-to-photon conversion in a broad frequency range. The experiment can be tuned for a given axion mass by controlling the spacing between the discs with micron-level precision. Arbitrarily many discs can be incorporated, thereby decoupling the volume where axions can convert into photons from the axion's mass.

The MADMAX collaboration has developed two indirect techniques to measure the "boost factor" of its dielectric haloscopes. In the first method, scanning a bead along the volume maps the three-dimensional induced electric field, from which the boost factor is then computed as the integral of the electric field over the sensitive volume. This method yielded 15% uncertainty for a prototype booster with a mirror and three 30 cm-diameter sapphire discs (see "A work in progress" figure). By studying the response of the prototype in the absence of an external magnetic field, the collaboration set the world's best limits on dark-photon dark matter in the mass range from 78.62 to 83.95 μeV.

The boost factor can alternatively be obtained by modelling the booster's response using physical properties extracted from reflectivity measurements and the behaviour of the power spectrum in the given frequency range. This method was applied to MADMAX prototypes inside the world's largest warm-bore superconducting dipole magnet. Named after the Italian physicist who designed it in the 1970s, the Morpurgo magnet is normally used to test subdetectors of the ATLAS experiment using beams from CERN's North Area. Since MADMAX requires no beam, a first axion search using the diameter aperture took place during the 2024 winter shutdown of the LHC. The prototype booster included a 20 cm-diameter mirror and three sapphire discs separated by aluminium rings. Frequencies around 19 GHz were explored by adjusting the mirror position. No significant excess consistent with an axion signal was observed. Despite coming from a small prototype, these results surpass astrophysical bounds and constraints from the CERN Axion Solar Telescope (CAST), demonstrating the detection power of dielectric haloscopes.

As a next step, a prototype booster with a mirror and up to twenty 30 cm-diameter discs is expected to deliver a factor 10 to 100 improvement over the 2024 tests. The positions of its discs will be adjusted inside its stainless-steel cryostat using cryogenic piezo motors. The setup is currently being commissioned and is set for installation in the Morpurgo magnet during the third long shutdown of the LHC from mid-2026 to 2029. An important goal is to prove the broad-band scanning capacity of dielectric haloscopes at cryogenic temperatures and conditions close to those of the final MADMAX design. Operating at 4 K will enhance MADMAX's sensitivity by reducing noise from thermal radiation. A prototype has already been successfully tested inside a custom-made glass fibre cryostat in the Morpurgo

The MADMAX collaboration has developed two indirect techniques to measure the "boost factor" of its dielectric haloscopes

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magnet in cooperation with CERN's cryogenic laboratory.

The final baseline detector foresees a 9 T superconducting dipole magnet with a warm bore of about 1.3 m. A first design has been developed and important aspects of its technological feasibility have already been tested, such as quench protection and conductor performance. As a first step, an intermediate 4 T warm-bore magnet is being purchased. It should be available around 2030. Once constructed, the magnet will be installed at DESY's axion platform inside the former HERA H1 iron yoke, where preparations for the required cryogenic infrastructure are underway.

With MADMAX's prototype booster scaling towards its final size, and quantum detection techniques such as travelling-wave parametric amplifiers and single-photon detectors being developed, significant improvements in sensitivity are on the horizon for dielectric haloscopes. MADMAX is on a promising path to probing axion dark matter in the 40 to 400 μeV mass range at sensitivities sufficient to discover axion dark matter at the classic Dine–Fischler–Srednicki–Zhitnitsky (DFSZ) and Kim–Shifman–Vainshtein–Zakharov (KSVZ) theory benchmarks. ●

Further reading

MADMAX Collab 2025 *Phys. Rev. Lett.* **135** 041001.

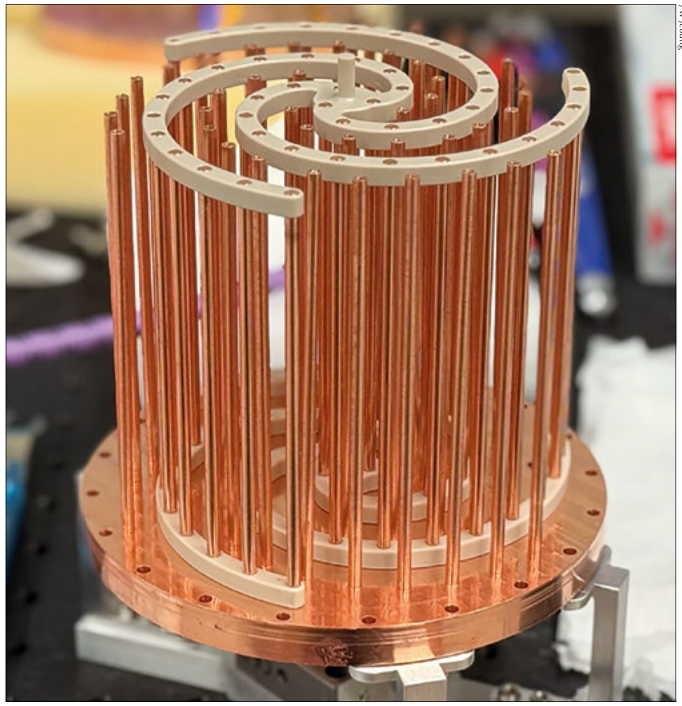
The ALPHA plasma haloscope

In a plasma, photons acquire an effective mass determined by the plasma frequency, which depends on the density of charge carriers. If the plasma frequency is close to the axion's Compton frequency, axion–photon mixing is resonantly enhanced. As the plasma could in principle be of any volume, the volume in which the axion field converts into photons has been decoupled from the axion mass – but tuning the plasma frequency is not feasible, preventing a detector based on this effect from scanning a wide range of masses.

In 2019, Matthew Lawson, Alexander Millar, Matteo Pancaldi, Edoardo Vitagliano and Frank Wilczek proposed performing this experiment using a metamaterial plasma with a tunable electromagnetic dispersion which mimics that of a real plasma. In a plasma haloscope, this metamaterial is a lattice of thin metallic wires embedded in vacuum. By adjusting the wire spacing, the diameter of the wires and their arrangement, the resonant plasma frequency can be tuned over a wide range.

The ALPHA collaboration was formed in 2021 to build a full-scale plasma haloscope capable of probing axion masses from 40 to 400 μeV, corresponding to axion frequencies from 10 to 100 GHz. While challenges related to detecting an extremely feeble signal remain, the simplicity of the cavity design, particularly in the magnet geometry and the tuning mechanism, offers flexibility.

ALPHA's design can be pictured as a large-bore superconducting solenoid magnet, and a resonator housing an array of thin copper or superconducting wires stretched along the field direction. Photons are extracted through waveguides and fed into an ultra-low-noise microwave receiver chain, cooled by a dilution refrigerator to below 100 mK, developing quantum-sensing techniques developed in close collaboration with the HAYSTAC collaboration. Photons are amplified with Josephson parametric amplifiers – the same technique used for qubits used in quantum computers, and the topic of the 2025 Nobel Prize in Physics awarded to John Clarke, Michel Devoret and John Martinis. Tests at room temperature in 2022 and 2023 demonstrated that the response of the meta-plasma can be tuned across the 10 to 20 GHz range with a modest number of configuration changes, and that the quality factors exceed 10^4 even before cooling down to cryogenic temperatures.



J W Jeoung

Plasma tuning *A resonator with a spiral design at Stockholm University.*

Two designs are being pursued to design a tuning mechanism that allows precise adjustment of the plasma frequency with minimal mechanical intervention: a spiral design where a single rotating rod tunes a set of three spiral arms relative to another set of fixed spiral arms (see "Plasma tuning" figure); and a design with multiple spinners rotating groups of wires relative to a fixed grid of wires.

ALPHA's development plan proceeds in two main stages. Phase I is currently being constructed at Yale University's Wright Laboratory, and focuses on employing established technology to demonstrate the technique and search for axions with masses from 40 to 80 μeV. Phase I's cavity, consisting of copper plasma resonators, will be immersed in a 9 T magnet, 17.5 cm in diameter and 50 cm tall. The expected conversion power in ALPHA's frequency range is of order 10^{-24} W – comparable to the thermal noise in a 50 Ω resistor cooled to 50 mK. The read-out chain therefore employs Josephson parametric amplifiers whose noise temperatures approach the standard quantum limit. The system is designed to scan continuously while maintaining sensitivity close to the KSVZ axion–photon coupling, a benchmark for well-motivated axion models. The data-acquisition strategy builds on techniques developed in ADMX and HAYSTAC: fast Fourier transforms of the time-stream, coherent stacking across overlapping frequency bins and real-time evaluation of excess-power statistics.

Several improvements are being developed in parallel for Phase II. Quantum sensing techniques have the potential to boost the signal while reducing noise. Such techniques include HAYSTAC-style noise squeezing, using cavity entanglement and state swapping to enhance the signal, and single-photon detection. Dramatically increasing the quality factor of superconducting plasma resonators will also significantly boost the signal. Last but not least, magnets with a larger bore and higher field, such as the ones being deployed at the neutron scattering facilities at Oak Ridge National Laboratory, are expected to expand the experimental reach up to 200 μeV and push the sensitivity to below the axion–photon coupling of the DFSZ model, another classic theoretical benchmark.

Beginning in 2026, ALPHA Phase I will start taking its first physics data, initially searching for dark photons – a dark-matter candidate that interacts with plasma without requiring the presence of a magnetic field. After commissioning ALPHA's magnet, a full axion search will commence during 2027 and 2028.

It is an exciting time for axion searches. New experiments are coming online, implementing new ideas to expand the accessible mass ranges. Groups in Italy, Japan and Korea are exploring alternative metamaterial geometries, including superconducting wire meshes and photonic crystals that replicate plasma behaviour at higher frequencies. European teams linked to the IAXO collaboration are considering hybrid systems that couple plasma-like resonators to strong dipole magnets. ALPHA will search for axions in the well-motivated region, first focusing between 40 and 80 μeV, and then between 80 and 200 μeV.

Intense efforts are underway. Discoveries may be just around the corner. ●

Further reading

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Floating world *Artist's impression of the Higgs potential, inspired by Katsushika Hokusai's woodblock print* The Great Wave off Kanagawa. *Today, the vacuum is thought to dwell at the minimum indicated by the peak of Mount Fuji, a symbol of stability and harmony. Measurements at the High-Luminosity LHC will shed light on the behaviour of the Higgs potential at higher field values, where quantum corrections may make it drop down to a lower minimum. (Credit: A Epshtein)*

WHAT CAN YOU DO WITH 380 MILLION HIGGS BOSONS?

What is the fate of the universe? Why is there more matter than antimatter? What lurks beyond the Standard Model? Valentina Cairo and Steven Lowette explore the physics reach of the High-Luminosity LHC.

The Higgs boson is uniquely simple – the only Standard Model particle with no spin. Paradoxically, this allows its behaviour to be uniquely complex, notably due to the "scalar potential" built from the strength of its own field. Shaped like a Mexican hat, the Higgs potential has a local maximum of potential energy at zero field, and a ring of minima surrounding it (see "The Higgs potential" panel).

In the past, the Higgs field settled into this ring, where it still dwells today. Since then, the field has been permanently "switched on" – a directionless field with a nonzero "vacuum expectation value" that is ubiquitous throughout the universe. Its interactions with a number of other fundamental particles give them mass. What remains unclear is how the Higgs field behaves once pushed from this familiar minimum. Where will it go next, how did it get there in the first place and might new physics modify this picture?

The LHC alone has shed experimental light on this physics. Further progress on this compelling frontier of fundamental science requires upgrades and new colliders. The next step along this path is the High-Luminosity LHC (HL-LHC), which is scheduled to begin operations in 2030. The HL-LHC is set to outperform the LHC by far, with a total dataset of 380 million Higgs bosons created inside the ATLAS and CMS experiments – a sample more than 10 times larger than any studied so far (see "A leap in technology" panel). We still need to unlock the full reach of the HL-LHC, but three scientific questions may serve to illustrate what can be studied with 380 million Higgs bosons.

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The Higgs potential

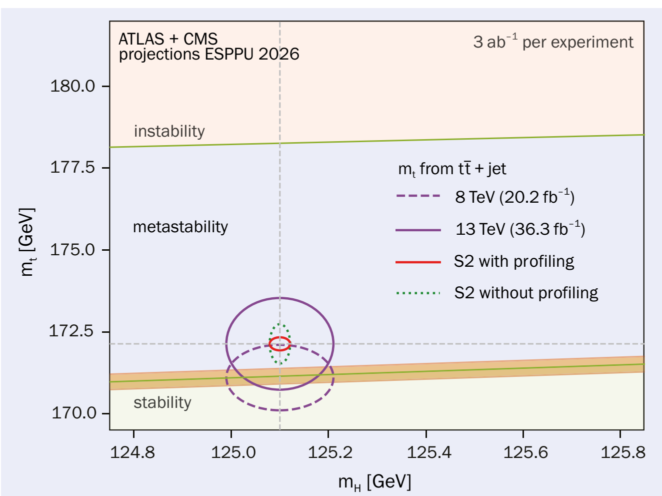
The Higgs boson is the only Standard Model particle with no spin – a quantum number that behaves as if fundamental particles were spinning, but which cannot correspond to a physical rotation without violating relativity theory.

This allows the Higgs field to experience a scalar potential – energy penalties that depend on the strength of the Higgs field itself. This is forbidden for fermions (spin ½) and massless bosons (spin 1) by Lorentz symmetry and gauge invariance.

In the Standard Model, the Higgs field is subject to the Higgs potential, shaped like a Mexican hat, with a maximum of potential energy at zero field, and a minimum at a ring in the complex plane of values of the Higgs field. Its polynomial form is restricted by gauge symmetry. Experimentally, it can be inferred by measuring properties of the Higgs boson such as its self-coupling λ_3.

Two effects then modify the Mexican-hat shape in ways that are difficult to predict but have important consequences for particle physics and cosmology. These are due to the interactions of the Higgs field with virtual particles and real thermal excitations. Quantum fluctuations modify the energy penalty of exciting the Higgs field due to virtual loops from all Standard Model particles. Changes in the temperature of the universe also generate changes in the shape of the Higgs potential due to the interaction of the Higgs field with real thermal excitations in the hot early universe. Properties such as λ_3 are also affected by these effects.

Davide De Biasio *associate editor*



A second minimum? *Data from the HL-LHC (red ellipse) may be able to resolve the "stability of the vacuum" – whether or not the Higgs field should be expected to transition to a lower energy state at a higher field strength, and on what timescales.*

What is the fate of the universe?

The stability of our universe hangs in a delicate balance. Quantum corrections could make the Higgs potential bend downward again at high values of the Higgs field, creating a lower-energy state beneath our own. Through quantum tunnelling, tiny regions of space could spontaneously make the transition, releasing energy as the Higgs field settles into a new minimum of the Higgs potential. Bubbles of the new vacuum would expand at the speed of light, changing the vacuum state of the regions they encounter.

Details matter. The Higgs potential is modified by the effect of virtual loops from all particles interacting with the Higgs field. Bosons push the Higgs potential upwards at high field values, and fermions pull it downwards. If the Standard Model remains valid up to high field values, perhaps as high as the Planck scale where quantum gravity is expected to become relevant, these corrections may determine the ultimate fate of the vacuum. As the most massive Standard Model particle yet discovered, the top quark makes a dominant negative contribution at high energies and field strengths. Together with a smaller effect from the mass of the Higgs boson itself, the top-quark mass defines three possible regimes.

In the stable case, the Higgs potential remains above the current minimum up to high field values, and no deeper minimum is present.

If a second, lower minimum forms at high field values, but is shielded by a large energy barrier, the vacuum can be "metastable". In that case, quantum tunnelling could in principle occur, but on timescales exceeding the age of the universe.

In the unstable regime, the barrier is low enough for decay to have already occurred.

Current observations place our universe safely within the metastable zone, far from any immediate change (see "A second minimum?" figure). Yet the precision of the latest LHC measurements, based on independent determinations of the top-quark mass (purple ellipses), leaves unresolved whether the universe is stable or metastable. Other uncertainties, such as that on the strength of nature's strong coupling, also affect the distinction between the two regimes, shifting the boundary between stability and metastability (orange band).

The HL-LHC will be well placed to help resolve the question of the stability of the vacuum thanks to improvements in the measurements of the top quark and Higgs-boson masses (red ellipse). This will rely on combining the HL-LHC's large dataset, the ingenuity of expected analysis improvements and theoretical progress in the fundamental interpretation of these measurements.

Why is there more matter than antimatter?

The Higgs potential wasn't always a Mexican hat. If the early universe got hot enough, interactions between the Higgs field and a hot plasma of particles shaped the Higgs potential into a steep bowl with a minimum at zero field, yielding no vacuum expectation value. As the universe cooled, this potential drooped into its familiar Mexican-hat shape, with a central peak surrounded by a ring of minima, where the Higgs field sits today. But did the Higgs field pass through an intermediate stage, with a "bump" separating the inner minimum from the ring?

The answer depends on the strength of the Higgs self-coupling, λ_3, which governs the trilinear coupling where three Higgs-boson lines meet at a single vertex in a Feynman diagram. But λ_3 is not yet measured. The most recent joint ATLAS and CMS analysis excludes values outside of −0.71 to 6.1 times its expected value in the Standard Model with 95% confidence.

In the Standard Model, the vacuum smoothly rolled from zero Higgs field to its new minimum in the outer ring. But if λ_3 were at least 50% stronger than in the Standard Model, this smooth "crossover" phase transition may have been prevented by an intermediate bump. The vacuum would then have experienced a strong first-order phase transition (FOPT), like ice melting or water boiling at everyday pressures. As the universe cooled, regions of space would have tunnelled into the new vacuum, forming bubbles that expanded and merged. These bubble-wall collisions, combined with additional processes beyond the Standard Model that violate the conservation of both charge and parity together, could have contributed to the observed excess of matter over antimatter – one of the deepest mysteries of modern physics, wherein there appears to have been an excess of baryons over antibaryons in the early universe of roughly one part in a billion, resulting in the surplus we observe today after the annihilation of the others into photons.

The most direct probe of λ_3 comes from Higgs-boson pair production (HH). HH production happens most often by the fusion of gluons from the colliding protons to create a top-quark loop that emits either two Higgs bosons or one Higgs boson splitting into two, yielding sensitivity to λ_3.

HH production happens only once for every thousand Higgs bosons produced in the LHC. Searches for this process are already underway, with analyses of the Run 2 dataset by the ATLAS and CMS collaborations showing that a signal 2.5 times larger than the Standard Model expectation is already excluded. This progress far exceeds early expectations, suggesting that the HL-LHC may finally bring λ_3 within experimental reach, clarifying the shape of the Higgs potential near its current minimum (see "Constraining the Higgs potential" figure).

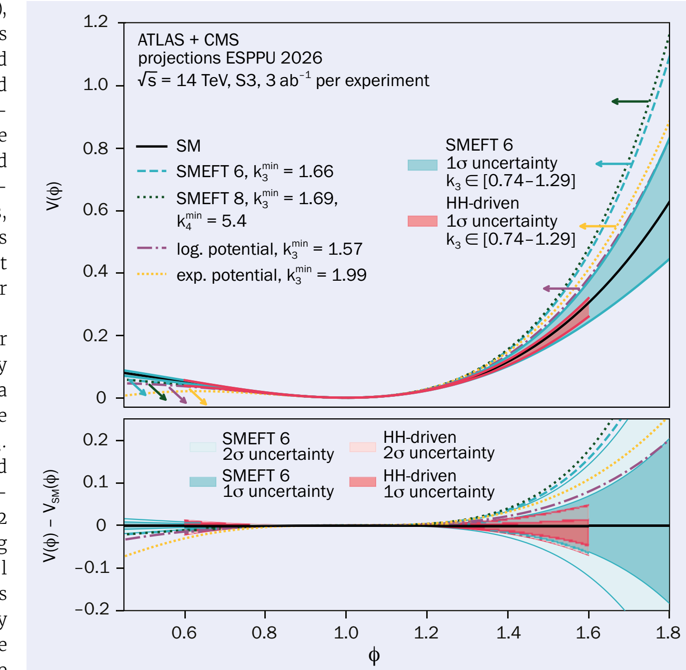
Measuring λ_3 at the HL-LHC would shed light on whether the Higgs potential follows the Standard Model prediction (black line) or alternative shapes (dashed lines), which may arise from physics beyond the Standard Model (BSM). The corresponding sensitivity can be illustrated through two complementary approaches: one based on HH production, assuming no effects beyond λ_3 and providing a largely model-independent view near the potential's minimum (red bands); and an approach that incorporates higher-order effects, which extend the reach over a broader range of the Higgs field (blue bands).

Since the previous update of the European Strategy for Particle Physics, the projected sensitivity has vastly improved. The combined ATLAS and CMS results are now expected to yield a discovery significance exceeding 7σ, should HH production occur at the Standard Model rate. By the end of the HL-LHC programme, the two experiments are expected to determine λ_3 with a 1σ uncertainty of about 30% – enough to exclude the considered BSM potentials at the 95% confidence level if the self-coupling matches the Standard Model prediction.

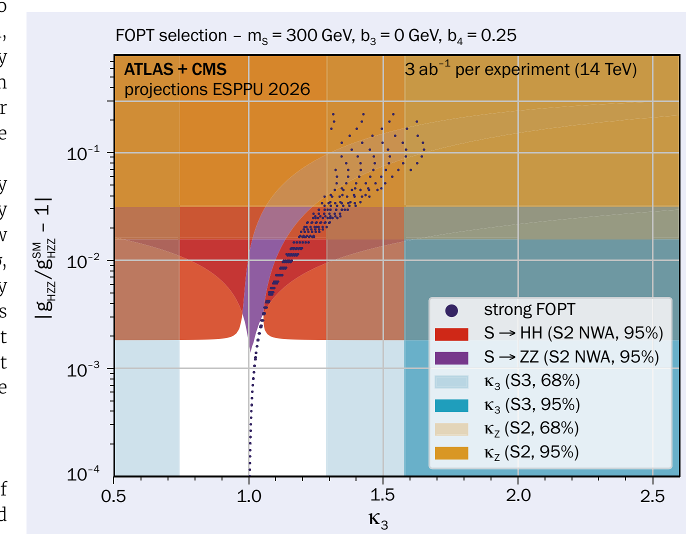
What lurks beyond the Standard Model?

Puzzles such as the origin of dark matter and the nature of neutrino masses suggest that new physics must lie beyond the Standard Model. With greatly expanded data sets at the HL-LHC, new phenomena may become detectable as resonant peaks from undiscovered particles or deviations in precision observables.

As an example, consider a BSM scenario that includes an additional scalar boson "S" that mixes with the Higgs boson but remains blind to other Standard Model fields (see



Constraining the Higgs potential *A snapshot of the Higgs potential in the radial direction of the Higgs field, zoomed in around the vacuum expectation value of the Higgs field in unitless dimensions. Measurements at the HL-LHC will be able to distinguish the Standard Model Higgs potential (black line) from BSM scenarios, which would yield a strong first-order phase transition in the early universe (dashed lines).*



Spotting a new scalar *Parameter space (blue points) for a new scalar boson "S" that mixes with the Higgs boson but remains blind to other Standard Model fields. HL-LHC measurements will be able to exclude the shaded regions in λ_3 (horizontal axis, plotted relative to its Standard Model value) and the HZZ coupling (vertical axis, plotted as the relative deviation from the Standard Model value). The symbol κ refers to the ratio of the parameter value to its Standard Model value.*

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A leap in technology

The HL-LHC will deliver proton–proton collisions at least five times more intensely than the LHC's original design. By the end of its lifetime, the HL-LHC is expected to accumulate an integrated dataset of around 3 ab^{-1} of proton–proton collisions – about six times the data collected during the LHC era.

ATLAS and CMS are undergoing extensive upgrades to cope with the intense environment created by a "pileup" of up to 200 simultaneous proton–proton interactions per bunch crossing. For this, researchers are building ever more precise particle detectors and developing faster, more intelligent software.

The ATLAS and CMS collaborations will implement a full upgrade of their tracking systems, providing extended detector coverage and improved spatial resolution (see "Tracking upgrades" figure). New capabilities are added to either or both experiments, such as precision timing layers outside the tracker, a more performant high-granularity forward calorimeter, new muon detectors designed to handle the increased particle flux, and modernised front- and back-end electronics across the calorimeter and muon systems, among other improvements.

Major advances are also being made in data readout, particle reconstruction and event selection. These include track reconstruction capabilities in the trigger and a significantly increased latency, allowing for more advanced decisions about which collisions to keep for offline analysis. Novel selection techniques are also emerging to handle very high event rates with minimal event content, along with AI-assisted methods for identifying anomalous events already in the first stages of the trigger chain.

Finally, detector advancements go hand-in-hand with innovation in algorithms. The reconstruction of physics objects is being revolutionised by higher detector granularity, precise timing, and the integration of machine learning and hardware accelerators such as modern GPUs. These developments will significantly enhance the identification of charged-particle tracks, interaction vertices, b-quark-initiated jets, tau leptons and other signatures – far surpassing the capabilities foreseen when the HL-LHC was first conceived.

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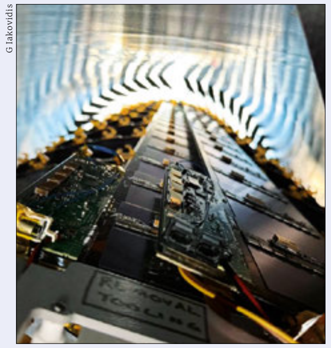

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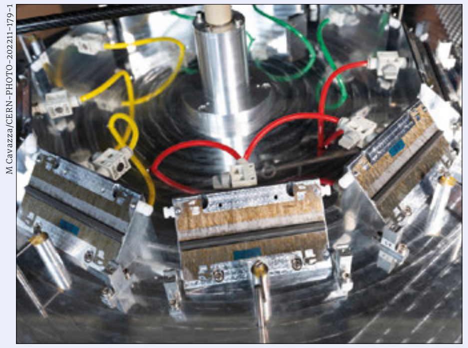

Tracking upgrades *Left: view inside the inner volume of the future ATLAS Inner Tracker (ITk). This carbon cylinder will host the ITk strip and pixel detectors. Prototype strip components called "staves" can be seen in the photo. These are lightweight structures with silicon strip modules mounted on both sides. The photo shows prototypes inserted in layer 2. Right: prototyping for the CMS Tracker Barrel with Pixel-Strip, part of the future CMS tracking detector with double-layer silicon detectors. Shown is a "tilted" section, where the silicon sensors will be uniquely inclined towards the LHC beam interaction point.*

"Spotting a new scalar" figure). S could induce observable differences in λ_3 (horizontal axis) and the coupling of the Higgs boson to the Z boson, g_{HZZ} (vertical axis). Both couplings are plotted as a factor of their expected Standard Model values. The figure explores scenarios where the coupling deviates from its Standard Model value by as little as a tenth of a permille, and where the trilinear self-coupling may be between 0.5 and 2.5 times the value. Such models could prove to be the underlying cause of deviations from the Standard Model such as contributing to the matter–antimatter asymmetry in the universe. Combinations of model parameters that could allow for a strong FOPT in the early universe are plotted as black dots.

This example analysis serves to illustrate the complementarity of precision measurements and direct searches at the HL-LHC. The parameter space can be narrowed by measuring the axis variables λ_3 and g_{HZZ} (blue and orange bands). Direct searches for $S \to HH$ and $S \to ZZ$ will be able to probe or exclude many of the remaining models (red and purple regions), leaving room for scenarios in which new physics is almost entirely decoupled from the Standard Model.

What's next?

What once might have seemed like science fiction has become a milestone in our understanding of nature. When Ursula von der Leyen, president of the European Commission, last visited CERN, she reflected on recent progress in the field.

"When you designed a 27 km underground tunnel where particles would clash at almost the speed of light, many thought you were daydreaming. And when you started looking for the Higgs boson, the chances of success seemed incredibly low, but you always proved the sceptics wrong. Your story is one of progress against all odds."

Today, at a pivotal moment for particle physics, we are redefining what we believe is possible. Plucked from the ATLAS and CMS collaborations' inputs to the 2026 update to the European Strategy for Particle Physics (*CERN Courier* November/December 2025 p23), the analyses described in this article are just a snapshot of what will be possible at the HL-LHC. In close collaboration with the theory community, experimentalists will use the unmatched datasets and detector capabilities of the HL-LHC and allow the field to explore a rich landscape of anticipated phenomena, including many signatures yet to be imagined.

The future starts now, and it is for us to build. ●

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SEVEN COLLIDERS FOR CERN

Gianluigi Arduini, Philip Burrows and Jacqueline Keintzel report on the findings of a working group mandated to compare seven proposals for CERN's next large-scale collider.

A Nowak/CERN

The view from Le Reculet *As part of the 2026 update to the European Strategy for Particle Physics, the European Strategy Group is evaluating seven proposals for large-scale collider projects to succeed the High-Luminosity LHC, which is being installed 100 m underground in the existing 27 km-long LEP/LHC tunnel that spans the border between France and Switzerland (pictured).*

Seven ambitious, diverse and technically complex colliders have been proposed as options for CERN's next large-scale collider project: CLIC, FCC-ee, FCC-hh, LCF, LEP3, LHeC and a muon collider. The European Strategy Group tasked a working group drawn from across the field (WG2a) to compare these projects on the basis of their technical maturity, performance expectations, risk profiles, and schedule and cost uncertainties. This evaluation is based on documentation submitted for the 2026 update to the European Strategy for Particle Physics (*CERN Courier* May/June 2025 p8). With WG2a's final report now published, clear-eyed comparisons can be made across the seven projects.

CLIC

The Compact Linear Collider (CLIC) is a staged linear collider that collides a polarised electron beam with an unpolarised positron beam at two interaction points (IPs) which share the luminosity (see "Collider concepts" figures and "Design parameters" table). It is based on a two-beam acceleration scheme where power from an intense 1 GHz drive beam is extracted and used to operate an X-band 12 GHz linac with accelerating gradients from 72 to 100 MV/m. The potential of two-beam acceleration to achieve high gradients enables a compact linear-collider footprint. Collision energies between 380 GeV and 1.5 TeV

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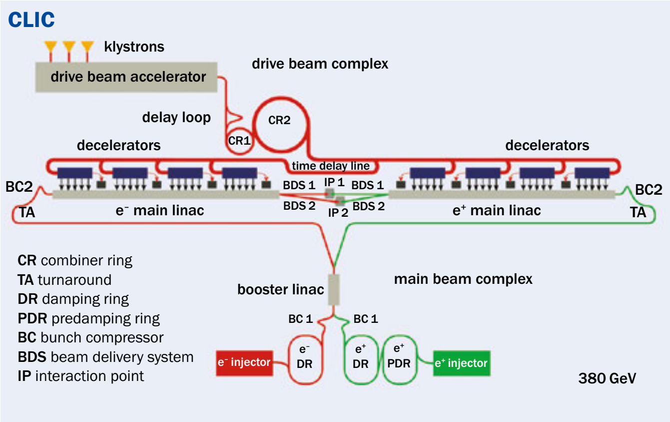
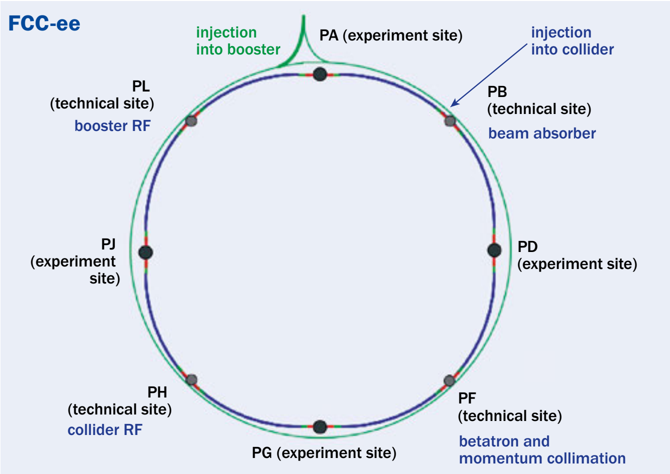
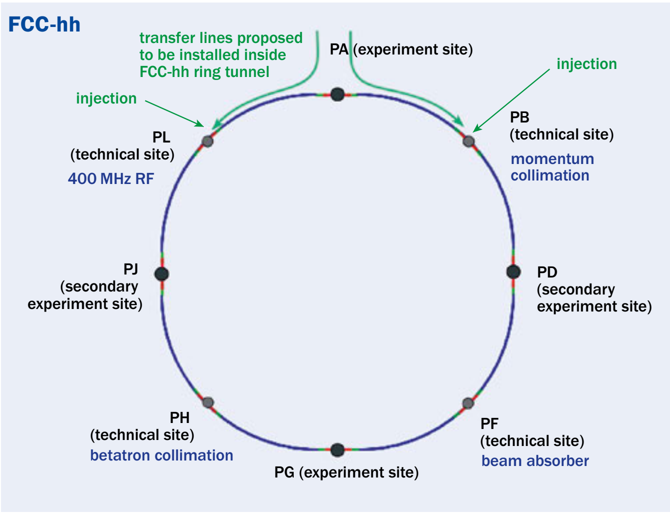






Collider concepts *Schematic layouts for CLIC, FCC-ee and FCC-hh (alphabetically first among the seven proposals).*

can be achieved with a total tunnel length of 12.1 or 29.4 km, respectively. The proof-of-concept work at the CLIC Test Facility 3 (CTF3) has demonstrated the principles successfully, but not yet at a scale representative of a full collider. A larger-scale demonstration with higher beam currents and more accelerating structures would be necessary to achieve full confidence in CLIC's construction readiness.

The project has a well developed design incorporating decades of effort, and detailed start-to-end (damping ring to IP) simulations have been performed indicating that CLIC's design luminosity is achievable. CLIC requires tight fabrication and alignment tolerances, active stabilisation, and various feedback and beam-based correction concepts. Failure to achieve all of its tight specifications could translate into a luminosity reduction in practical operation. CLIC still requires a substantial preparation phase and territorial implementation studies, which introduces some uncertainty on its proposed timeline.

FCC-ee

The electron–positron Future Circular Collider (FCC-ee) is the proposed first stage of the integrated FCC programme. This double-ring collider, with a 90.7 km circumference, enables collision centre-of-mass energies up to 365 GeV and allows for four IPs.

FCC-ee stands out for its level of detail and engineering completeness. The FCC Feasibility Study, including a cost estimate, was recently completed and has undergone scrutiny by expert committees, CERN Council and its subordinate bodies (*CERN Courier* May/June 2025 p9). This preparation translates into a relatively high technical-readiness level (TRL) across major subsystems, with only a few lower-level/lower-cost elements requiring targeted R&D. The layout has been chosen after a detailed placement study considering territorial, geological and environmental constraints. Dialogue with the public and host-state authorities has begun.

Performance estimates for FCC-ee are considered robust: previous experience with machines such as LEP, PEP-II, DAΦNE and SuperKEKB has provided guidance for the design and bodes well for achieving the performance targets with confidence. In terms of readiness, FCC-ee is the only project that already possesses a complete risk-management framework integrated into its construction planning.

FCC-hh

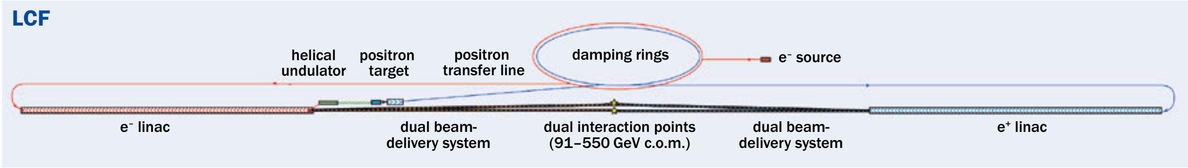
The hadron version of the Future Circular Collider (FCC-hh) would provide proton–proton collisions up to a nominal energy of 85 TeV – the maximum achievable in the 90.7 km tunnel for the target dipole field of 14 T. As a second stage of the integrated FCC programme, it would occupy the tunnel after the removal of FCC-ee, and so could potentially start operation in the mid-2070s. FCC-hh's cost uncertainty is currently dominated by its magnets. The baseline design uses superconducting Nb_3Sn dipoles operating at 1.9 K, though high-temperature superconducting (HTS) magnets could reduce the electricity consumption or allow higher fields and beam energies for the same power consumption. Both technology approaches are active research directions of Europe's high-field magnet programme.

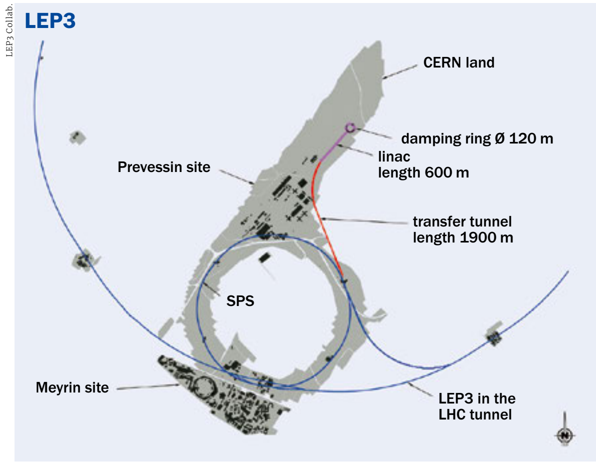
The required Nb_3Sn technology is progressing steadily, but still needs 15 to 20 years of R&D before industry-ready designs could be available. HTS cables satisfying the specifications required for the magnets of a high-luminosity collider, although extremely promising, are at an even earlier stage of development. If FCC-hh were to proceed as a standalone project, operations could possibly start around 2055 from a technical perspective. In that case the magnets would need to be based on Nb_3Sn technology, as HTS accelerator-magnet technology is not expected to be available in that timeframe.

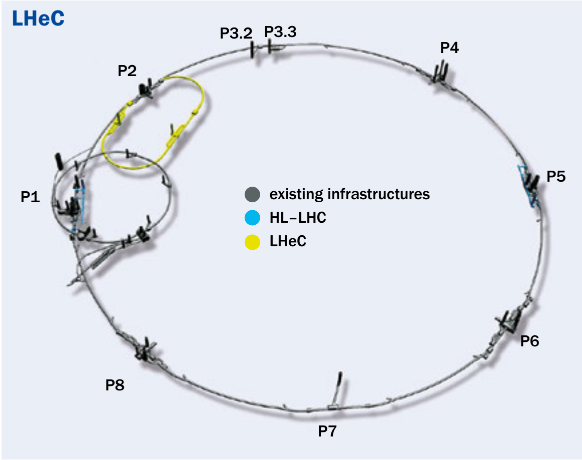
FCC-hh's performance expectations draw strength from the LHC experience, though the achievable integrated luminosity would depend on the required "luminosity levelling" scenario that might be determined by pile-up control at the experiments. Luminosity levelling is a technique used in particle colliders such as the LHC to keep the instantaneous luminosity approximately constant at the maximum level compatible with detector readout, rather than letting it start very high and then decay rapidly.

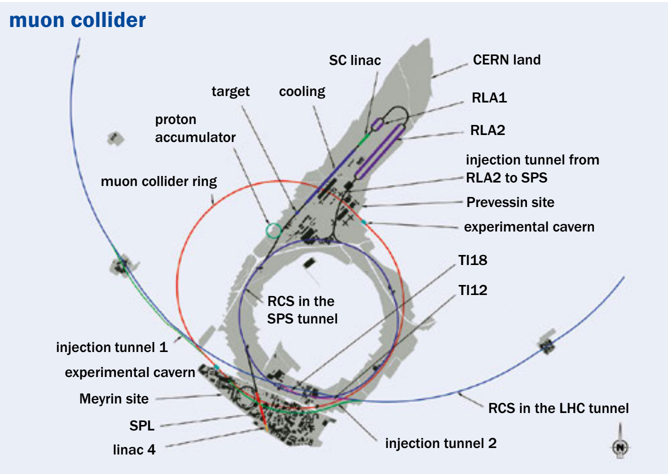
LCF

The Linear Collider Facility (LCF) is a linear electron-positron collider, based on the design of the International Linear Collider (ILC), in a 33.5 km tunnel with two IPs sharing the pulses delivered by the collider and with double the repetition rate of ILC. The first phase aims at a centre-of-mass energy of 250 GeV, though the tunnel is sized to accommodate an upgrade to 550 GeV. LCF's main linacs incorporate 1.3 GHz bulk-Nb superconducting radiofrequency (SRF) cavities for acceleration, operated at an average gradient of 31.5 MV/m and a cavity quality factor twice that of the ILC design at the same accelerating gradient. The quality factor of an RF cavity is a measure of how efficiently the cavity stores electromagnetic energy compared with how much it loses per cycle. LCF can deliver polarised positron and electron beams. Its engineering definition is solid and its SRF technology widely used in several operational facilities, most prominently at the European XFEL, however, the specific performance targets exceed what has been routinely achieved in operation to date. Demonstrating this combination of high gradient and high quality remains a central R&D requirement.









Collider concepts *Schematic layouts for LCF, LEP3, LHeC and the proposed muon collider at CERN.*

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	Colliding particles	Number of interaction points (IPs)	Tunnel length [km]	Centre-of-mass energy [GeV]	Peak instantaneous luminosity per IP [10^{34} cm^{-2} s^{-1}]	Peak power consumption [MW]
CLIC	e^+e^-	2	12.1	380	2.2	166
		2	15	550	3.2	210
		1	29.6	1500	3.7	287
FCC-ee	e^+e^-	4	90.7	91.2	140	251
				160	20	276
				240	7.5	297
				365	1.4	381
FCC-hh	pp	4	90.7	84600	30	355
LCF (low power)	e^+e^-	2	33.5	250	1.35	143
LCF (full power)	e^+e^-	2	33.5	91.2	0.28	123
				250	2.7	182
				550	3.85	322
LEP3	e^+e^-	2	27.6	91.2	40	200
				160	6.2	226
				230	1.6	250
LHeC	e^-p	1	27.6 + 9.2	1180	2.3	220
Muon collider	$\mu^+\mu^-$	2	4.8/11	3200	0.9/2	117
			8.7/11	7600	7.9/10.1	182

G Arduini et al. 2025 CERN-ESU-ESG-WG2a-full-report

Design parameters *Key characteristics of the seven large-scale collider proposals considered by WG2a, based on inputs to the 2026 update to the European Strategy for Particle Physics. For the LHeC, the length is divided into the circumference of the HL-LHC and an additional 50 GeV ERL. The power consumption indicated for the LHeC does not include that of the HL-LHC injectors. For the muon collider, two configurations are presented for each collision energy. Full details are available in WG2a's report.*

Several lower-TRL components – such as the polarised positron source, beam dumps and certain RF systems – also require focused development. Final-focus performance, which is more critical in linear colliders compared to circular colliders, relies on validation at KEK's Accelerator Test Facility 2, which is being extended and upgraded. The overall schedule is credible but depends on securing the needed R&D funding and would require a preparation phase including detailed territorial implementation studies and geological investigations.

LEP3

The Large Electron Positron collider 3 (LEP3) proposal explores the reuse of the existing LEP/LHC tunnel for a new circular electron–positron (e^+e^-) collider. LEP3 has two IPs and the potential for collision energies ranging from 91 to 230 GeV; its luminosity performance and energy range are limited by synchrotron radiation emission, which is more severe than in FCC-ee due to its smaller radius and the limited space available for the SRF installation.

The LEP3 proposal is not yet based on a conceptual or technical design report. Its optics and performance estimates depend on extrapolations from FCC-ee and earlier preliminary studies, and the design has not undergone full simulation-based validation. The current design relies on HTS combined quadrupole and sextupole focusing magnets. Though they would be central to LEP3 achieving a competitive luminosity and power efficiency, these components currently have low TRL scores.

Although tunnel reuse simplifies territorial planning, logistics such as dismantling HL-LHC components introduce non-trivial uncertainties for LEP3. In the absence of a conceptual design report, timelines, costs and risks are subject to significant uncertainty.

LHeC

The Large Hadron–Electron Collider (LHeC) proposal incorporates a novel energy-recovery linac (ERL) coupled to the LHC. High-luminosity collisions take place between a 7 TeV proton beam from the HL-LHC and a high-intensity 50 GeV electron beam accelerated in the new ERL. The LHeC ERL would consist of two linacs based on bulk-Nb SRF 800 MHz cavities, connected by recirculation arcs, resulting in a total machine circumference equal to one third that of the LHC. After acceleration, the beam will collide with the proton beam and will be successively decelerated in the same SRF cavities, "giving back" the energy to the RF system.

The LHeC's performance depends critically on demonstrating high-current, multi-pass energy recovery at multi-GeV energies, which has not yet been demonstrated. The PERLE (Powerful Energy Recovery Linac for Experiments) demonstrator under construction at IJCLab in Orsay will test critical elements of this technology. The main LHeC performance uncertainties relate to the efficiency of energy recovery and beam-loss control of the electron beam during the deceleration process after colliding with the proton beam. Schedule, cost and performance will depend on the outcomes demonstrated at PERLE.

Muon collider

Among the large-scale collider proposals submitted to the European Strategy for Particle Physics update, a muon collider offers a potentially energy-efficient path toward high-luminosity lepton collisions at a centre-of-mass energy of 10 TeV. The larger mass of the muons, as compared with electrons and positrons, reduces the amount of synchrotron radiation emitted in a circular collider of a given energy and radius. The muons are generated from the decays of pions produced by the collision of a high-power proton beam with a target. "Ionisation cooling" of the muon beams via energy loss in absorbers made of low-atomic-number materials and acceleration by means of high-gradient RF cavities immersed in strong magnetic fields is required to reduce the energy spread and divergence of this tertiary beam. Fast acceleration is then needed to extend the muons' lifetimes in the laboratory frame, thereby reducing the fraction that decays before collision. To achieve this, novel rapid-cycling synchrotrons (RCSs) could be installed in the existing SPS and LHC tunnels.

Neutrino-induced radiation and technological challenges such as high-field solenoids and operating radiofrequency cavities in multi-Tesla magnetic fields present major challenges that require extensive R&D. Demonstrating the required muon cooling at the required level in all six dimensions of phase space is a necessary ingredient to validate the performance, schedule and cost estimates.

WG2a's comparison, together with the analysis conducted by the other working groups of the European Strategy Group, notably that of WG2b, which is providing an assessment of the physics reach of the various proposals, provides vital input to the recommendations that the European particle-physics community will make for securing the future of the field. ●

Further reading

G Arduini *et al.* 2025 CERN-ESU-ESG-WG2a-full-report.

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OPINION VIEWPOINT

There's more g–2 physics over the horizon

In June last year, an updated theory prediction and a new measurement of the magnetic moment of the muon may have resolved a longstanding tension. Is this the end of the road for muon g–2?

Clara Matteuzzi, *director emerita of research at INFN, is chair of the MUonE institutional board.*

Regis University

Frederick Gray, *professor at Regis University, is chair of the MUonE editorial board.*

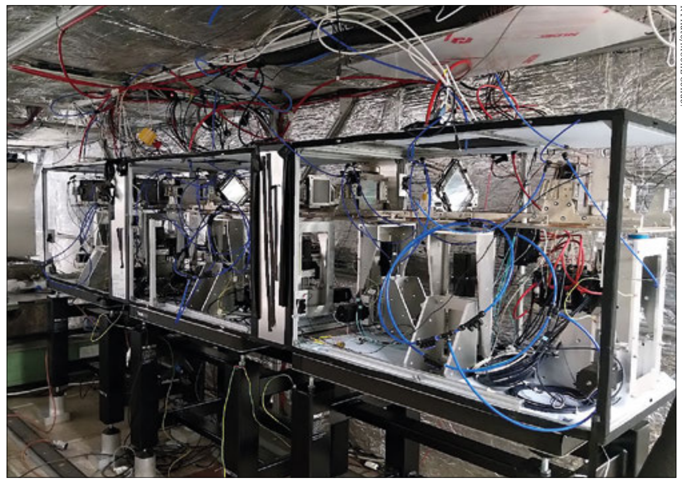
Some have argued that the good agreement between lattice-QCD and the final measurement of Fermilab's muon g–2 experiment means that the g–2 anomaly has now been solved. However, this dramatically oversimplifies the situation: the magnetic moment of the muon remains an intriguing puzzle.

The extraordinary precision of 127 parts per billion (ppb) achieved at Fermilab deserves to be matched by an equally impressive theoretical prediction. At 530 ppb, theory is currently the limiting factor in any comparison. This is the longer-term goal that the Muon g–2 Theory Initiative is now working towards, with inputs from all possible sources (see p41). In the near future, it will not be possible to reach this precision with lattice QCD alone. Other approaches are needed to make a competitive Standard Model prediction.

Tensions remain

Essentially, all of the uncertainty in g–2 arises from the hadronic vacuum polarisation (HVP) – a quantum correction whereby a radiated virtual photon briefly transforms into a hadronic state before being reabsorbed. Historically, HVP has been evaluated by applying a dispersion relation to cross sections for hadron production in electron–positron collisions, but this method was displaced by lattice-QCD calculations in the theory initiative's most recent white paper. The lattice community must be congratulated for the level of agreement that has been reached between groups working independently (*CERN Courier* July/August 2025 p7). By contrast, data-driven predictions are at present inconsistent across the experiments in the low-energy region; even if results from the CMD-3 experiment are excluded as an outlier, tensions remain, suggesting that some systematic errors may not have been completely addressed (*CERN Courier* March/April 2025 p21). Could a novel experimental technique help resolve the confusion?

The MUonE collaboration proposes a completely independent approach based on a new experimental method



R Pilato/MUonE Collab

Another way *The MUonE experiment.*

The MUonE collaboration proposes a completely independent approach based on a new experimental method. In MUonE, we will determine the running of the electromagnetic coupling, a fundamental quantity that is driven by the same kinds of quantum fluctuations as muon g–2. We will extract it from a precise measurement of the differential cross section for elastic scattering of muons from electrons as a function of the momentum transferred.

MUonE is a relatively inexpensive experiment that we can set up in the existing M2 beamline in CERN's North Area, already home to the AMBER and NA64-μ experiments. Three years of running, within the conditions of M2 parameters and the performance of the MUonE detector, would reach a statistical precision of approximately 180 ppb with a comparable level of systematic uncertainty.

MUonE will take advantage of silicon sensors that are already being developed for the CMS tracker upgrade. From the results, we will be able to use a dispersion relation to extract HVP's contribution to g–2. Perhaps more importantly, however, as our method directly measures a function that is part of the lattice calculation, we can directly verify that method. The big challenge will be to keep the systematic uncertainties in the measurement small enough. However, MUonE does not suffer from the intrinsic problem that existing data-driven techniques have, which is that they must numerically integrate over the sharp peaks of hadron production by low-energy resonances. In contrast, the function derived from the space-like process that it will measure is smooth and well-behaved.

Piecing the puzzle

CERN was the origin of the first brilliant muon g–2 measurements starting back in the 1950s (*CERN Courier* September/October 2024 p53), and now the laboratory has an opportunity to put another important piece into the g–2 puzzle through the MUonE project. Another component of great importance in this domain will be the new g–2/EDM experiment planned for J-PARC, which will also be performed in completely different conditions, and therefore with very different systematics to the Fermilab experiment.

Further reading

J Komijani *et al.* 2024 CERN-SPSC-2024-015.

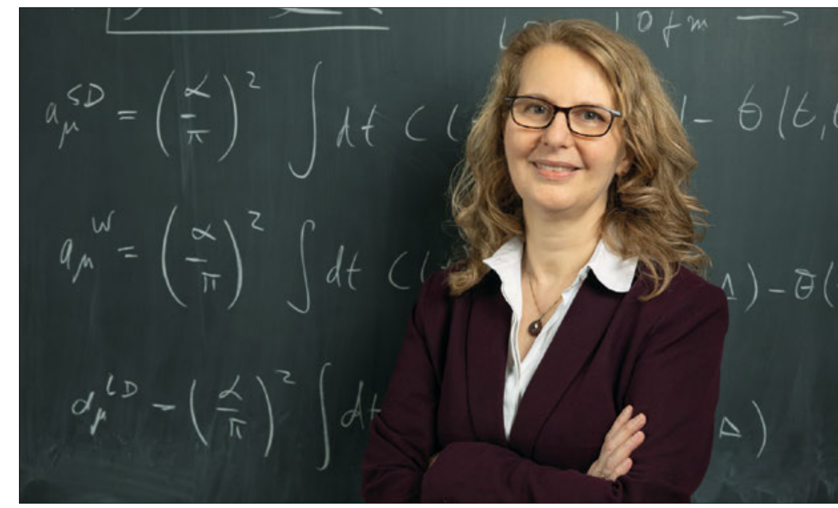
OPINION INTERVIEW

How I learnt to stop worrying and love QCD predictions

In recent years, no Standard Model prediction has come under greater scrutiny than the magnetic moment of the muon. The *Courier* caught up with Muon g–2 Theory Initiative chair Aida El-Khadra on conflicting datasets, disparate calculations and hot competition between research groups.

To begin, could you explain what the muon's magnetic moment is, and why it should be anomalous?

Particles react to magnetic fields like tiny bar magnets, depending on their mass, electric charge and spin – a sort of intrinsic angular momentum lacking a true classical analogue. These properties combine into the magnetic moment, along with a quantum-mechanical g-factor which sets the strength of the response. Dirac computed g to be precisely two for electrons, with a formula that applies equally to the other, then-unknown, leptons. We call any deviation from this value anomalous. The name stuck because the first measurements differed from Dirac's prediction, which initially was not understood. The anomalous piece is a natural probe of new physics, as it arises entirely from quantum fluctuations that may involve as-yet unseen new particles.



University of Illinois Urbana-Champaign

Strong interactions *Aida El-Khadra is a theoretical particle physicist at the University of Illinois Urbana-Champaign and chair of the Muon g–2 Theory Initiative's Steering Committee.*

What ingredients from the Standard Model go into computing g–2?

Everything. All sectors, all particles, all Standard Model (SM) forces contribute. The dominant and best quantified contributions are due to QED, having been computed through fifth order in the fine structure constant α. We are talking about two independent calculations of more than 12,000 Feynman diagrams, accounting for more than 99.9% of the total SM prediction. Interestingly, two measurements of α disagree at more than 5σ, resulting in an uncertainty of about two parts per billion. While this discrepancy needs to be resolved, it is negligible for the muon g–2 observable. The electroweak contribution was computed at the two-loop level long ago, and updated with better measured input parameters and calculations of nonperturbative effects in quark loops. The resulting uncertainty is close to 40 times smaller than that of the g–2 experiment. Then, the overall uncertainty is determined by our knowledge of the hadronic corrections, which are by far the most difficult to constrain.

What sort of hadronic effects do you have in mind here? How are they calculated?

There are two distinct effects: hadronic vacuum polarisation (HVP) and hadronic light-by-light (HLbL). The former arises at second order in α, is the larger of the two, and the largest source of uncertainty. While interacting with an external magnetic field, the muon emits a virtual photon that can further split into a quark loop before recombining. The HLbL contribution arises at third order and is now known with sufficient precision. The challenge is that loop diagrams must be computed at all virtual energies, down to where the strong force (QCD) becomes non-perturbative and quarks hadronise. There are two ways to tackle this.

Instead of computing the hadronic bubble directly, the data-driven "dispersive" approach relates it to measurable quantities, for example the cross section for electron–positron annihilation into hadrons. About 75% of the total HVP comes from $e^+e^- \to \pi^+\pi^-$, so the measurement errors

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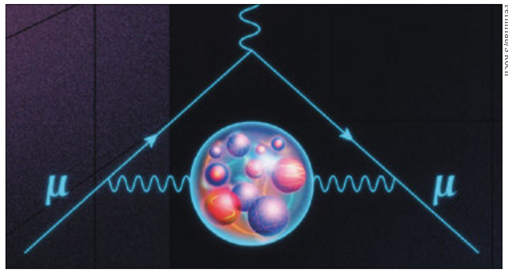
in this channel determine the overall uncertainty. The decays of tau leptons into hadrons can also be used as inputs. Since the process is mediated by a charged W boson, instead of a photon, it requires an isospin rotation from the charged to the neutral current. At low energies, this is another challenging non-perturbative problem. While there are phenomenological estimates of this effect, no complete theoretical calculation exists – which means that the uncertainties are not fully quantified. Differing opinions on how to assess them led to controversy over the inclusion of tau decays in the SM prediction of g–2. An alternative to data-driven methods is lattice QCD, which allows for ab initio calculations of the hadronic corrections.

What does "ab initio" mean, in this context?
It means that there are no simplifying assumptions in the QCD calculation. The approximations used in the lattice formulation of QCD come with adjustable parameters and can be described by effective field theories of QCD. For example, we discretise space and time: the distance separating nearest-neighbour points is given by the lattice spacing and the effective field theory guides the approach of the lattice theory to the continuum limit, enabling controlled extrapolations. To evaluate path integrals using Monte Carlo methods, which themselves introduce statistical errors, we also rotate to imaginary time. While not affecting the HVP, this limits the quantities we can compute.

How do you ensure that the lattice predictions are unbiased?
Good question! Lattice calculations are complicated, and it is therefore important to have several results from independent groups for consolidating averages. An important cultural shift in the community is that numerical analyses are now routinely blinded to avoid confirmation bias, making agreements more meaningful. This shifts the focus from central values to systematic errors. For our 2025 White Paper (WP25), the main lattice inputs for HVP were obtained from blinded analyses.

How did you construct the SM prediction for your 2025 White Paper?
To summarise how the SM prediction in WP25 was obtained, sufficiently precise lattice results for HVP arrived just in time. Since measurements of the $e^+e^- \to \pi^+\pi^-$ channel are presently in disagreement with each other, the 2025 prediction solely relied on the lattice average for the HVP. In contrast, the 2020 White Paper (WP20) prediction employed the data-driven method, as the lattice-QCD results were not precise enough to weigh in.



Fermilab/S Koch

Hadronic contribution *An artist's illustration of the contribution of hadronic vacuum polarisation to the anomalous magnetic moment of the muon.*

While the theory error in WP25 is larger than in WP20, it is a realistic assessment of present uncertainties, which we know how to improve. I stress that the combination of the SM theory error being four times larger than the experimental one and the remaining puzzles, particularly on the data-driven side, means that the question "Does the SM account for the experimental value of the muon's anomalous magnetic moment?" has not yet been satisfactorily answered. Given the high level of activity, this will, however, happen soon.

Where are the tensions between lattice QCD, data-driven predictions and experimental measurements?
All g–2 experiments are beautifully consistent, and the lattice-based WP25 prediction differs from them by less than one standard deviation. At present, we don't know if the data-driven method agrees with lattice QCD due to the differences in the $e^+e^- \to \pi^+\pi^-$ measurements. In particular, the 2023 CMD-3 results from the Budker Institute of Nuclear Physics are compatible with lattice results, but disagree with CMD-2, KLOE, BaBar, BESIII and SND, which formed the basis for WP20. All the experimental collaborations are now working on new analyses. BaBar is expected to release a new $e^+e^- \to \pi^+\pi^-$ result soon, and others, including Belle II, will follow. There is also ongoing work on radiative corrections and Monte Carlo generators, both of which are important in solving this puzzle. Once the dust settles, we will see whether the new data-driven evaluation agrees with the lattice average or the g–2 experiment. Either way, this may yield profound insights.

> **With the experiment's expected precision jump, it seemed vital for theory to follow suit**

How did the Muon g–2 Theory Initiative come into being?
The first spark came when I received a visiting appointment from Fermilab, offering resources to organise meetings and workshops. At the time, my collaborators and I were gearing up to calculate the HVP in lattice QCD, and the Fermilab g–2 experiment was about to start. With the experiment's expected precision jump, it seemed vital for theory to follow suit by bringing together communities working on different approaches to the SM contributions, with the goal of pooling our knowledge, reducing theoretical uncertainties and providing reliable predictions.

As Fermilab received my idea positively, I contacted the RBC collaboration and Christoph Lehner joined me with great enthusiasm to shape the effort. We recruited leaders in the experimental and theoretical communities to our Steering Committee. Its role is to coordinate efforts, organise workshops to bring the community together and provide the structure to map out scientific directions and decide on the next steps.

What were the main challenges you faced in coordinating such a complex collaboration?
With so many authors and such high stakes, disagreements naturally arise. In WP20, a consensus was emerging around the data-driven method. The challenge was to come up with a realistic and conservative error estimate, given the up to 3σ tensions between different data sets, including the two most precise measurements of $e^+e^- \to \pi^+\pi^-$ at the time.

As we were finalising our WP20, the picture was unsettled by a new lattice calculation from the Budapest–Marseille–Wuppertal (BMW) collaboration, consistent with earlier lattice results but far more precise. While the value was famously in tension with data-driven methods, the preprint also presented a calculation of the "intermediate window" contribution to the HVP – about 30% of the total – which disagreed with a published RBC/UKQCD result and with data-driven evaluations (*CERN Courier* March/April 2025 p21). Since BMW was still updating their results and the paper wasn't yet published, we described the result but excluded it from our SM prediction. Later, in 2023, further complications came from the CMD-3 measurement.

Consolidation between lattice results was first observed for the intermediate window contribution, in 2022 and 2023. This, in turn, revealed a tension with the corresponding data-driven evaluations. Results for the difficult-to-compute long-distance contributions arrived in late fall 2024, yielding consolidated lattice averages for the total HVP, where we had to sort out a few subtleties. This was intense – a lot of work in very little time.

On the data-driven side, we faced the aforementioned tensions between the $e^+e^- \to \pi^+\pi^-$ cross-section measurements. In light of these discrepancies, consensus was reached that we would not attempt a new data-driven average of HVP for WP25, leaving it for the next White Paper. Real conflict arose on the assessment of the quality of the uncertainty estimates for HVP contributions from tau decays and on whether to include them.

And how did you navigate these disagreements?
When the discussions around the assessment of tau-decay uncertainties stopped to converge, we proposed a conflict resolution procedure using the Steering Committee (SC) as the arbitration body, which all authors signed. If a conflict is brought to the SC for resolution, SC members first engage all parties involved to seek resolution. If none is found, the SC makes a recommendation and, if appropriate, the differing scientific viewpoints may be reflected in the document, followed by the recommendation. In the end, just having a conflict-resolution process in place was really helpful. While the SC negotiated a couple of presentation issues, the major disagreements were resolved without triggering the process.

The goal of WP25 was to wrap up a prediction before the announcement of the final Fermilab g–2 measurement. Adopting an internal conflict-resolution process was essential in getting our result out just in time, six days before the deadline.

> **Lattice QCD has really come of age**

What other observables can benefit from advances in lattice QCD?
There are many, and their number is growing – lattice QCD has really come of age. Lattice QCD has been used for years to provide precise predictions of the hadronic parameters needed to describe weak processes, such as decay constants and form factors. A classic example, relevant to the LHC experiments, is the rare decay $B_s \to \mu^+\mu^-$, where, thanks to lattice QCD calculations of the B_s-meson decay constant, the SM prediction is more precise than current experimental measurements. While precision continues to improve with refined methods, the lattice community is broadening the scope with new theoretical frameworks and improved computational methods, enabling calculations once out of reach – such as the (smeared) R-ratio, inclusive decay rates and PDFs.

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

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OPINION REVIEWS

If Einstein had known

Si Einstein avait su
By Alain Aspect
Odile Jacob

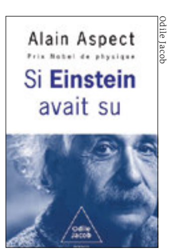
How would Einstein have reacted to Bell's theorem and the experimental results derived from it? Alain Aspect's new French-language book *Si Einstein avait su* (If Einstein had known) can be recommended to anybody interested in the Einstein–Bohr debates about quantum mechanics, how a CERN theorist, John Stewart Bell (1928–1990), weighed in in 1964, and how experimentalists converted Bell's idea into ingenious physical experiments. Aspect shared the 2022 Nobel Prize in Physics with John F Clauser and Anton Zeilinger for this work.

The core part of Aspect's book covers his own contributions to the experimental test of Bell's inequality spanning 1975 to 1985. He gives a very personal account of his involvement as an experimental physicist in this matter, starting soon after he visited Bell at CERN in spring 1975 for advice concerning his French *Thèse d'État*. With anecdotes that give the reader the impression of sitting next to the author and listening to his stories, Aspect recounts how, in 1975, captivated by Bell's work, he set up experiments in underground rooms at the Institut d'Optique in Orsay to test hidden-variable theories. He explains his experiments in detail with diagrams and figures from his original publications as well as images of the apparatus used. By 1981 and for several years to come, it was Aspect's experiments that came closest to Bell's idea on how to test the inequality formulated in 1964. Aspect defended his thesis in 1983 in a packed auditorium with illustrious examiners such as J S Bell, C Cohen-Tannoudji and B d'Espagnat. Not long afterwards, Cohen-Tannoudji invited him to the Collège de France and the Paris ENS to work on the laser cooling and manipulation of atoms – a quite different subject. At that time, Aspect didn't see any point in closing some of the remaining loopholes in his experiments.

To prepare the terrain for his story, Aspect first tells the history of quantum mechanics from 1900 to 1935. He begins with a discussion of Planck's blackbody

©Laboratoire Kastler-Brossel

Sage, sleuth and subversive *Alain Aspect (middle) with John Bell (right) and Albert Messiah (left) in 1985.*



Odile Jacob

radiation (1900), Einstein's description of the photoelectric effect (1905) and the heat capacity of solids (1907), the wave–particle duality of light, first Solvay Congress (1911), Bohr's atomic model (1913) and matter–radiation interaction according to Einstein (1916). He then covers the Einstein–Bohr debates at the Solvay congresses of 1927 and 1930 on the interpretation of the probability aspects of quantum mechanics.

Aspect then turns to the Einstein, Podolsky, Rosen (EPR) paper of 1935, which discusses a *gedankenexperiment* involving two entangled quantum mechanical particles. Whereas the previous Einstein–Bohr debates ended with convincing arguments by Bohr refuting Einstein's point of view, Bohr didn't come up with a clear answer to Einstein's objection of 1935, namely that he considered quantum mechanics to be incomplete. In 1935 and the following years, for most physicists the Einstein–Bohr debate had been considered uninteresting and purely philosophical. It had practically no influence on the success of the application of quantum mechanics. Between 1935 and 1964, the EPR subject was nearly dormant, apart from David Bohm's interventions during the 1950s. In 1964 Bell took up the EPR paradox, which had been advanced as an argument that quantum mechanics should be supplemented by additional variables (*CERN Courier* July/August 2025 p21).

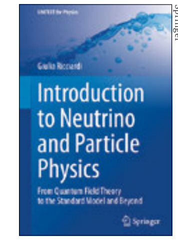
Aspect describes clearly and convincingly how Bell entered the scene and how the inequality with his name triggered experimentalists to get involved: experiments with polarisation-entangled photons and their correlations could decide whether Einstein or Bohr's view of quantum mechanics was correct. Bell's discovery transferred the Einstein–Bohr debate from epistemology to the realm of experimental physics. At the end of the 1960s the first experiments based on Bell's inequality started to take form. Aspect describes how these analysed the polarisation correlation of the entangled photons at a separation of a few metres. He discusses their difficulties and limitations, starting with the experiments launched by Clauser *et al.*

In the final chapter, covering 1985 to the present, Aspect explains why he decided not to continue his research with entangled photons and to switch subject. His opinion was that the technology at the time wasn't ripe enough to close some of the remaining loopholes in his experiments – loopholes of a type that Bell considered less important. Aspect was convinced that if quantum mechanics was faulty, one would have seen indications of that in his experiments. It took until 2015 for two of the loopholes left open by Aspect's experiments (the locality and detection loophole) to be simultaneously closed. Yet no experiment, as ideal as it is, can be said to be totally loophole-free, as Aspect says. The final chapter also covers more philosophical aspects of quantum non-locality and speculations about how Einstein would have reacted to the violation of Bell's inequalities. In complementary sections, Aspect speaks about the no-cloning theorem, technological applications of quantum optics like quantum cryptography according to Ekert, quantum teleportation and quantum random number generators.

Who will profit from reading this book? First one should say that it is not a quantum-mechanics or quantum-optics textbook. Most of the material is written in such a way that it will be accessible and enjoyable to the educated layperson. For the more curious reader, supplementary sections cover physical aspects in deeper detail, and the book cites more than 80 original references. Aspect's long experience and honed pedagogical skills are evident throughout. It is an engaging and authoritative introduction to one of the most profound debates in modern physics.

Thomas Bohl *CERN.*

Introduction to Neutrino and Particle Physics: From Quantum Field Theory to the Standard Model and Beyond
By Giulia Ricciardi
Springer



Springer

Neutrino physics is a vibrant field of study, with spectacular recent advances. To this day, neutrino oscillations are the only experimental evidence of physics beyond the Standard Model, and, 25 years after this discovery, breathtaking progress has been achieved in both theory and experiment. Giulia Ricciardi's new textbook provides a timely new resource in a fast developing field.

Entering this exciting field of research can be intimidating, thanks to the breadth of topics that need to be mastered. As well as particle physics, neutrinos touch astroparticle physics, cosmology, astrophysics, nuclear physics and geophysics, and many neutrino textbooks assume advanced knowledge of quantum field theory and particle theory. Ricciardi achieves a brilliant balance by providing a solid foundation in these areas, alongside a comprehensive overview of neutrino theory and experiment. This sets her book apart from most other literature on the subject and makes it a precious resource for newcomers and experts alike. She provides a self-contained introduction to group theory, symmetries, gauge theories and the Standard Model, with an approach that is both accessible and scientifically rigorous, putting the emphasis on understanding key concepts rather than abstract formalisms.

With the theoretical foundations in place, Ricciardi then turns to neutrino masses, neutrino mixing, astrophysical neutrinos and neutrino oscillations. Dirac, Majorana and Dirac-plus-Majorana mass terms are explored, alongside the "see-saw" mechanism and its possible implementations. A full chapter is devoted to neutrino oscillations in the vacuum and in matter, preparing the reader to explore neutrino oscillations in experiments, first from natural sources, such as the Sun, supernovae, the atmosphere and cosmic neutrinos; a subsequent chapter then covers reactor and accelerator neutrinos, giving a detailed overview of the key theoretical and experimental issues. Ricciardi avoids a common omission in neutrino textbooks by addressing neutrino-nucleus interactions – a fast developing topic in theory and a crucial aspect of interpreting current and future experiments. The book concludes with a look at the current research and future prospects, including a discussion of neutrino-mass measurements and neutrinoless double-beta decay.

The clarity with which Ricciardi links theoretical concepts to experimental observations is remarkable. Her book is engaging and eminently enjoyable. I highly recommend it.

Silvia Pascoli
University of Bologna and INFN.

CERNCOURIER
Volume 66 Number 1 January/February 2026

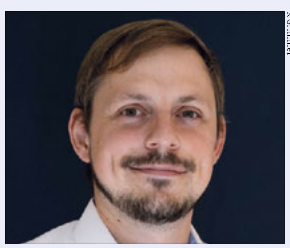
Appointments and awards

Primakoff award to Pinetti
Elena Pinetti (Flatiron Institute) has received the 2026 Henry Primakoff Award for Early-Career Particle Physics for her research on dark matter and high-energy astrophysical phenomena. Pinetti investigates dark matter in unconventional environments such as intercluster filaments and cosmic voids. She is recognised for original ideas and innovative research in the study of particle dark matter, compact astrophysical objects, high-energy astrophysical sources and cosmic radiation across the electromagnetic spectrum.

Butler wins Panofsky prize
Joel Butler (Fermilab) has been awarded the 2026 Panofsky Prize by the American Physical Society for his leadership in quark-flavour experiments at Fermilab and his contributions to collider physics at the LHC. Butler began his career at Fermilab in 1979, playing key roles in fixed-target experiments and helping to establish the laboratory's computing division. He also served as chair of the American Physical Society's Division of Particles and Fields in 2022. Awarded every year since 1985, the $10,000 prize is named after Wolfgang K H Panofsky, physicist and founding director of SLAC whose work helped shape modern accelerator-based particle physics.

ERC synergy grants 2025
Andrii Neronov (University Paris Cité), Franco Vazza (University of Bologna), Chiara Caprini (CERN) and Axel Brandenburg (University of Stockholm) have been awarded an ERC Synergy Grant to probe the universe's first microseconds using cosmological magnetic fields based on observations of radio waves, gamma rays and gravitational waves. Six DESY scientists were also funded for research projects related to accelerator technology, including Andreas Maier, who heads up the laboratory's effort to produce miniature plasma accelerators (*CERN Courier* July/August 2025 p8). In astroparticle physics, scientists from CNRS, Pennsylvania State University, the Sorbonne and the Universidade de Santiago de Compostela were funded to track neutrino bursts associated with cosmic-ray sources and reveal the mechanisms behind the violent astrophysical phenomena. Synergy grants are among the most prestigious grants in the world, offering substantial funding and academic freedom to a small group of principal investigators over six years.

Ireland's engineer of the year
CERN's Robert Grimmer has been named Ireland's Chartered Engineer of the Year 2025, an award that recognises professional integrity and innovation.


R Grimmer

A graduate of University College Cork in electrical engineering, Grimmer's expertise spans electronic design, radiofrequency systems and industrial controls. At CERN, he develops next-generation control electronics for the Electrical Power Converter group, enhancing the reliability and performance of CERN's high-precision power-conversion systems.

New teams at ALICE and CMS
On 1 January, Kai Schweda (GSI Helmholtz Centre) takes over as spokesperson of the ALICE collaboration, assisted by Andrea Dainese (INFN Padova) and Anthony Timmins (University of Houston) as deputies. With CMS spokesperson Gautier Hamel de Monchenault (CEA Paris-Saclay) taking on a new role as CERN's director of research, the CMS collaboration has elected Anadi

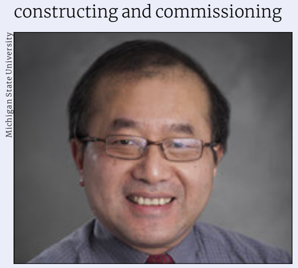
Canepa (Fermilab, pictured), formly CMS deputy spokesperson, as its new spokesperson to the role. Hafeez Hoorani (National Centre for Physics, Pakistan) continues as deputy spokesperson.

Giuseppe Occhialini Medal
Francesca Di Lodovico (King's College London) has been awarded the Giuseppe Occhialini Medal and Prize by the UK's Institute of Physics and the Italian Physical Society. The award recognises significant contributions to neutrino physics, the study of oscillation parameters in the neutrino and quark sectors, and Di Lodovico's leadership of future long-baseline neutrino experiments.

Sustainable cooling systems
CERN has received the 2025 ATMO Europe "Best in Sector/Industrial End User" award for ongoing upgrades to the primary CO_2 cooling systems serving the LHC's particle detectors. Pierre Hanf, project leader for refrigeration, cooling and ventilation, accepted the prize at the ATMOsphere Europe Summit. The award recognises excellence in natural-refrigerant technologies. CERN's project, developed with teams across the Laboratory, the Norwegian University of Science and Technology, and industrial partners, is expected to reduce emissions by around 40,000 tonnes of CO_2-equivalent per year in the ATLAS and CMS experiments.

Sakurai prize to Donoghue
John Donoghue (University of Massachusetts) has been awarded the 2026 Sakurai Prize for Theoretical Particle Physics for his contribution to original advances to effective field theory, allowing reliable low-energy predictions in quantum gravity. Donoghue showed that this approach can be used to make quantum predictions within general relativity, despite the absence of a full theory of quantum gravity. This insight has become central to understanding how gravity fits alongside the other theories of the Standard Model. Donoghue is also known for his earlier theoretical work on weak interactions, CP violation and the low-energy dynamics of quarks. The prize, one of the most prestigious in particle theory, was endowed in 1984 as a memorial to the accomplishments of J J Sakurai.

Robert R. Wilson Prize to Jie Wei
Jie Wei (Michigan State University) has been awarded the American Physical Society's 2026 Robert R. Wilson Prize for his leadership in developing, constructing and commissioning


Michigan State University

the Facility for Rare Isotope Beams (FRIB), and for his work in high-intensity hadron accelerator physics and technology. Wei obtained his PhD in physics at Stony Brook University in 1989. He was inspired to work on particle-accelerator physics by his doctoral advisor, C N Yang, who, in 1986, stated that "the future of high-energy physics is in accelerator physics," and earned his PhD jointly under Yang and E D Courant. Yang passed away in October (see p47).

PEOPLE OBITUARIES

Chen-Ning Yang 1922–2025

A towering figure in science

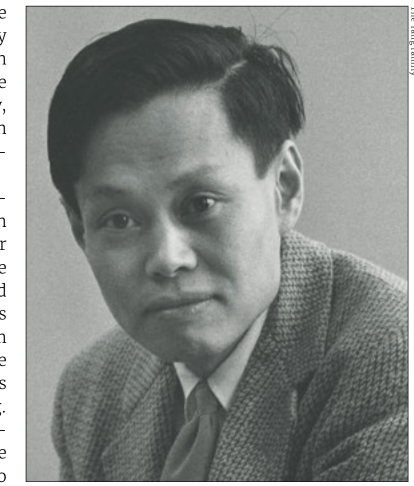
Chen-Ning Yang, a towering figure in science whose numerous insights shaped contemporary theoretical physics, passed away in Beijing on 18 October 2025 at the age of 103. Yang was one of the greatest physicists of the 20th century, whose profound contributions, often based on principles of symmetry, are central to our contemporary understanding of nature.

Yang was born in 1922 in China's Anhui province, moving as a child to Tsinghua University in Beijing, when his father was appointed professor of mathematics. Displaced by war, in 1938 he enrolled at the National Southwest Associated University in Kunming, where he earned his Master of Science in 1944, not fully removed from ongoing hostilities in the Second Sino-Japanese War. Yang wrote that his taste in physics was already formed from his education in Kunming.

He was awarded a fellowship for further graduate study in the US and enrolled in 1945 at the University of Chicago. He studied with Enrico Fermi and wrote his thesis on applications of group theory to nuclear physics in 1948 with Edward Teller as his advisor. In 1949, Yang joined the Institute for Advanced Study in Princeton, New Jersey, where he emerged as one of the world's leading scientists. He wrote that he would probably have taken Fermi's advice and returned to Chicago, but remained in Princeton to be nearer to Chih Li Tu, whom he married in 1951.

Landmark papers

His years in Princeton were extraordinarily productive, with many landmark papers in particle physics, including a famous analysis of particle decays into two photons, and statistical mechanics, including the celebrated Ising model Lee–Yang circle theorem. Most significantly of all, Yang developed non-abelian gauge theories with Robert Mills in 1954. These have the property that once the gauge groups are identified, new gauge particles and their interactions are determined. Over the subsequent 30 years, a combination of theoretical advances and experimental discoveries identified the gauge particles of our world, establishing Yang–Mills theories as a cornerstone of modern physics, alongside Maxwell's equations and Einstein's theory of general relativity. A spontaneously broken Yang–Mills theory, incorporating the Higgs boson, and combined with a Maxwell field, describes the electromagnetic and weak interactions, while a fully unbroken theory, quantum chromodynamics, describes the strong interactions. None of this could have


The Yang family

Chen-Ning Yang leaves an opus of exceptional creativity and breadth.

been foreseen in 1954, but as Yang later wrote, "we thought it was beautiful and should be published".

Yang's collaboration with Tsung-Dao Lee in 1956 on the groundbreaking possibility of parity non-conservation in weak interactions earned them the 1957 Nobel Prize in Physics, making them the first Nobel laureates of Chinese origin. The confirmation of non-conservation in the experiments of Chien-Shiung Wu and other groups led to further work, with Lee and Rudolf Oehme, on the possibility of charge conjugation and time reversal non-invariance, which were subsequently observed and are now recognised as relevant to the predominance of matter over antimatter in the universe. Around the time of the Nobel Prize, Yang, now famous, reunited with his father from China at CERN. This was their first time together since he left for his doctoral studies in Chicago.

In 1966, Yang accepted the position of Albert Einstein Professor at the new State University of New York at Stony Brook, to which he relocated with his family. In the same year, the Institute for Theoretical Physics, now the C.N. Yang Institute for Theoretical Physics, was founded, and he led it until his retirement from Stony Brook in 1999. At Stony Brook, he continued work in particle physics, and broke new ground in the quantum structure of integrable models and the geometry of gauge field theories. He also profoundly shaped statistical physics, in 1967, discovering the pivotal relation for one-dimensional quantum many-body problems, the Yang-Baxter equation, which opened new directions for research in statistical physics, integrable models, quantum groups and related fields of physics and mathematics.

Building bridges

In 1971, his visit to China sparked a wave of visits there by other well-known scholars, earning him recognition as a pioneer in building bridges of academic exchange between China and the US. As a prominent public figure, he went on to support the restoration and strengthening of basic scientific research in China. He also helped inspire a renaissance of fruitful interplay between physics and mathematics, through his work on the geometry of gauge fields, relating gauge theories to the mathematical concept of fibre bundles, a realisation that grew out of conversations in the 1970s with the mathematician James Simons.

Starting in 1997, he served as honorary director of the newly established Center for Advanced Study at Tsinghua University, now the Institute for Advanced Study, and became a professor at Tsinghua University in 1999. In 2003, he returned as a widower to his childhood home, the campus of Tsinghua University, also spending time at the Chinese University in Hong Kong. In his words, his "life can be said to form a circle", including a second marriage, with Fan Weng. He took on developing the Institute for Advanced Study as his new mission. Yang poured immense effort into advancing fundamental disciplines and cultivating talents at Tsinghua, making contributions that greatly impacted the reform and development of Chinese higher education.

Yang was elected member or foreign member of more than 10 national and regional academies of sciences, received honorary doctorates from more than 20 prestigious universities worldwide, and was honoured with numerous awards.

In his collected papers, Yang wrote that "taste and style are so important in scientific research, as they are in literature, art and music." With his own taste having served as his guide, Chen-Ning Yang leaves an opus of exceptional creativity and breadth, providing tools that have enabled generations of physicists to make new discoveries of their own.

Hui Zhai *Tsinghua University and*
George Sterman *Stony Brook University.*

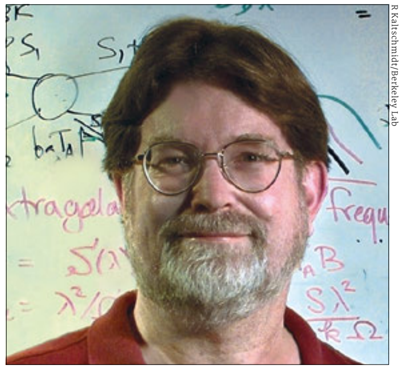
George Smoot 1945–2025

Seeing back to the Big Bang

George Smoot, who led the team that first measured tiny fluctuations in the cosmic microwave background (CMB) and began a revolution in cosmology, passed away in Paris on 18 September 2025.

George earned his undergraduate and doctoral degrees at the Massachusetts Institute of Technology (MIT), and then moved to Berkeley, where he held positions at Lawrence Berkeley National Laboratory (Berkeley Lab) and the Space Sciences Laboratory at the University of California, Berkeley (UC Berkeley). Though trained as a particle physicist, he switched to cosmology and developed research projects, including using differential microwave radiometers (DMRs) on U-2 spy planes to detect the dipole anisotropy of the CMB, a consequence of the motion of the Earth relative to the universe as a whole. He then devoted himself to the measurement of the CMB in detail, and this undertaking occupied him from his proposal of a satellite experiment using DMRs in 1974 to the results of the Cosmic Background Explorer (COBE) satellite in 1992. George subsequently continued research and teaching as a member of the faculty of the UC Berkeley physics department.

In 2006, the Nobel Prize committee recognised John Mather for leading a team that determined the CMB spectrum was a blackbody (arising from thermal equilibrium) to exquisite precision, and George for leading a team that detected temperature variations across the sky in the CMB at the level of one part in a hundred thousand. Those variations were signatures of the primordial density fluctuations that gave rise to galaxies, and so eventually to us. They have been called the DNA of cosmic structure and provide a remarkable window on the early universe and high-energy physics beyond our particle accelerators. The excitement caused by the COBE CMB results was dramatically expressed by Stephen Hawking, who declared them to be "the discovery of the century, if not all time."



George Smoot led the team that first measured tiny fluctuations in the cosmic microwave background.

His open online course "Gravity! From the Big Bang to Black Holes" taught nearly 100,000 students

After the Nobel Prize, George intensified his efforts in science education and training young scientists. Indeed, on the day of the prize, George continued to teach his undergraduate introductory physics class.

George created new research institutes internationally to support young scientists. He used his prize money to found the Berkeley Center for Cosmological Physics, a joint effort between UC Berkeley and Berkeley Lab. He also started an annual Berkeley Lab summer workshop for high-school students and teachers, now in its 19th year. Later, he founded the Instituto Avanzado de Cosmología and the international Essential Cosmology for the Next Generation winter schools in Mexico, the Paris Centre for Cosmological Physics, the Institute for the Early Universe in South Korea at the world's largest women's university, and more. Many of the scientists trained at those institutes went on to become faculty in their home countries and internationally, and formed their own research groups.

George took special pride in the Oersted Medal awarded to him by the American Association of Physics Teachers in 2009 for "outstanding, widespread, and lasting impact" on the teaching of physics. His massive open online course "Gravity! From the Big Bang to Black Holes" with Pierre Binétruy taught nearly 100,000 students.

In his later years, George's scientific interests spanned not only the CMB (in particular the Planck satellite), but new sensor technologies such as kinetic inductance detectors and ultrafast detectors that could open up new windows on astrophysical phenomena, gravitational waves and gravitational lensing, features in the inflationary primordial fluctuation spectrum, and dark-matter properties.

The primordial density fluctuations for which George was awarded the Nobel Prize lie at the heart of almost every aspect of cosmology. The revolution started by the COBE results led to the convergence of cosmology and particle physics, exemplified by the centrality of dark matter as a primary issue for both disciplines. George will be remembered for this, for the many students whose lives he touched and whose research he inspired, and for his advocacy of international science.

Robert Cahn *Berkeley Lab and*
Eric Linder *Berkeley Lab and UC Berkeley.*

Rohini Godbole 1952–2024

A guiding force in Indian particle physics

Rohini Madhusudan Godbole, one of India's most influential particle physicists, passed away in her hometown of Pune on 25 October 2024.

Rohini was born on 12 November 1952 to Madhusudan and Malati Godbole. Theirs was a cultured and highly educated family, and she grew up in an atmosphere of intellectual freedom and progressive ideas. Educated at the best schools and colleges in Pune, she joined the Indian Institute of Technology at Bombay, from which she graduated in 1972. She then moved to Stony Brook, where she completed her PhD in particle physics with Jack Smith in 1979. Returning to India, she worked temporarily at the Tata Institute of Fundamental Research before joining the faculty at the University of Bombay (now Mumbai). There she remained until 1997, when she moved to the Centre for High Energy Physics at the Indian Institute of Science at Bangalore (now Bengaluru). She worked there for the rest of her life, continuing after her formal retirement as an emeritus professor. It was only a few months before the end that she moved back to her hometown, to be with her family in her last days.

Rohini was indefatigable in promoting the cause of women in science

Rohini was a prolific researcher. She will probably be best remembered pioneering the development, with Manuel Drees, of photon structure functions for use with photon beams at future colliders, but her contributions spanned vacuum polarisation, Higgs physics, top-quark physics with polarised beams, and beyond the Standard Model physics, especially low-energy supersymmetry. She authored a well-known textbook on the latter subject with Probir Roy and Drees.

Rohini's broad understanding and warm character combined to make her the best-known face of elementary particle physics from India. She worked tirelessly to promote high-energy physics inside India, organising schools and workshops, and often represented the country in international forums, such as to monitor India's participation in the LHC and other large international collaborative experiments. Rohini was a dedicated teacher and mentor to a long series of graduate students and postdocs, and a universal elder sister or aunt for the entire community of younger particle physicists in India.

No description of Rohini can be complete without mentioning her indefatigable efforts to promote the cause of women in science. Having herself faced gender discrimination in her younger days, she was determined to ensure that young women scientists received proper opportunities and recognition. She authored two books highlighting the work of Indian women scientists, thereby setting up role models to inspire the younger generation. Even more than these books, however, her own presence and encouragement left a mark on two generations of particle physicists, in India and abroad.

Rohini Godbole worked tirelessly to promote high-energy physics in India.

Rohini's signal contributions were recognised by many awards and distinctions. The government of India awarded her the coveted Padma Shri in 2019, and the government of France awarded her the Ordre National du Mérite in 2021, mentioning her important role in furthering scientific collaboration between India and France. But her true memorial lies in the unique place she holds in the hearts of thousands of students, collaborators, friends and acquaintances. She was an extraordinary person who carved out a niche all by herself, with her scientific talents, her indefatigable energy, her universal amiability and her indomitable will. Her loss is sorely felt.

Sreerup Raychaudhuri *Banaras Hindu University.*

Hendrik Verweij 1931–2025

Mastery of microelectronics

Hendrik Verweij, who was for many years a driving force in the development of electronics for high-energy physics, passed away on 11 August 2025 in Meyrin, Switzerland, at the age of 93.

Born in Linschoten near Gouda in the Netherlands, Henk earned a degree in electrical engineering at the Technical High School in Hilversum and started his career as an instrumentation specialist at Philips, working on oscilloscopes. He joined CERN in July 1956, bringing his expertise in electronics to the newly founded laboratory. With Ian Pizer, group leader of the electronics group of the nuclear-physics-division, he published CERN Yellow Report 61-15 on a nanosecond-sampling oscilloscope, followed by a paper on a fast amplifier one year later.

During the next four decades, developments in electronics profoundly transformed the world. Henk played a crucial role in bringing this transformation to CERN's electronics instrumentation, and he eventually succeeded Pizer as group leader. Over the years he worked with numerous colleagues on fast signal-processing circuits. The creation of a collection of standardised modules facilitated the setup of a variety of CERN experiments. With Bjorn Hallgren and others, he realised the simultaneous, fast time and amplitude digitisation of the inner drift detector of the innovative UA1 experiment at CERN's Super Proton Synchrotron, which discovered the W and Z bosons together with the UA2 experiment.

Henk Verweij was a great supporter of international standardisation and collaboration with industry.

A driving force in the development of electronics for high-energy physics

In the 1960s, recognising the importance of standardisation for engaging industry, Henk built close ties with colleagues in the US, including at Lawrence Berkeley Laboratory, SLAC and the National Bureau of Standards (NBS). He took part in the discussions that led to the Nuclear Instrumentation Module (NIM) standard, defined in 1964 by the US Atomic Energy Commission, and served on the NIM committee chaired by Lou Costrell of the NBS.

Henk was also a member of the ESONE committee for the CAMAC and later FASTBUS standards, working alongside colleagues such as Bob Dobinson, Fred Iselin, Phil Ponting, Peggie Rimmer, Tim Berners-Lee and many others from across Europe and the US in this international effort. He contributed hardware for standard modules both before and after the publication of the FASTBUS specification in 1984, and reported regularly at conferences on the status of European developments. A strong advocate of collaboration with industry, he also helped persuade LeCroy to establish a facility near CERN.

Towards the end of his career, Henk became group leader of the microelectronics group at CERN, closing the loop in this transformational electronics evolution with integrated circuit developments for silicon microstrip, hybrid pixel and other detectors. When he retired in the 1990s, the group had built up the necessary expertise to design optimised application-specific integrated circuits (ASICs) for the LHC detectors. Ultimately, these allow the recording of millions of frames per second and event selection from the on-chip stored data.

Retirement did not diminish Henk's interest in CERN and its electronics activities. He often passed by in the microelectronics group at CERN, regularly participating in Medipix meetings on the development of hybrid pixel-detector read-out chips for medical imaging and other applications.

Henk played an important role in making advances in microelectronics available to the high-energy physics community. His friends and colleagues will miss his experience, vision and irrepressible enthusiasm.

Erik Heijne, **Walter Snoeys** *and*
Michael Campbell *CERN.*

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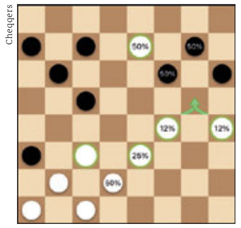
BACKGROUND

Notes and observations from the high-energy physics community

Quantum checkers

Physicists at Leiden University have taken the familiar rules of checkers and subjected them to superposition, entanglement and interference (M Raat *et al.* 2025 arXiv:2506.05962). At the highest levels of gameplay, pieces can split, merge or linger on several squares at once, collapsing into a definite position only when observed (cheqqers.com).



Cheqqers

~26 quadrillion

Inelastic collisions delivered to both ATLAS and CMS in Run 3 (so far)*.
***Priceless (as reported by departing CERN director of accelerators and technology Mike Lamont)**

Media corner

"Initally, however, the reaction of the acerbic theorist Wolfgang Pauli was so damning that Yang's nascent career was in jeopardy."

Frank Close describes reactions to Yang–Mills theory at a 1954 seminar at the Institute of Advanced Study in Princeton (*The Guardian*, 21 October 2025).

"This could be the beginning of a golden age of exotic-state research that will deepen understanding of a fundamental force that shapes the universe."

Elena Santopinto writes in a News & Views article in *Nature*, where she discusses new measurements by the CMS collaboration on all-charm tetraquarks and their implications for future studies of the strong interaction (3 December 2025).

"I appreciate the author's hard work and dedication, but we need extraordinary evidence for an extraordinary claim."

Kinwah Wu, astrophysicist at University College London, responding in *The Guardian* to Tomonori Totani of the University of Tokyo's claim that his analysis of gamma-ray data from NASA's Fermi Gamma-ray Space Telescope "could be a crucial breakthrough in unravelling the nature of dark matter" (26 November 2025).

"The most important place at CERN is the cafeteria: not because the food is exceptional, but because that's where scientists chat with each other, where the most interesting and stimulating discussions take place, where ideas are born."

Nobel laureate **Giorgio Parisi** speaking alongside **Mark Thomson**, future CERN Director-General, at the "Physics for the Future" meeting in Rome (*Wired.it* 29 November 2025).

"I would like to go back to doing hands-on, active research, because I am clearly a researcher and research is what I am most passionate about. As for the rest… we'll see!"

Fabiola Gianotti on the upcoming end of her term as CERN Director-General (*RSI Radiotelevisione svizzera* 3 December 2025).

From the archive: January/February 1986

Pole apart?

CERN

Hildred Blewett and John Mulvey at the CERN Accelerator School banquet at The Queen's College, Oxford.

After 340 days of closely monitored running, a sophisticated Superconducting Quantum Interference Device – SQUID – at London's Imperial College in South Kensington had nothing to report: another painstaking experiment diligently chipping away at the observational limits of something which might not be there anyway. Then on 11 August last year came the 'South Kensington Event', a signal compatible with the passage of a lone magnetic charge – a magnetic monopole – through a 0.2 m^2 loop in the magnetic vacuum of the apparatus.

The reluctance of free magnetic poles to show themselves has long intrigued physicists, as the equations of classical electromagnetism appear symmetric with respect to electric and magnetic charge. In 1931 Paul Dirac revived interest, and the quest received a further boost with bold new theories which postulated the existence of huge monopoles, relics of the 'Big Bang'.

Excitement rose in 1981 when a SQUID at Stanford reported a monopole-like signal in its two-inch induction detector. This was soon found to be incompatible with limits established by ionization detectors and the event was discounted. Using improved and larger detectors, teams at Stanford and elsewhere saw no further candidates, until the 'South Kensington Event'.

The London team have looked at all kinds of explanations, some of which have been ruled out, others deemed unlikely but possible. It is still too early to say that a free magnetic charge has definitely been seen, and the delicate magnetometers continue running.

● Text adapted from *CERN Courier* January/February 1986 pp17–18.

Compiler's note

Forty years on, the magnetic monopole continues to elude observation, as does the much sought for axion (p21). Both are under scrutiny in experiments that continue to "chip away diligently at the observational limits of something which [arguably] might not be there anyway". The CERN Accelerator School is now one of the lab's flagship programmes. Established at CERN in 1983, the first basic course on accelerator physics was given in Orsay in September 1984. A year later, 114 participants converged on Oxford for an advanced course, diluted with visits and a banquet. Attendees included Canadian accelerator physicist Hildred Blewett, well known at CERN since the days of the PS, and Oxford's John Mulvey, who gave the school's opening address. As chairman of ECFA he had done much to initiate the 1984 Lausanne workshop at which the ideas for the LHC began to take shape.