WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September/October 2025 issue of *CERN Courier*.

The quark model. The Ω^-. The cosmic microwave background. Charm. The Brout–Englert–Higgs mechanism. CP violation. Colour. 1964 was a remarkable year for invention and discovery (p30). The story of quarkonia began one year earlier, in 1963. As the ATLAS collaboration joins CMS in reporting an excess near the top–antitop production threshold (p9), John Ellis asks whether quarkonia's final chapter is now being written (p35).

In 2025, the community has the opportunity to shape strategic investments for decades to come. CERN Council president Costas Fountas and European strategy secretary Karl Jakobs report a growing consensus on the future of the field (p24).

The cover is a classic photograph of the OPAL detector at LEP – just one of the historic experiments whose software and data are being given a new lease of life, decades after data-taking ended. As the LHC surpasses one exabyte of stored data, Cristinel Diaconu and Ulrich Schwickerath call for new collaborations to join a global effort in data preservation, to allow future generations to unearth the hidden treasures (p41).

Elsewhere in these pages: should dark energy evolve? (p47); scalable technology for precision neutrino physics with small detectors (p7); tips from IBM's head of science and technology on how to get a job in industry (p53); an update on the ATOMKI anomaly (p8); Andreas Hoecker's highlights from EPS–HEP (p17); and much more.

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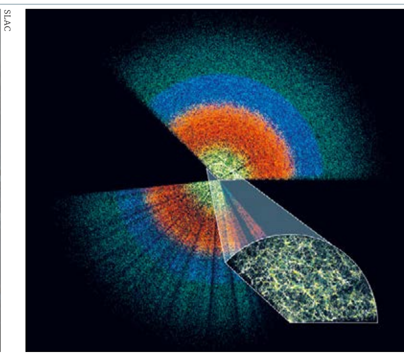
EDITOR: MARK RAYNER

IN THIS ISSUE

VOLUME 65 NUMBER 5 SEPTEMBER/OCTOBER 2025

Hidden treasure *Data preservation allows the search for signals not imagined during an experiments' lifetime.* **41**



Cosmologically inconstant *Robert Brandenberger argues that dark energy should be time-dependent.* **47**

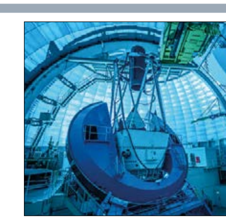
Shifting gears *Tips for transitioning to industry from IBM's head of science and technology.* **53**

NEWS

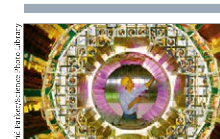
PEOPLE

FEATURES

OPINION



DEPARTMENTS



On the cover *How data preservation can unlock hidden treasures.* **41**

FROM THE EDITOR

Historic resonances that still resonate

Mark Rayner
Editor

Separation, annihilation and decay. These are the ends of quarkonia. The ϕ meson ($s\bar{s}$) decays via the separation of its constituent quarks to create two kaons. The J/ψ and Υ mesons ($c\bar{c}$ and $b\bar{b}$) decay via the annihilation of their constituent quarks into gluons or photons. But toponium – the simplest explanation for the threshold excess observed last year by CMS and now also observed by ATLAS (p9) – will be completely different. Not a spike but a pancake on energy spectra. Its constituent top quark and top antiquark have less than a yoctosecond to exchange gluons before one of them decays via the weak interaction.

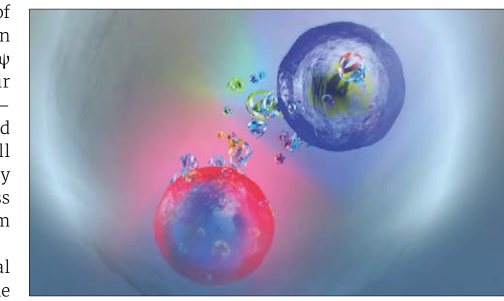
The story of quarkonia, and their spin, orbital and radial excitations, has shaped the course of particle physics (p35). The November Revolution of 1974 is well known, but a sharp peak of creativity and discovery also took place in 1964, in the year immediately following the discovery of the ϕ: an unexpectedly narrow resonance with an odd proclivity to decay into kaons rather than the energetically favoured pions.

1964 saw the publication of the quark model and the observation of the Ω^- baryon (sss). Penzias and Wilson unwittingly observed the cosmic microwave background. Glashow and Bjorken proposed the charm quantum number. Brout, Englert, Higgs, Guralnik, Hagen and Kibble exorcised the ghost of the Goldstone boson from gauge theories. Cronin and Fitch discovered CP violation. Greenberg glimpsed the mathematics of colour.

As living memory of 1964 fades, science historian Michael Riordan recounts the events of the year with a contextualist philosophy which emphasises ideas that shaped physics at the time (p30). One casualty of this approach is Swiss theorist André Petermann, who reasoned his way to three-spinor baryons and spinor–antispinor mesons in a publication submitted to *Nuclear Physics* in 1963 that languished on referees' desks until 1965.

If the dam is once again to burst, experiment and theory must work in concert

If the dam is once again to burst, experiment and theory must work in concert. Strategy may come from the top down, as in a new US report by an expert committee selected by the National Academies of Sciences, Engineering, and Medicine (p10), or from the bottom up, as in the ongoing update to the European strategy for particle physics – a process where postdocs and junior faculty spend countless hours writing white papers and serving as secretaries of working groups. CERN Council president Costas Fountas and strategy secretary Karl Jakobs have key roles to play, representing the interests of CERN Member States and the high-energy-physics community. In an extended strategy feature, they report a growing consensus on the future of the field (p24).



D Dominguez/CERN

Threshold enhancement? Artist's impression of toponium.

This edition's cover is a classic photograph of the OPAL detector at LEP – just one of the historic experiments whose software and data are being given a new lease of life, decades after data-taking ended. As the LHC surpasses one exabyte of stored data – perhaps the largest scientific data set ever accumulated – Cristinel Diaconu and Ulrich Schwickerath call for new collaborations to join a global effort in data preservation, to allow future generations to unearth the hidden treasures (p41).

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Reporting on international high-energy physics

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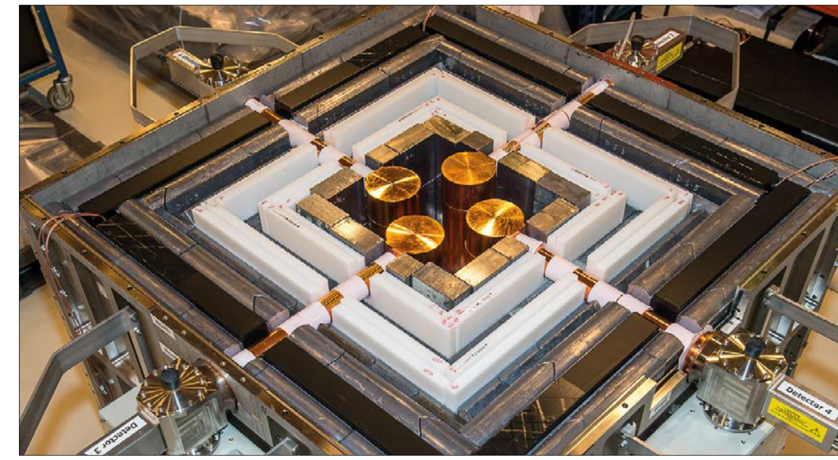
NEWS ANALYSIS

NEUTRINOS

Full coherence at fifty

The most common neutrino interactions are the most difficult to detect. But thanks to advances in detector technology, coherent elastic neutrino–nucleus scattering (CEνNS) is emerging from behind backgrounds, 50 years after it was first hypothesised. These low-energy interactions are insensitive to the intricacies of nuclear or nucleon structure, making them a promising tool for precision searches for physics beyond the Standard Model. They also offer a route to miniaturising neutrino detectors.

"I am convinced that we are seeing the beginning of a new field in neutrino physics based on CEνNS observations," says Manfred Lindner (Max Planck Institute for Nuclear Physics in Heidelberg), the spokesperson for the CONUS+ experiment, which reported the first evidence for fully coherent CEνNS in July. "The technology of CONUS+ is mature and seems scalable. I believe that we are at the beginning of precision neutrino physics with CEνNS and CONUS+ is one of the door openers!"



CONUS Collab.

Shielded semiconductors *CONUS+'s four detector modules have ultra-low energy thresholds.*

Act of hubris

Daniel Z Freedman is not best known for CEνNS, but in 1974 the future supergravity architect suggested that experimenters search for evidence of neutrinos interacting not with nucleons but "coherently" with entire nuclei. This process should dominate when the de Broglie wavelength of the neutrino is the diameter of the nucleus or larger. The question of which specific neutron exchanged a Z boson with the incoming neutrino would sum in the quantum amplitude rather than the probability, leading to an N^2 dependence on the number of neutrons. As a result, CEνNS cross sections are typically enhanced by a factor of between 100 and 1000.

Freedman noted that his proposal may have been an "act of hubris", because the interaction rate, detector resolution and backgrounds would all pose grave experimental difficulties. His caveat was perspicacious. It took until 2017 for indisputable evidence for CEνNS to emerge at Oak Ridge National Laboratory in the US, where the COHERENT experiment observed CEνNS by neutrinos with a maximum energy of 52 MeV, emerging from pion decays at rest (*CERN Courier* October 2017 p8). At these energies, the coherence condition is only partially fulfilled, and nuclear structure still plays a role.

I am convinced that we are seeing the beginning of a new field in neutrino physics based on CEνNS observations

The CONUS+ collaboration now presents evidence for CEνNS in the fully coherent regime. The experiment – one of many launched at nuclear reactors following the COHERENT demonstration – uses reactor electron anti-neutrinos with energies below 10 MeV generated across 119 days at the Leibstadt Nuclear Power Plant in Switzerland. The team observed 395 ± 106 neutrinos compared to a Standard Model expectation of 347 ± 59 events, corresponding to a statistical significance for the observation of CEνNS of 3.7σ.

It is no wonder that detection took 50 years. The only signal of CEνNS is a gentle nuclear recoil – an effect often compared to the effect of a ping-pong ball on a tanker. In CONUS+, the nuclear recoils of the CEνNS interactions are detected using the ionisation signal of point-contact high-purity germanium detectors with ultra-low energy thresholds as low as 160 eV.

The team has now increased the mass of their four semiconductor detectors from 1 to 2.4 kg to provide better statistics and potentially a lower threshold energy. CONUS+ is highly sensitive to physics beyond the Standard Model, says the team, including non-standard interaction parameters, new light mediators and electromagnetic properties of the neutrino such as electrical millicharges or neutrino magnetic moments. Lindner estimates that the CONUS+ technology could be scaled up to 100 kg, potentially yielding 100,000 CEνNS events per year of operation.

Into the neutrino fog

One researcher's holy grail is another's curse. In 2024, dark-matter experiments reported entering the "neutrino fog", as their sensitivity to nuclear recoils crossed the threshold to detect a background of solar-neutrino CEνNS interactions. The PandaX-4T and XENONnT collaborations reported 2.6σ and 2.7σ evidence for CEνNS interactions in their liquid-xenon time projection chambers, based on estimated signals of 79 and 11 interactions, respectively. These were the first direct measurements of nuclear recoils from solar neutrinos with dark-matter detectors. Boron-8 solar neutrinos have slightly higher energies than those detected by CONUS+, and are also in the fully ▷

CERNCOURIER

VOLUME 65 NUMBER 5 SEPTEMBER/OCTOBER 2025

coherent regime.

"The neutrino flux in CONUS+ is many orders of magnitude bigger than in dark-matter detectors," notes Lindner, who is also co-spokesperson of the XENON collaboration. "This is compensated by a much larger target mass, a larger CEνNS cross section due to the larger number of neutrons in xenon versus germanium, a longer running time and differences in detection efficiencies. Both experiments have in common that all backgrounds of natural or imposed radioactivity must be suppressed by many orders of magnitude such that the CEνNS process can be extracted over backgrounds."

The current experimental frontier for CEνNS is towards low energy thresholds, concludes COHERENT spokesperson Kate Scholberg of Duke University. "The coupling of recoil energy to observable energy can be in the form of a dim flash of light picked up by light sensors, a tiny zap of charge collected in a semiconductor detector, or a small thermal pulse observed in a bolometer. A number of collaborations are pursuing novel technologies with sub-keV thresholds, among them cryogenic bolometers. A further goal is measurement over a range of nuclei, as this will test the SM prediction of an N^2 dependence of the CEνNS cross section. And for higher-energy neutrino sources, for which the coherence is not quite perfect, there are opportunities to learn about nuclear structure. Another future possibility is directional recoil detection. If we are lucky, nature may give us a supernova burst of CEνNS recoils. As for societal applications, CEνNS has promise for nuclear-reactor monitoring for nonproliferation purposes due to its large cross section and interaction threshold below that for inverse-beta-decay of 1.8 MeV."

CEνNS has promise for nuclear-reactor monitoring

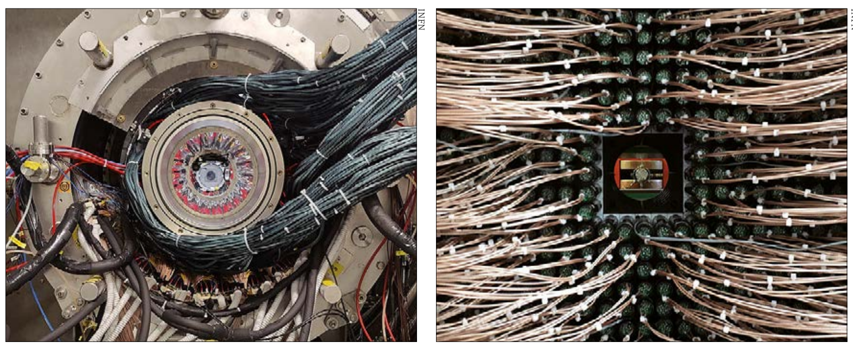
Further reading

N Ackermann *et al.* 2025 *Nature* **643** 1229.
PandaX Collab. 2024 *Phys. Rev. Lett.* **133** 191001.
XENON Collab. 2024 *Phys. Rev. Lett.* **133** 191002.

Searches for new physics

Mixed signals from X17

Almost a decade after ATOMKI researchers reported an unexpected peak in electron–positron pairs from beryllium nuclear transitions, the case for a new "X17" particle remains open. Proposed as a light boson with a mass of about 17 MeV and very weak couplings, it would belong to the sometimes-overlooked low-energy frontier of physics beyond the Standard Model. Two recent results now pull in opposite directions: the MEG II experiment at the Paul Scherrer Institute found no signal in the same transition, while the PADME experiment at INFN Frascati reports a modest excess in electron–positron scattering at the corresponding mass.



INFN

Square peg in a round hole *Independent checks by the MEG II (left) and PADME (right) experiments report conflicting early indications on the true nature of the ATOMKI anomaly.*

The story of the elusive X17 particle began at the Institute for Nuclear Research (ATOMKI) in Debrecen, Hungary, where nuclear physicist Attila János Krasznahorkay and colleagues set out to study the de-excitation of a beryllium-8 state. Their target was the dark photon – a particle hypothesised to mediate interactions between ordinary and dark matter. In their setup, a beam of protons strikes a lithium-7 target, producing an excited beryllium nucleus that releases a proton or de-excites to the beryllium-8 ground state by emitting an 18.1 MeV gamma ray – or, very rarely, an electron–positron pair.

Controversial anomaly

In 2015, ATOMKI claimed to have observed an excess of electron–positron pairs with a statistical significance of 6.8σ. Follow-up measurements with different nuclei were also reported to yield statistically significant excess at the same mass. The team claimed the excess was consistent with the creation of a short-lived neutral boson with a mass of about 17 MeV. Given that it would be produced in nuclear transitions and decay into electron–positron pairs, the X17 should couple to nucleons, electrons and positrons. But many relevant constraints squeeze the parameter space for new physics at low energies, and independent tests are essential to resolve an unexpected and controversial anomaly that is now a decade old.

In November 2024, MEG II announced a direct cross-check of the anomaly, publishing their results in July 2025. Designed for high-precision tracking and calorimetry, the experiment combines dedicated background monitors with a spectrometer based on a lightweight, single-volume drift chamber that records the ionisation trails of charged particles. The detector is designed to search for evidence of the rare lepton-flavour-violating decay $\mu^+ \to e^+\gamma$, with the collaboration recently reporting world-leading limits at EPS-HEP (see p17). It is also well suited to probing electron–positron final states, and has the mass resolution required to test the narrow-resonance interpretation of the ATOMKI anomaly.

Motivated by interest in X17, the collaboration directed a proton beam with energy up to 1.1 MeV onto a lithium-7 target, to study the same nuclear process as ATOMKI. Their data disfavours the ATOMKI hypothesis and imposes an upper limit on the branching ratio of 1.2×10^{-5} at 90% confidence.

"While the result does not close the case," notes Angela Papa of INFN, the University of Pisa and the Paul Scherrer Institute, "it weakens the simplest interpretations of the anomaly."

But MEG II is not the only cross check in progress. In May, the PADME collaboration reported an independent test that doesn't repeat the ATOMKI experiment, but seeks to disentangle the X17 question from the complexities of nuclear physics. ▷

Initially designed to search for evidence of states that decay invisibly, like dark photons or axion-like particles, PADME collides a positron beam with energies reaching 550 MeV with a 100 μm-thick active diamond target. Annihilations of positrons with electrons bound in the target material are reconstructed by detecting the resulting photons, with any peak in the missing-mass spectrum signalling an unseen product. The photon energy and impact position is measured by a finely segmented electromagnetic calorimeter with crystals refurbished from the L3 experiment at LEP.

"The PADME approach relies only on the suggested interaction of X17 with electrons and positrons," remarks spokesperson Venelin Kozhuharov of Sofia University and INFN Frascati. "Since the ATOMKI excess was observed in electron–positron final states, this is the minimal possible assumption that can be made for X17."

For theorists, X17 is an awkward fit

Instead of searching for evidence of unseen particles, PADME varied the beam energy to look for an electron–positron resonance in the expected X17 mass range. The collaboration claims that the combined dataset displays an excess near 16.90 MeV with a local significance of 2.5σ.

For theorists, X17 is an awkward fit. Most consider dark photons and axions to be the best motivated candidates for low mass, weakly coupled new physics states, says Claudio Toni of LAPTh. Another possibility, he says, is a bound state of known particles, though QCD states such as pions are about eight times heavier, and pure QED effects usually occur at much lower scales than 17 MeV.

"We should be cautious," says Toni. "Since X17 is expected to couple to both protons and electrons, the absence of signals elsewhere forces any theoretical proposal to respect stringent constraints. We should focus on its phenomenology."

Further reading

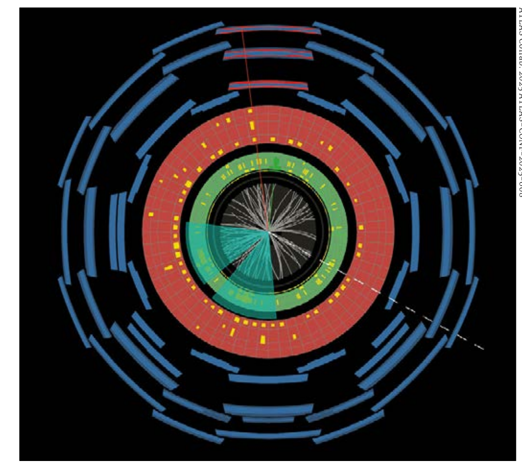
MEG II Collab. 2025 *Eur. Phys. J. C* **85** 763.
PADME Collab. 2025 arXiv:2505.24797.

Top-quark physics

ATLAS confirms top–antitop excess

At the LHC, almost all top–antitop pairs are produced in a smooth invariant-mass spectrum described by perturbative QCD. In March, the CMS collaboration announced the discovery of an additional 1% localised near the energy threshold to produce a top quark and its antiquark (*CERN Courier* May/June 2025 p7). The ATLAS collaboration has now confirmed this observation.

"The measurement was challenging due to the small cross section and the limited mass resolution of about 20%," says Tomas Dado of the ATLAS collaboration and CERN. "Sensitivity was achieved by exploiting high statistics, lepton angular variables sensitive to spin correlations, and by carefully constraining modelling uncertainties."



ATLAS Collab. 2025 ATLAS-CONF-2025-008

Quasi-bound candidate *An event display of an interaction consistent with the formation of toponium in the ATLAS detector. The final state includes two b jets (turquoise cones), a muon (red line) and an electron (green line). 99 GeV of missing transverse momentum is indicated by the dashed white line.*

Toponium

The simplest explanation for the excess appears to be a spectrum of "quasi-bound" states of a top quark and its antiquark that are often collectively referred to as toponium, by reference to the charmonium and bottomonium states discovered in the November Revolution of 1974 (see p35). But there the similarities end. Thanks to the unique properties of the most massive fundamental particle yet discovered, toponium is expected to be exceptionally broad rather than exceptionally narrow in energy spectra, and to disintegrate via the weak decay of its constituent quarks rather than via their mutual annihilation.

"Historically, it was assumed that the LHC would never reach the sensitivity required to probe such effects, but ATLAS and CMS have shown that this expectation was too pessimistic," says Benjamin Fuks of the Sorbonne. "This regime corresponds to the production of a slowly moving top–antitop pair that has time to exchange multiple gluons before one of the top quarks decays. The invariant mass of the system lies slightly below the open top–antitop threshold, which implies that at least one of the top quarks is off-shell. This contrasts with conventional top–antitop production, where the tops are typically produced far above threshold, move relativistically and do not experience significant non-relativistic gluon dynamics."

While CMS fitted a pseudo-scalar resonance that couples to gluons and top quarks – the essential features of the ground state of toponium – the new ATLAS analysis employs a model recently published by Fuks and his collaborators that additionally includes all S-wave excitations. ATLAS reports a cross-section for such quasi-bound excitations of 9.0 ± 1.3 pb, consistent with CMS's measurement of 8.8 ± 1.3 pb. ATLAS's measurement rises to 13.9 ± 1.9 pb when applying the same signal model as CMS.

Future measurements of top quark–antiquark pairs will compare the threshold excess to the expectations of non-relativistic QCD, search for the possible presence of new fields beyond the Standard Model, and study the quantum entanglement of the top and antitop quarks.

"At the High-Luminosity LHC, the main objective is to exploit the much larger dataset to go beyond a single-bin description of the sub-threshold top–antitop invariant mass distribution," says Fuks. "At a future electron–positron collider, the top–antitop threshold scan has long been recognised as a cornerstone measurement, with toponium contributions playing an essential role."

For Dado, this story reflects a satisfying interplay between theorists and the LHC experiments.

"Theorists proposed entanglement studies, ATLAS demonstrated entangled top–antitop pairs and CMS applied spin-sensitive observables to reveal the quasi-bound-state effect," he says. "The next step is for theory to deliver a complete description of the top–antitop threshold."

Further reading

ATLAS Collab. 2025 ATLAS-CONF-2025-008.
B Fuks *et al.* 2025 *Eur. Phys. J. C* **85** 157.

CERNCOURIER

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POLICY

US publishes 40-year vision for particle physics

Big science requires long-term planning. In June, the US National Academies of Sciences, Engineering, and Medicine published an unprecedented 40-year strategy for US particle physics titled *Elementary Particle Physics: The Higgs and Beyond*. Its recommendations include participating in the proposed Future Circular Collider at CERN and hosting the world's highest-energy elementary particle collider around the middle of the century (see "Eight recommendations" panel). The report assesses that a 10 TeV muon collider would complement the discovery potential of a 100 TeV proton collider.

"The shift to a 40-year horizon in the new report reflects a recognition that modern particle-physics projects and scientific questions are of unprecedented scale and complexity, demanding a much longer-term strategic commitment, international cooperation and investment for continued leadership," says report co-chair Maria Spiropulu of the California Institute of Technology. "A staggered approach towards large research-infrastructure projects, rich in scientific advancement, technological breakthroughs and collaboration, can shield the field from stagnation."

The report is authored by a committee of leading scientists selected by the National Academies. Its mandate complements the grassroots-led Snowmass process and the budget-conscious P5 process (*CERN Courier* January/February 2024 p7). The previous report in this series, *Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics* was published in 2006. It called for the full exploitation of the LHC, a strategic focus on linear-collider R&D, expanding particle astrophysics, and pursuing an internationally coordinated, staged programme in neutrino physics.

Two conclusions underpin the new report's recommendations. The first identifies three workforce issues currently threatening the future of particle physics: the morale of early-career scientists, a shortfall in the number of accelerator scientists, and growing barriers to international exchanges. The second urges US leadership in elementary particle physics, citing benefits to science, the nation and humanity.

Eight recommendations

1. The US should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider R&D programme to enable the construction of a demonstrator of the key new technologies and their integration.
2. The US should participate in the international Future Circular Collider Higgs factory currently under study at CERN to unravel the physics of the Higgs boson.
3. The US should continue to pursue and develop new approaches to questions ranging from neutrino physics and tests of fundamental symmetries to the mysteries of dark matter, dark energy, cosmic inflation and the excess of matter over antimatter in the universe.
4. The US should explore new synergistic partnerships across traditional science disciplines and funding boundaries.
5. The US should invest for the long journey ahead with sustained R&D funding in accelerator science and technology, advanced instrumentation, all aspects of computing, emerging technologies from other disciplines and a healthy core research programme.
6. The federal government should provide the means and the particle-physics community should take responsibility for recruiting, training, mentoring and retaining the highly motivated student and postdoctoral workforce required for the success of the field's ambitious science goals.
7. The US should engage internationally through existing and new partnerships, and explore new cooperative planning mechanisms.
8. Funding agencies, national laboratories and universities should work to minimise the environmental impact of particle-physics research and facilities.

Source: National Academies of Sciences, Engineering, and Medicine 2025 *Elementary Particle Physics: The Higgs and Beyond*. Washington, DC: The National Academies Press.

ASTROWATCH

Einstein Probe detects exotic gamma-ray bursts

Supernovae are some of the most well-known astrophysical phenomena. The energies involved in these powerful explosions are, however, dwarfed by a gamma-ray burst (GRB). These extragalactic explosions form the most powerful electromagnetic explosions in the universe and play an important role in its evolution. First detected in 1967, they consist of a bright pulse of gamma rays, lasting from several seconds to several minutes. This is followed by an afterglow emission that can be measured from X-rays down to radio energies for days or even months. Thanks to 60 years of observations of these events by a range of detectors, we now know that the longer GRBs are an extreme version of a core-collapse supernova. In GRBs, the death of the heavy star is accompanied by two powerful relativistic jets. If such a jet points towards Earth we can detect gamma-ray photons even for GRBs at distances of billions of light years. Thanks to detailed observations, the afterglow is now understood to be the result of synchrotron emission produced as the jet crashes into the interstellar medium.


ESA

Something fishy *Inspired by the eyes of lobsters, the Einstein Probe is a novel X-ray telescope composed of hundreds of thousands of square tubes that guide X-rays down to CMOS light detectors.*

After the detection of over 10,000 gamma-ray components of GRBs by dedicated gamma-ray satellites, the most common models associate the longer ones with supernovae. This has been confirmed thanks to detections of afterglow emission coinciding with supernova events in other galaxies. The exact characteristics that cause some heavy stars to produce a GRB remain, however, poorly understood. Furthermore, many open questions remain regarding the nature and origin of the relativistic jets and how the gamma rays are produced within them.

While the emission has been studied extensively in gamma rays, detections at soft X-ray energies are limited. This changed in early 2024 with the launch of the Einstein Probe (EP) satellite. EP is a novel X-ray telescope, developed by the Chinese Academy of Sciences (CAS) in collaboration with ESA, the Max Planck Institute for Extraterrestrial Physics and the Centre National d'Études Spatiales. EP is unique in its wide field of view (1/11th of the sky) in soft X-rays, made possible thanks to complex X-ray optics. As GRBs occur at random positions in the sky at random times, the large field of view increases its chance to observe them. Within its first year EP detected several GRB events, most of which challenge our understanding of them.

One of these occurred on 14 April 2024. It consisted of a bright flash of X-rays lasting about 2.5 minutes. The event was also observed by ground-based optical and radio telescopes that were alerted to its location in the sky by EP. These observations at lower photon energies were consistent with a weak afterglow together with the signatures from a relatively standard supernova-like event. The supernova emission showed it to originate from a star which, prior to its death, had already shed its outer layers of hydrogen and helium. Along with the spectrum detected by EP, the detection of an afterglow indicates the existence of a relativistic jet. The overall picture is therefore consistent with a GRB. However, a crucial part was missing: a gamma-ray component.

In addition, the emission spectrum observed by EP looks significantly softer as it peaks at keV rather than the 100s of keV energies typical for GRBs. The results hint at this being at an explosion that produced a relativistic jet which – for unknown reasons – was not energetic enough to produce the standard gamma-ray emission. The progenitor star therefore appears to bridge the stellar population which causes a "simple" core collapse supernova and those that produce GRBs.

Another event, detected on 15 March 2024, produced soft X-rays consisting of six separate epochs spread out over 17 minutes. Here, a gamma-ray component was detected by NASA's Swift BAT instrument, confirming it to be a GRB. However, unlike any other GRB, the gamma-ray emission started long after the onset of the X-ray emission. This lack of gamma-ray emission in the early stages is difficult to reconcile with standard emission models. There, the emission comes from a single uniform jet where the highest energies are emitted at the start when the jet is at its most energetic.

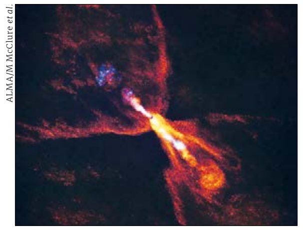
In their publication in *Nature Astronomy*, the EP collaboration suggests the possibility that the early X-ray emission comes from either shocks from the supernova explosion itself or from weaker relativistic jets preceding the main powerful jet. Other proposed explanations include complex jet structures and pose that EP observed the jet far away from its centre. In this explanation, the matter in the jet moves faster in the centre while at the edges its Lorentz factor (or velocity) is significantly slower, thereby producing a lower-energy longer-lasting emission, undetectable before the launch of EP.

Overall, the two detections appear to indicate that the GRBs detected over the last 60 years, where the emission was dominated by gamma rays, were only a subset of a more complex phenomenon. At a time where two of the most important instruments in GRB astronomy from the last two decades, NASA's Fermi and Swift missions, are proposed to be switched off, EP is taking over an important role and opening the window to soft X-ray observations.

Further reading
Y Liu *et al*. 2025 *Nat. Astron.* **9** 564.
H Sun *et al*. 2025 *Nat. Astron.* **9** 1073.

CERNCOURIER
VOLUME 65 NUMBER 5 SEPTEMBER/OCTOBER 2025

NEWS DIGEST



ALMA/M McClure et al.

Molecular emission by HOPS-315.

Birth of a solar system

The Atacama Large Millimeter Array and James Webb Space Telescope have captured the earliest known stages of the formation of a planetary system. Observations of the protostar HOPS-315, located approximately 420 parsecs from Earth, revealed molecular emission of carbon monoxide (orange) and silicon monoxide (blue) from the infant star. The findings suggest that some planets' chemical and physical evolution can be driven by the sublimation of interstellar solids, such as dust grains and ice that are heated and transform into gas, followed by rapid recondensation of refractory materials, forming into silicides and metal oxides as the gas cools. Analysts suggest that this process may be occurring on a comparable timeline to the formation of our own solar system 4.5 billion years ago (M K McClure 2025 *Nature* **643** 649).

Hyper-K cavern complete

The excavation of the 94 m-tall cavern of the Hyper-Kamiokande neutrino detector was completed on 31 July. The structure, carved 600 m below the Hida Highlands in the Gifu Prefecture, Japan, consists of a 21 m-radius domed ceiling atop a 73 m-tall cylindrical shaft of diameter 69 m. The cavern will be filled with 260,000 cubic metres of ultra-pure water, 8.4 times the volume of its predecessor, Super-Kamiokande, making it the largest water Cherenkov detector ever built. Equipped with more than 20,000 newly developed photodetectors to capture Cherenkov light from neutrino interactions, the detector's goals will include precision neutrino-oscillation measurements, proton-decay searches and the detection of astrophysical neutrinos. Construction now transitions to tank lining, water purification systems and instrument installation, targeting operation in 2028.

The first antimatter qubit

On 23 July, CERN's Baryon-Antibaryon Symmetry Experiment (BASE) published a paper detailing the first-ever antimatter qubit (BASE Collab. 2025 *Nature* **644** 64). Researchers successfully maintained a single trapped antiproton oscillating coherently between two spin states for approximately 50 seconds, using coherent quantum transition spectroscopy to overcome previously limiting magnetic-field fluctuations. "This represents the first antimatter qubit and opens up the prospect of applying the entire set of coherent spectroscopy methods to single matter and antimatter systems in precision experiments," says BASE spokesperson Stefan Ulmer (RIKEN).

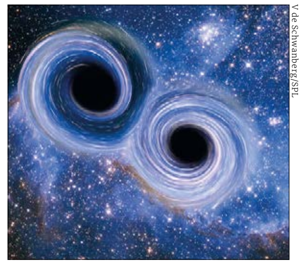
CERN

The BASE experiment.

"Most importantly, it will help BASE to perform antiproton moment measurements in future experiments with 10- to 100-fold improved precision."

Big binary black-hole merger

The LIGO-Virgo-KAGRA collaboration reports the detection of the most massive binary black-hole merger ever observed (LVK Collab. 2025 arXiv:2507.08219). Black holes with masses 137^{+22}_{-17} and 103^{+20}_{-52} times that of the Sun combined



V de Schwanberg/SPL

Artist's impression of two black holes merging.

to form a final black hole that exceeds the previous mass record of 142 solar masses by over 50%. Both black holes exhibit high spins – $0.9^{+0.10}_{-0.19}$ and $0.80^{+0.20}_{-0.51}$ – and lie in or above the mass gap between 60 and 130 solar masses where black holes are theorised to be rare due to pair instability mechanisms.

Bigger, simpler, faster

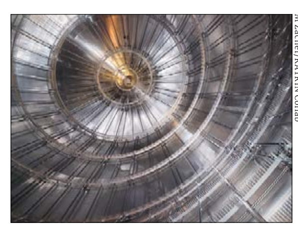
As part of the next long-term EU budget from 2028–2034, the European Commission is proposing to double the budget of the research and innovation framework programme to €175 billion. This means that Horizon Europe, which is closely tied to the European Competitiveness Fund, will have the capacity to develop "moonshot projects". These projects would move from research to demonstration and real-world deployment. They would be supported by pooled funding from the EU (Horizon Europe and the European Competitiveness Fund), national, public and private sources. Designed to position Europe as a global leader in strategic fields, these moonshot projects would drive progress in areas such as the FCC, quantum computing and next-generation AI, says the press release.

First oxygen, neon collisions

Between 29 June and 9 July, the LHC conducted two days of proton–oxygen ion collisions, followed by two days of oxygen–oxygen collisions and one day of neon–neon collisions – all for the first time. The proton–ion collisions posed the biggest challenge, said LHC ion specialist Roderik Bruce (CERN). "This is because the electromagnetic field inside the accelerator affects protons and oxygen ions differently, due to their different charge-to-mass ratios. In other words, without corrections the two beams would collide in different places at each turn." To overcome this problem, the engineers carefully adjusted the frequency of revolution and the momentum of each beam, so that the collisions take place at the heart of the experiments.

New neutrino mass constraint

On 10 April, the Karlsruhe Tritium Neutrino (KATRIN) experiment released its latest upper limit for the neutrino mass: 0.45 eV at 90% confidence, implying that the mass of a neutrino is less than one millionth the mass of an electron (KATRIN Collab. 2025 *Science* **388** 180). By measuring the energy of 36 million electrons over 259 days between 2019 and 2021, KATRIN



M Zacher/KATRIN Collab.

KATRIN's main spectrometer.

tightened its previous upper bound by a factor of almost two on the effective electron–neutrino mass. KATRIN's data-taking campaign will end in 2025 after 1000 days of data acquisition, once the experiment has reached its target sensitivity of between 0.2 and 0.3 eV.

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

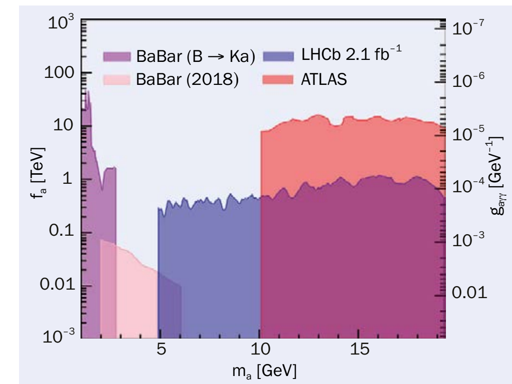
LHCb

Closing the gap on axion-like particles

Axion-like particles (ALPs) are some of the most promising candidates for physics beyond the Standard Model. At the LHC, searches for ALPs that couple to gluons and photons have so far been limited to masses above 10 GeV due to trigger requirements that reduce low-energy sensitivity. In its first ever analysis on purely neutral final states, the LHCb collaboration has now extended this experimental reach and set new bounds on the ALP parameter space.

When a global symmetry is spontaneously broken, it gives rise to massless excitations called Goldstone bosons, which reflect the system's freedom to transform continuously without changing its energy. It is thought that ALPs may arise via a similar mechanism, acquiring a small mass though, as they originate from symmetries that are only approximate. Depending on the underlying theory, they could contribute to dark matter, solve the strong-CP problem, or mediate interactions with a hidden sector. Their coupling to known particles varies across models, leading to a range of potential experimental signatures. Among the most compelling are those involving gluons and photons.

Thanks to the magnitude of the strong coupling constant, even a small interaction with gluons can dominate the production and decay of ALPs. This makes searches at the LHC challenging since low-energy jets in proton–proton collisions are often indistinguishable from the expected ALP decay signature. In this environment, a more effective approach is to focus on the photon channel and search for ALPs that are produced in proton–



LHCb Collab. 2025 arXiv:2507.14390

Fig. 1. *Limits on the ALP decay constant f_a and its coupling to photons $g_{a\gamma\gamma}$, as a function of ALP mass m_a. Results from the LHCb analysis (blue) are compared to two measurements from BaBar (pink and purple) and one from ATLAS (red). The shaded parameter space is excluded at 95% confidence.*

proton collisions – mostly via gluon–gluon fusion – and that decay into photon pairs. These processes have been investigated at the LHC, but previous searches were limited by trigger thresholds requesting photons with large momentum components transverse to the beam. This is particularly restrictive for low-mass ALPs, whose decay products are often too soft to pass these thresholds.

The new search, based on Run-2 data collected in 2018, overcomes this limitation by leveraging the LHCb detector's flexible software-based trigger system, lower pile-up and forward geometry. The latter enhances sensitivity to products with a small momentum component transverse to the beam, making it well suited to probe resonances in the 4.9 to 19.4 GeV mass region. This is the first LHCb analysis of a purely neutral final state, hence requiring a new trigger and selection strategy, as well as a dedicated calibration procedure. Candidate photon pairs are identified from two high-energy calorimeter clusters, produced in isolation from the rest of the event, which could not originate from charged particles or neutral pions. ALP decays are then sought using maximum likelihood fits that scan the photon-pair invariant mass spectrum for peaks.

No photon-pair excess is observed over the background-only hypothesis, and upper limits are set on the ALP production cross-section times decay branching. These results constrain the ALP decay rate and its coupling to photons, probing a region of parameter space that has so far remained unexplored (see figure 1). The investigated mass range is also of interest beyond ALP searches. Alongside the main analysis, the study targeted two-photon decays of $B^0_{(s)}$ and the little-studied η_b meson, almost reaching the sensitivity required for its detection.

The upgraded LHCb detector, which began operations with Run 3 in 2022, is expected to deliver another boost in sensitivity. This will allow future analyses to benefit from the extended flexibility of its purely software trigger, significantly larger datasets and a wider energy coverage of the upgraded calorimeter.

Further reading

LHCb Collab. 2025 arXiv:2507.14390.

CMS

CP symmetry in diphoton Higgs decays

In addition to giving mass to elementary particles, the Brout–Englert–Higgs mechanism provides a testing ground for the fundamental symmetries of nature. In a recent analysis, the CMS collaboration searched for violations of charge-parity (CP) symmetry in the decays of Higgs bosons into two photons. The results set some of the strongest limits to date on anomalous Higgs-boson couplings that violate CP symmetry.

CP symmetry is particularly interesting as violations reveal fundamental differences in the behaviour of matter and antimatter, potentially explaining why the former appears to be much more abundant in the observed universe. While the Standard Model predicts that CP symmetry should be violated, the effect is not sufficient to account for the

> **The results set some of the strongest limits to date**

observed imbalance, motivating searches for additional sources of CP violation. CP symmetry requires that the laws of physics remain the same when particles are replaced by their corresponding antiparticles (C symmetry) and their spatial coordinates are reflected as in a mirror (P symmetry). In 1967, Andrei Sakharov established CP violation as one of three necessary requirements ▷

CERNCOURIER
VOLUME 65 NUMBER 5 SEPTEMBER/OCTOBER 2025

for a cosmic imbalance between matter and antimatter.

The CMS collaboration probed Higgs-boson interactions with electroweak bosons and gluons, using decays into two energetic photons. This final state is particularly precise: photons are well reconstructed thanks to the energy resolution of the CMS electromagnetic calorimeter and backgrounds can be accurately estimated. The analysis employed 138 fb^{-1} of proton–proton collision data at a centre-of-mass energy of 13 TeV and focused on two main channels. Electroweak production of the Higgs boson, via vector boson fusion (VBF) or in association with a W or Z boson (VH), tests the Higgs boson's couplings to electroweak gauge bosons. Gluon fusion, which occurs through loops dominated by the top quark, is sensitive to possible CP-violating interactions with fermions. A full angular analysis was performed to separate different coupling hypotheses, exploiting both the kinematic properties of the photons from the Higgs boson decay and the particles produced alongside it.

The matrix element likelihood approach (MELA) was used to minimise the number of observables, while retaining all essential information. Deep neural networks and boosted decision trees classified events based on their topology and kinematic properties, isolating signal-like events from background or alternative new-physics scenarios. Events were then grouped into analysis categories, each optimised to enhance sensitivity to anomalous couplings for a specific production mode.

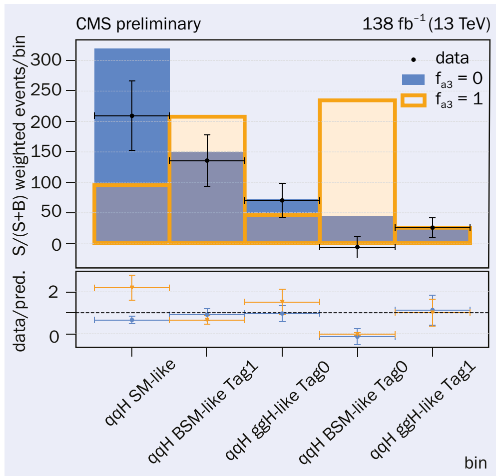


Fig. 1. *Distribution of events weighted by S/(S+B), using bins optimised for the VBF production mode. S denotes the resonant signal and B the non-resonant background. Event yields are shown in each bin within the Higgs-boson mass window, for both the Standard Model hypothesis (f_{a3} = 0, blue) and a pure CP-violating scenario (f_{a3} = 1, orange). The data points (black dots) indicate the observed events after background subtraction and include statistical uncertainties.*

The data favour the Standard Model configuration, with no significant deviation from its predictions (see figure 1). By placing some of the most stringent constraints yet on CP-violating interactions between the Higgs boson and vector bosons, the study highlights how precise measurements in simple final states can yield insights into the symmetries governing particle physics. With the upcoming data from Run 3 of the LHC and the High-Luminosity LHC, CMS is well positioned to push these limits further and potentially uncover hidden aspects of the Higgs sector.

Further reading

CMS Collab. 2025 CMS-PAS-HIG-24-006.

ALICE

Charming energy–energy correlators

Narrow sprays of particles called jets erupt from high-energy quarks and gluons. The ALICE collaboration has now measured so-called energy–energy correlators (EECs) of charm-quark jets for the first time – revealing new details of the elusive "dead cone" effect.

Unlike in quantum electrodynamics, the quantum chromodynamics (QCD) coupling constant gets weaker at higher energies – a feature known as asymptotic freedom. This allows high-energy partons to scatter and radiate additional partons, forming showers. As their energy splits between more and more products, decreasing toward the characteristic QCD confinement scale, interactions grow strong enough to bind partons within colour-neutral hadrons. The structure, energy profile and angular distribution of particles within the jets bear traces of the initial collision and the parton-to-hadron transitions, making them powerful probes of both perturbative and non-perturbative QCD effects. To understand the interplay between these two regimes, researchers track how jet properties vary with the mass and colour of the initiating partons.

Due to the gluon's larger colour charge, QCD predicts gluon-initiated jets to be broader and contain more low-momentum particles than those from quarks. Additionally, the significant mass of heavy quarks should suppress collinear gluon emission, inducing the so-called "dead-cone" effect at small angles. These expectations can be tested by comparing jet substructure across flavours. A key observable for this purpose is the EEC, which measures how energy is distributed within a jet as a function of the angular separation R_L between particle pairs. The large-R_L region is dominated by early partonic splittings, reflecting perturbative dynamics, while a small R_L value corresponds to later radiation shaped by final-state hadrons. The intermediate-R_L region captures the transition where hadronisation begins to affect the jet structure. This characteristic shape enables the separation of perturbative and non-perturbative regimes, revealing flavour-dependent dynamics of jet formation and hadronisation.

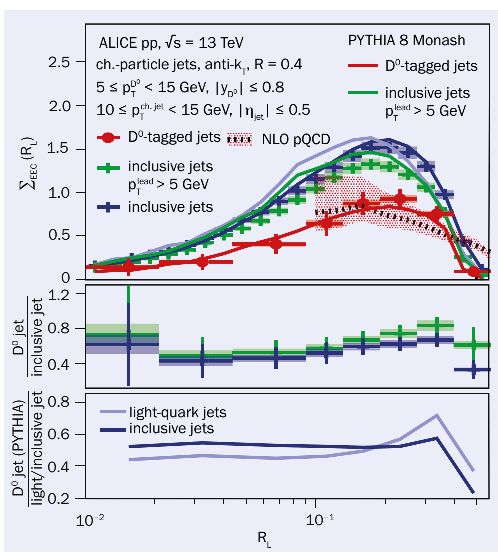


Fig. 1. *Energy–energy correlators (EECs) of D^0-tagged jets compared to inclusive jets, shown with (green) and without (blue) a leading-track p_T selection of 5 GeV. Data are compared to next-to-leading-order (NLO) pQCD calculations (dashed) and PYTHIA 8 simulations. The middle panel shows the data ratio of D^0-tagged to inclusive jets. The bottom panel displays the same ratio in PYTHIA 8, also including light-quark jets.*

The ALICE Collaboration measured the EEC for charm-quark jets tagged with D^0 mesons, reconstructed via the $D^0 \to K^- \pi^+$ decay mode (branching ratio 3.93 ± 0.04%), in proton–proton collisions at centre-of-mass energy 13 TeV. Jets are inferred from charged-particle tracks using the anti-k_T algorithm, clustering products in momentum space with a resolution parameter R = 0.4.

At low transverse momentum, where the effect of the charm-quark mass is most prominent, the EEC amplitude is found to be significantly suppressed for charm jets relative to inclusive jets initiated by light-quarks and gluons. The difference is more pronounced at small angles due to the dead-cone effect (see figure 1). Despite the sizable charm-quark mass, the distribution peak position remains similar across the two populations, pointing to a complex mix of parton flavour effects in the shower evolution and enhanced non-perturbative contributions such as hadronisation. Perturbative QCD calculations reproduce the general shape at large R_L but show tension near the peak, indicating the need for theoretical improvements for heavy-quark jets. The upward trend in the ratio of charm to inclusive jets as a function of R_L, reproduced with PYTHIA 8, suggests that they deviate in fragmentation.

This provides an essential vacuum baseline for future studies in heavy-ion collisions

This first measurement of the heavy-flavour jet EEC helps disentangle perturbative and non-perturbative QCD effects in jet formation, constraining theoretical models. Furthermore, it provides an essential vacuum baseline for future studies in heavy-ion collisions, where the quark–gluon plasma is expected to alter jet properties.

Further reading

ALICE Collab. 2025 arXiv:2504.03431.

ATLAS

Mapping rare Higgs-boson decays

Rare, unobserved decays of the Higgs boson are natural places to search for new physics. At the EPS-HEP conference, the ATLAS collaboration presented new improved measurements of two highly suppressed Higgs decays: into a pair of muons; and into a Z boson accompanied by a photon. Producing a single event of either $H \to \mu\mu$ or $H \to Z\gamma \to (ee/\mu\mu)\gamma$ at the LHC requires, on average, around 10 trillion proton–proton collisions. The $H \to \mu\mu$ and $H \to Z\gamma$ signals appear as narrow resonances in the dimuon and $Z\gamma$ invariant mass spectra, atop backgrounds some three orders of magnitude larger.

In the Standard Model, the Brout–Englert–Higgs mechanism gives mass to the muon through its Yukawa coupling to the Higgs field, which can be tested via the rare $H \to \mu\mu$ decay. An indirect comparison with the well-known muon mass, determined to 22 parts per billion, provides a stringent test of the mechanism in the second fermion generation and is a powerful probe of new physics. With a branching ratio of just 0.02%, and a large background dominated by the Drell–Yan production of muon pairs through virtual photons or Z bosons, the inclusive signal-over-background ratio plunges to the level of one part in a thousand. To single out its decay signature, the ATLAS collaboration employed machine-learning techniques for background suppression and generated over five billion Drell–Yan Monte Carlo events at next-to-leading-order accuracy in QCD, all passed through the full detector simulation. This high-precision sample provides templates to refine the background model and minimise bias on the tiny $H \to \mu\mu$ signal.

The Higgs boson can decay into a Z boson and a photon via loop diagrams involving W bosons and heavy charged fermions, like the top quark. Detecting this rare process would complete the suite of established decays into electroweak boson pairs and offer a window on physics beyond the Standard Model. To reduce QCD background and improve sensitivity, the ATLAS analysis focused on Z bosons further decaying into electron or muon pairs, with an overall branching fraction of 7%. This additional selection reduces the event rate to about one in 10,000 Higgs decays, with an inclusive signal-over-background ratio at the per-mille level. The low momenta of final-state particles, combined with the high-luminosity conditions of LHC Run 3, pose additional challenges for signal extraction and suppression of Z + jets backgrounds. To enhance signal significance, the ATLAS collaboration improved background modelling techniques, optimised event categorisation by Higgs production mode, and employed machine learning to boost sensitivity.

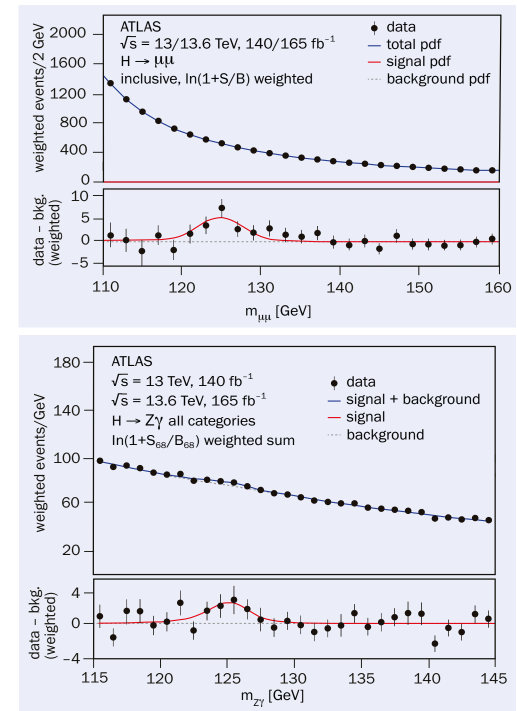


Fig. 1. *Combined Run 2 and Run 3 results for weighted dimuon (top) and Zγ (above) invariant mass spectra, summed over all event categories. The data are compared to the fitted probability density functions (PDFs) for background (dashed grey), signal (red) and their sum (blue). The fitted signal strengths are consistent with Standard Model expectations.*

The two ATLAS searches are based on 165 fb^{-1} of LHC Run 3 proton–proton collision data collected between 2022 and 2024 at $\sqrt{s}$ = 13.6 TeV, with a rigorous blinding procedure in place to prevent biases. Both channels show excesses at the Higgs-boson mass of 125.09 GeV, with observed (expected) 2.8σ (1.8σ) significance for H to μμ and 1.4σ (1.5σ) for H to Zγ. These results are strengthened by combining them with 140 fb^{-1} of Run-2 data collected at $\sqrt{s}$ = 13 TeV, updating the $H \to \mu\mu$ and $H \to Z\gamma$ observed (expected) significances to 3.4σ (2.5σ) and 2.5σ (1.9σ), respectively (see figure 1). The measured signal strengths are consistent with the Standard Model within uncertainties.

These results mark the ATLAS collaboration's first evidence for the $H \to \mu\mu$ decay, following the earlier claim by CMS based on Run-2 data (see *CERN Courier* September/October 2020 p7). Meanwhile, the $H \to Z\gamma$ search achieves a 19% increase in expected significance with respect to the combined ATLAS–CMS Run-2 analysis, which first reported evidence for this process. As Run 3 data-taking continues, the LHC experiments are closing in on establishing these two rare Higgs decay channels. Both will remain statistically limited throughout the LHC's lifetime, with ample room for discovery in the high-luminosity phase.

Further reading

ATLAS Collab. 2025 arXiv:2507.03595.
ATLAS Collab. 2025 arXiv:2507.12598.

CERNCOURIER
Volume 65 Number 5 September/October 2025

FIELD NOTES

Reports from events, conferences and meetings

EPS-HEP 2025

High-energy physics meets in Marseille

Centre stage at the Palais du Pharo *The European Physical Society Conference on High Energy Physics in Marseille showcased the remarkable creativity and innovation in both experiment and theory, driving progress across all scales of fundamental physics in this pivotal year for the HEP community.*

The 2025 European Physical Society Conference on High Energy Physics (EPS-HEP), held in Marseille from 7 to 11 July, took centre stage in this pivotal year for high-energy physics as the community prepares to make critical decisions on the next flagship collider at CERN to enable major leaps at the high-precision and high-energy frontiers. The meeting showcased the remarkable creativity and innovation in both experiment and theory, driving progress across all scales of fundamental physics. It also highlighted the growing interplay between particle, nuclear, astroparticle physics and cosmology.

Advancing the field relies on the ability to design, build and operate increasingly complex instruments that push technological boundaries. This requires sustained investment from funding agencies, laboratories, universities and the broader community to support careers and recognise leadership in detectors, software and computing. Such support must extend across construction, commissioning and operation, and include strategic and basic R&D. The implementation of detector R&D (DRD) collaborations, as outlined in the 2021 ECFA roadmap, is an important step in this direction.

Advancing the field relies on the ability to design, build and operate increasingly complex instruments that push technological boundaries

Physics thrives on precision, and a prime example this year came from the Muon g–2 collaboration at Fermilab, which released its final result combining all six data runs, achieving an impressive 127 parts-per-billion precision on the muon anomalous magnetic moment (*CERN Courier* July/August 2025 p7). The result agrees with the latest lattice-QCD predictions for the leading hadronic-vacuum-polarisation term, albeit within a four times larger theoretical uncertainty than the experimental one. Continued improvements to lattice QCD and to the traditional dispersion-relation method based on low-energy e^+e^- and τ data are expected in the coming years.

Runaway success

After the remarkable success of LHC Run 2, Run 3 has now surpassed it in delivered luminosity. Using the full available Run-2 and Run-3 datasets, ATLAS reported 3.4σ evidence for the rare Higgs decay to a muon pair, and a new result on the quantum-loop mediated decay into a Z boson and a photon, now more consistent with the Standard Model prediction than the earlier ATLAS and CMS Run-2 combination (see p15). ATLAS also presented an updated study of Higgs pair production with decays into two b-quarks and two photons, whose sensitivity was increased beyond statistical gains thanks to improved reconstruction and analysis. CMS released a new Run-2 search for Higgs decays to charm quarks in events produced with a top-quark pair, reaching sensitivity comparable to the traditional weak-boson-associated production. Both collaborations also released new combinations of nearly all their Higgs analyses from Run 2, providing a wide set of measurements. While ATLAS sees overall agreement with predictions, CMS observes some non-significant tensions.

A highlight in top-quark physics this year was the observation by CMS of an excess in top-pair production near threshold, confirmed at the conference by ATLAS (see p9). The physics of the strong interaction predicts highly compact, colour-singlet, quasi-bound pseudoscalar top–antitop state effects arising from gluon exchange. Unlike bottomonium or charmonium, no proper bound state is formed due to the rapid weak decay of the top quark (see p35). This "toponium" effect can be modelled with the use of non-relativistic QCD. Both experiments observed a cross section about 100 times smaller than for inclusive top-quark pair production. The subtle signal and complex threshold modelling make the analysis challenging, and warrant further theoretical and experimental investigation.

A major outcome of LHC Run 2 is the lack of compelling evidence for physics beyond the Standard Model. In Run 3, ATLAS and CMS continue their searches, aided by improved triggers, reconstruction and analysis techniques, as well as a dataset more than twice as large, enabling a more sensitive exploration of rare or ▷

suppressed signals. The experiments are also revisiting excesses seen in Run 2, for example, a CMS hint of a new resonance decaying into a Higgs and another scalar was not confirmed by a new ATLAS analysis including Run-3 data.

Hadron spectroscopy has seen a renaissance since Belle's 2003 discovery of the exotic X(3872), with landmark advances at the LHC, particularly by LHCb. CMS recently reported three new four-charm-quark states decaying into J/ψ pairs between 6.6 and 7.1 GeV. Spin-parity analysis suggests they are tightly bound tetraquarks rather than loosely bound molecular states (*CERN Courier* November/December 2024 p33).

Rare observations

Flavour physics continues to test the Standard Model with high sensitivity. Belle-II and LHCb reported new CP violation measurements in the charm sector, confirming the expected small effects. LHCb observed, for the first time, CP violation in the baryon sector via Λ_b decays, a milestone in CP violation history. NA62 at CERN's SPS achieved the first observation of the ultra-rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ with a branching ratio of 1.3×10^{-10}, matching the Standard Model prediction. MEG-II at PSI set the most stringent limit to date on the lepton-flavour-violating decay $\mu \to e\gamma$, excluding branching fractions above 1.5×10^{-13}. Both experiments continue data taking until 2026.

Heavy-ion collisions at the LHC provide a rich environment to study the quark–gluon plasma, a hot, dense state of deconfined quarks and gluons, forming a collective medium that flows as a relativistic fluid with an exceptionally low viscosity-to-entropy ratio. Flow in lead–lead collisions, quantified by Fourier harmonics of spatial momentum anisotropies, is well described by hydrodynamic models for light hadrons. Hadrons containing heavier charm and bottom quarks show weaker collectivity, likely due to longer thermalisation times, while baryons exhibit stronger flow than mesons due to quark coalescence. ALICE reported the first LHC measurement of charm–baryon flow, consistent with these effects.

Neutrino physics has made major strides since oscillations were confirmed 27 years ago, with flavour mixing parameters now known to a few percent. Crucial questions still remain: are neutrinos their own antiparticles (Majorana fermions)? What is the mass ordering – normal or inverted? What is the absolute mass scale and how is it generated? Does CP violation occur? What are the properties of the right-handed neutrinos? These and other

Spin-parity analysis suggests the states are tightly bound tetraquarks

questions have wide-ranging implications for particle physics, astrophysics and cosmology.

Neutrinoless double-beta decay, if observed, would confirm that neutrinos are Majorana particles. Experiments using xenon and germanium are beginning to constrain the inverted mass ordering, which predicts higher decay rates. Recent combined data from the long-baseline experiments T2K and NOvA show no clear preference for either ordering, but exclude vanishing CP violation at over 3σ in the inverted scenario. The KM3NeT detector in the Mediterranean, with its ORCA and ARCA components, has delivered its first competitive oscillation results, and detected a striking ~220 PeV muon neutrino, possibly from a blazar (*CERN Courier* March/April 2025 p7). The next-generation large-scale neutrino experiments JUNO (China), Hyper-Kamiokande (Japan) and LBNF/DUNE (USA) are progressing in construction, with data-taking expected to begin in 2025, 2028 and 2031, respectively. LBNF/DUNE is best positioned to determine the neutrino mass ordering, while Hyper-Kamiokande will be the most sensitive to CP violation. All three will also search for proton decay, a possible messenger of grand unification.

There is compelling evidence for dark matter from gravitational effects across cosmic times and scales, as well as indications that it is of particle origin. Its possible forms span a vast mass range, up to the ~100 TeV unitarity limit for a thermal relic, and may involve a complex, structured "dark sector". The wide complementarity among the search strategies gives the field a unifying character. Direct detection experiments looking for tiny, elastic nuclear recoils, such as XENONnT (Italy), LZ (USA) and PandaX-4T (China), have set world-leading constraints on weakly interacting massive particles. XENONnT and PandaX-4T have also reported first signals from boron-8 solar neutrinos, part of the so-called "neutrino fog" that will challenge future searches. Axions, introduced theoretically to suppress CP violation in strong interactions, could be viable dark-matter candidates. They would be produced in the early universe with enormous number density, behaving, on galactic scales, as a classical, nonrelativistic, coherently oscillating bosonic field, effectively equivalent to cold dark matter. Axions can be detected via their conversion into photons in strong magnetic fields. Experiments using microwave cavities have begun to probe the relevant μeV mass range of relic QCD axions, but the detection becomes harder at higher masses. New concepts, using dielectric disks or wire-based plasmonic resonance, are under development to overcome these challenges.

Cosmological constraints

Cosmology featured prominently at EPS-HEP, driven by new results from the analysis of DESI DR2 baryon acoustic oscillation (BAO) data, which include 14 million redshifts. Like the cosmic microwave background (CMB), BAO also provides a "standard ruler" to trace the universe's expansion history – much like supernovae (SNe) do as standard candles. Cosmological surveys are typically interpreted within the ΛCDM model, a six-parameter framework that remarkably accounts for 13.8 billion years of cosmic evolution, from inflation and structure formation to today's energy content, despite offering no insight into the nature of dark matter, dark energy or the inflationary mechanism. Recent BAO data, when combined with CMB and SNe surveys, show a preference for a form of dark energy that weakens over time. Tensions also persist in the Hubble expansion rate derived from early-universe (CMB and BAO) and late-universe (SN type-Ia) measurements (*CERN Courier* March/April 2025 p28). However, anchoring SN Ia distances in redshift remains challenging, and further work is needed before drawing firm conclusions.

Cosmological fits also constrain the sum of neutrino masses. The latest CMB and BAO-based results within ΛCDM appear inconsistent with the lower limit implied by oscillation data for inverted mass ordering. However, firm conclusions are premature, as the result may reflect limitations in ΛCDM itself. Upcoming surveys from the Euclid satellite and the Vera C. Rubin Observatory (LSST) are expected to significantly improve cosmological constraints.

Cristinel Diaconu and Thomas Strebler, chairs of the local organising committee, together with all committee members and many volunteers, succeeded in delivering a flawlessly organised and engaging conference in the beautiful setting of the Palais du Pharo overlooking Marseille's old port. They closed the event with a memorial phrase of British cyclist Tom Simpson: "There is no mountain too high."

Andreas Hoecker *CERN.*

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FIELD NOTES

INTERNATIONAL COSMIC RAY CONFERENCE 2025

Geneva witnesses astroparticle boom

ICRC 2025

Booming field *The 2025 ICRC conference looked at how constraints on astroparticle physics have multiplied quickly in recent years.*

The 39th edition of the International Cosmic Ray Conference (ICRC), a key biennial conference in astroparticle physics, was held in Geneva from 15 to 24 July. Plenary talks covered solar, galactic and ultra-high-energy cosmic rays. A strong multi-messenger perspective combined measurements of charged particles, neutrinos, gamma rays and gravitational waves. Talks were informed by limits from the LHC and elsewhere on dark-matter particles and primordial black-holes. The bundle of constraints has improved very significantly over the past few years, allowing more meaningful and stringent tests.

Solar modelling

The Sun and its heliosphere, where the solar wind offers insights into magnetic reconnection, shock acceleration and diffusion, are now studied *in situ* thanks to the Solar Orbiter and Parker Solar Probe spacecraft. Long-term PAMELA and AMS data, spanning over an 11-year solar cycle, allow precise modelling of solar modulation of cosmic-ray fluxes below a few tens of GeV. AMS solar proton data show a 27-day periodicity up to 20 GV, caused by corotating interaction regions where fast solar wind overtakes slower wind, creating shocks. AMS has recorded 46 solar energetic particle (SEP) events, the most extreme reaching a few GV, from magnetic-reconnection flares or fast coronal mass ejections. While isotope data once suggested such extreme events occur every 1500 years, Kepler observations of Sun-like stars indicate they may happen every 100 years, releasing more than 10^{34} erg, often during weak solar minima, and linked to intense X-ray flares.

The spectrum of galactic cosmic rays, studied with high-precision measurements from satellites (DAMPE) and ISS-based experiments (AMS-02, CALET, ISS-CREAM), is not a single power law but shows breaks and slope changes, signatures of diffusion or source effects. A hardening at about 500 GV, common to all primaries, and a softening at 10 TV, are observed in protons and He spectra by all experiments – and for the first time also in DAMPE's O and C. As the hardening is detected in primary spectra scaling at the same rigidity (charge, not mass) as in secondary-to-primary ratios, they are attributed to propagation in the galaxy and not to source-related effects. This is supported by secondary (Li, Be, B) spectra with breaks about twice as strong as primaries (He, C, O). A second hardening at 150 TV was reported by ISS-CREAM (p) and DAMPE (p + He) for the first time, broadly consistent – within large hadronic-model and statistical uncertainties – with indirect ground-based results from GRAPES and LHAASO.

Ratios of secondary over primary species versus rigidity R (energy per unit charge) probe the ratio of the galactic halo size H to the energy-dependent diffusion coefficient D(R), and so measure the "grammage" of material through which cosmic rays propagate. Unstable/stable secondary isotope ratios probe the escape times of cosmic rays from the halo (H^2/D(R)), so from both measurements H and D(R) can be derived. The flattening evidenced by the highest energy point at 10 to 12 GeV/nucleon of the ^{10}Be/^{9}Be ratio as a function of energy, hints at a possibly larger halo than previously believed beyond 5 kpc, to be tested by HELIX. AMS-02 spectra of single elements will soon allow separation of the primary and secondary fractions for each nucleus, also based on spallation cross-sections. Anomalies remain, such as a flattening at ~7 TeV/nucleon in Li/C and B/C, possibly indicating reacceleration or source grammage. AMS-02's ^{7}Li/^{6}Li ratio disagrees with pure secondary models, but cross-section uncertainties preclude firm conclusions on a possible Li primary component, which would be produced by a new population of sources.

A strong multi-messenger perspective combined measurements of charged particles, neutrinos, gamma rays and gravitational waves

The muon puzzle

The dependency of ground-based cosmic-ray measurements on hadronic models has been widely discussed by Boyd and Pierog, highlighting the need for more measurements at CERN, such as the recent proton–O run being analysed by LHCf. The EPOS–LHC model, based on the core–corona approach, shows reduced muon discrepancies, producing more muons and a heavier composition, namely deeper shower maxima (+20 g/cm²) than earlier models. This clarifies the muon puzzle raised by Pierre Auger a few years ago of a larger muon content in atmospheric showers than simulations. A fork-like structure remains in the knee region of the proton spectrum, where the new measurements presented by LHAASO are in agreement with IceTop/IceCube, and could lead ▷

to a higher content of protons beyond the knee than hinted at by KASCADE and the first results of GRAPES. Despite the higher proton fluxes, a dominance of He above the knee is observed, which requires a special kind of close-by source to be hypothesised.

Multi-messenger approaches

Gamma-ray and neutrino astrophysics were widely discussed at the conference, highlighting the relevance of multi-messenger approaches. LHAASO produced impressive results on UHE astrophysics, revealing a new class of pevatrons: microquasars alongside young massive clusters, pulsar wind nebulae (PWNe) and supernova remnants.

Microquasars are gamma-ray binaries containing a stellar-mass black hole that drives relativistic jets while accreting matter from their companion stars. Outstanding examples include Cyg X-3, a potential PeV microquasar, from which the flux of PeV photons is 5–10 times higher than in the rest of the Cygnus bubble.

Five other microquasars are observed beyond 100 TeV: SS 433, V4641 Sgr, GRS 1915 + 105, MAXI J1820 + 070 and Cygnus X-1. SS 433 is a microquasar with two gamma-ray emitting jets nearly perpendicular to our line of sight, terminated at 40 pc from the black hole (BH) identified by HESS and LHAASO beyond 10 TeV. Due to the Klein–Nishina effect, the inverse Compton flux above ~10 TeV is gradually suppressed, and an additional spectral component is needed to explain the flux around 100 TeV.

Gamma-ray and neutrino astrophysics were widely discussed at the conference

Beyond 100 TeV, LHAASO also identifies a source coincident with a giant molecular cloud; this component may be due to protons accelerated close to the BH or in the lobes. These results demonstrate the ability to resolve the morphology of extended galactic sources. Similarly, ALMA has discovered two hotspots, both at 0.28° (about 50 pc) from GRS 1915 + 105 in opposite directions from its BH. These may be interpreted as two lobes, or the extended nature of the LHAASO source may instead be due to the spatial distribution of the surrounding gas, if the emission from GRS 1915 + 105 is dominated by hadronic processes.

Further discussions addressed pulsar halos and PWNe as unique laboratories for studying the diffusion of electrons and mysterious as-yet-unidentified pevatrons, such as MGRO J1908 + 06, coincident with a SNR (favoured) and a PSR. One of these sources may finally reveal an excess in KM3NeT or IceCube neutrinos, proving their cosmic-ray accelerator nature directly.

The identification and subtraction of source fluxes on the galactic plane is also important for the measurement of the galactic plane neutrino flux by IceCube. This currently assumes a fixed spectral index of $E^{-2.7}$, while authors like Grasso *et al.* presented a spectrum becoming as soft as $E^{-2.4}$, closer to the galactic centre. The precise measurements of gamma-ray source fluxes and the diffuse emission from galactic cosmic rays interacting in the interstellar matter lead to better constraints on neutrino observations and on cosmic ray fluxes around the knee.

Cosmogenic origins

KM3NeT presented a neutrino of energy well beyond the diffuse cosmic neutrino flux of IceCube, which does not extend beyond 10 PeV (*CERN Courier* March/April 2025 p7). Its origin was widely discussed at the conference. The large error on its estimated energy – 220 PeV, within a 1σ confidence interval of 110 to 790 PeV – makes it nevertheless compatible with the flux observed by IceCube, for which a 30 TeV break was first hypothesised at this conference. If events of this kind are confirmed, they could have transient or dark-matter origins, but a cosmogenic origin is improbable due to the IceCube and Pierre Auger limits on the cosmogenic neutrino flux.

Teresa Montaruli *and* **Roland Walter** *University of Geneva.*

QUANTUM GRAVITY 2025

Quantum gravity beyond frameworks

Reconciling general relativity and quantum mechanics remains a central problem in fundamental physics. Though successful in their own domains, the two theories resist unification and offer incompatible views of space, time and matter. The field of quantum gravity, which has sought to resolve this tension for nearly a century, is still plagued by conceptual challenges, limited experimental guidance and a crowded landscape of competing approaches. Now in its third instalment, the "Quantum Gravity" conference series addresses this fragmentation by promoting open dialogue across communities. Organised under the auspices of the International Society for Quantum Gravity (ISQG), the 2025 edition took place from 21 to 25 July at Penn State University. The event gathered researchers working across a variety of frameworks – from random geometry and loop quantum gravity to string theory, holography and quantum information. At its core was the recognition that, regardless of specific research lines or affiliations, what matters is solving the puzzle.

G E Gorelik

Foundational work *During the 1930s, Matvej Bronštejn conducted the first in-depth study of quantum gravity, exposing its difference from quantum electrodynamics.*

One step to get there requires understanding the origin of dark energy, which drives the accelerated expansion of the universe and is typically modelled by a cosmological constant Λ. Yasaman K Yazdi (Dublin Institute for Advanced Studies) presented a case for causal set theory, reducing spacetime to a discrete collection of events, partially ordered to capture cause–effect relationships. In this context, like a quantum particle's position and momentum, the cosmological constant and the spacetime volume are conjugate variables. This leads to the so-called "ever-present Λ" models, where fluctuations in the former scale as the inverse square root of the latter, decreasing over time but never vanishing. The intriguing agreement between the predicted size of these fluctuations and the observed amount of dark energy, while far from resolving quantum cosmology, stands as a compelling motivation for pursuing the approach.

In the spirit of John Wheeler's "it from bit" proposal, Jakub Mielczarek (Jagiellonian University) suggested that our universe may itself evolve by computing – or at least admit a description in terms of quantum information processing. In loop quantum gravity, space is built from granular graphs known as spin networks, which capture the quantum properties of geometry. Drawing on ideas from tensor networks and holography, Mielczarek proposed that these structures can be reinterpreted as quantum circuits, with their combinatorial patterns reflected in the logic of algorithms. This dictionary offers a natural route to simulating quantum geometry, and could help clarify quantum theories that, like general relativity, do not rely on a fixed background.

Once the domain of pure theory, quantum gravity has become eager to engage with experiment

Quantum clues

What would a genuine quantum theory of spacetime achieve, though? According to Esteban Castro Ruiz (IQOQI), it may have to recognise that reference frames, which are idealised physical systems used to define spatio-temporal distances, must themselves be treated as quantum objects. In the framework of quantum reference frames, notions such as entanglement, localisation and superposition become observer-dependent. This leads to a perspective-neutral formulation of quantum mechanics, which may offer clues for describing physics when spacetime is not only dynamical, but quantum.

The conference's inclusive vocation came through most clearly in the thematic discussion sessions, including one on the infamous black-hole information problem chaired by Steve Giddings (UC Santa Barbara). A straightforward reading of Stephen Hawking's 1974 result suggests that black holes radiate, shrink and ultimately destroy information – a process that is incompatible with standard quantum mechanics. Any proposed resolution must face sharp trade-offs: allowing information to escape challenges locality, losing it breaks unitarity and storing it in long-lived remnants undermines theoretical control. Giddings described a mild violation of locality as the lesser evil, but the controversy is far from settled. Still, there is growing consensus that dissolving the paradox may require new physics to appear well before the Planck scale, where quantum-gravity effects are expected to dominate.

Among the few points of near-universal agreement in the quantum-gravity community has long been the virtual impossibility of detecting a graviton, the hypothetical quantum of the gravitational field. According to Igor Pikovski (Stockholm University), things may be less bleak than once thought. While the probability of seeing graviton-induced atomic transitions is negligible due to the weakness of gravity, the situation is different for massive systems. By cooling a macroscopic object close to absolute zero, Pikovski suggested, the effect could be amplified enough, with current interferometers simultaneously monitoring gravitational waves in the correct frequency window. Such a signal would not amount to a definitive proof of gravity's quantisation, just as the photoelectric effect could not definitely establish the existence of photons, nor would it single out a specific ultraviolet model. However, it could constrain concrete predictions and put semiclassical theories under pressure. Giulia Gubitosi (University of Naples Federico II) tackled phenomenology from a different angle, exploring possible deviations from special relativity in models where spacetime becomes non-commutative. There, coordinates are treated like quantum operators, leading to effects like decoherence, modified particle speeds and soft departures from locality. Although such signals tend to be faint, they could be enhanced by high-energy astrophysical sources: observations of neutrinos corresponding to gamma-ray bursts are now starting to close in on these scenarios. Both talks reflected a broader, cultural shift: quantum gravity, once the domain of pure theory, has become eager to engage with experiment.

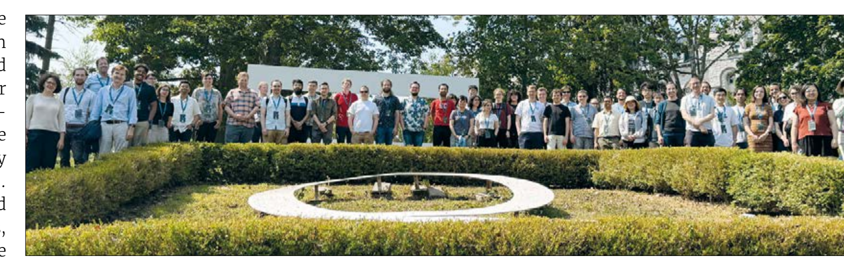
Quantum Gravity 2025 offered a wide snapshot of a field still far from closure, yet increasingly shaped by common goals, the convergence of approaches and cross-pollination. As intended, no single framework took centre stage, with a dialogue-based format keeping focus on the central, pressing issue at hand: understanding the quantum nature of spacetime. With limited experimental guidance, open exchange remains key to clarifying assumptions and avoiding duplication of efforts. Building on previous editions, the meeting pointed toward a future where quantum-gravity researchers will recognise themselves as part of a single, coherent scientific community.

Davide De Biasio *associate editor.*

DARK MATTER AND STARS 2025

Probing the dark side from Kingston

The nature of dark matter remains one of the greatest unresolved questions in modern physics. While ground-based experiments persist in their quest for direct detection, astrophysical observations and multi-messenger studies have emerged as powerful complementary tools for constraining its properties. Stars across the Milky Way and beyond – including neutron stars, white dwarfs, red giants and main-sequence stars – are increasingly recognised as natural laboratories for probing dark matter through its interactions with stellar interiors, notably via neutron-star cooling, asteroseismic diagnostics of solar oscillations and gravitational-wave emission.



ICDMS 2025

Multi-messenger probes *ICDMS 2025 took place in Kingston, Ontario in July.*

The international conference Dark Matter and Stars: Multi-Messenger Probes of Dark Matter and Modified Gravity (ICDMS) was held at Queen's University in Kingston, Ontario, Canada, from 14 to 16 July. The meeting brought together around 70 researchers from across astrophysics, cosmology, particle physics and gravitational theory. The goal was to foster interdisciplinary dialogue on how observations of stellar systems, gravitational waves and cosmological data can help shed light on the dark ▷

CERNCOURIER
VOLUME 65 NUMBER 5 SEPTEMBER/OCTOBER 2025

sector. The conference was specifically dedicated to exploring how astrophysical and cosmological systems can be used to probe the nature of dark matter.

The first day centred on compact objects as natural laboratories for dark-matter physics. Giorgio Busoni (University of Adelaide) opened with a comprehensive overview of recent theoretical progress on dark-matter accumulation in neutron stars and white dwarfs, highlighting refinements in the treatment of relativistic effects, optical depth, Fermi degeneracy and light mediators – all of which have shaped the field in recent years. Melissa Diamond (Queen's University) followed with a striking talk with a nod to *Dr. Strangelove*, exploring how accumulated dark matter might trigger thermonuclear instability in white dwarfs. Sandra Robles (Fermilab) shifted the perspective from neutron stars to white dwarfs, showing how they constrain dark-matter properties. One of the authors highlighted post-merger gravitational-wave observations as a tool to distinguish neutron stars from low-mass black holes, offering a promising avenue for probing exotic remnants potentially linked to dark matter. Axions featured prominently throughout the day, alongside extensive discussions of the different ways in which dark matter affects neutron stars and their mergers.

ICDMS continues to strengthen the interface between fundamental physics and astrophysical observations

On the second day, attention turned to the broader stellar population and planetary systems as indirect detectors. Isabelle John (University of Turin) questioned whether the anomalously long lifetimes of stars near the galactic centre might be explained by dark-matter accumulation. Other talks revisited stellar systems – white dwarfs, red giants and even speculative dark stars – with a focus on modelling dark-matter transport and its effects on stellar heat flow. Complementary detection strategies also took the stage, including neutrino emission, stochastic gravitational waves and gravitational lensing, all offering potential access to otherwise elusive energy scales and interaction strengths.

The final day shifted toward galactic structure and the increasingly close interplay between theory and observation. Lina Necib (MIT) shared stellar kinematics data used to map the Milky Way's dark-matter distribution, while other speakers examined the reliability of stellar stream analyses and subtle anomalies in galactic rotation curves. The connection to terrestrial experiments grew stronger, with talks tying dark matter to underground detectors, atomic-precision tools and cosmological observables such as the Lyman-alpha forest and baryon acoustic oscillations. Early-career researchers contributed actively across all sessions, underscoring the field's growing vitality and introducing a fresh influx of ideas that is expanding its scope.

The ICDMS series is now in its third edition. It began in 2018 at Instituto Superior Técnico, Portugal, and is poised to become an annual event. The next conference will take place at the University of Southampton, UK, in 2026, followed by the Massachusetts Institute of Technology in the US in 2027. With increasing participation and growing international interest, the ICDMS series continues to strengthen the interface between fundamental physics and astrophysical observations in the quest to understand the nature of dark matter.

Basudeb Dasgupta *Tata Institute of Fundamental Research, Mumbai,* **Ilídio Lopes** *Center for Astrophysics and Gravitation, Instituto Superior Técnico, Lisbon and* **Violetta Sagun** *University of Southampton.*

LOOPSUMMIT-2

Loopsummit returns to Cadenabbia

Measurements at high-energy colliders such as the LHC, the Electron–Ion Collider (EIC) and the FCC will be performed at the highest luminosities. The analysis of the high-precision data taken there will require a significant increase in the accuracy of theoretical predictions. To achieve this, new mathematical and algorithmic technologies are needed. Developments in precision Standard Model calculations have been rapid since experts last met for Loopsummit-1 at Cadenabbia on the banks of Lake Como in 2021 (*CERN Courier* November/December 2021 p24). Loopsummit-2, held in the same location from 20 to 25 July this year, summarised this formidable body of work.

Scaling up *The participants of Loopsummit-2 meet at Lake Como.*

As higher experimental precision relies on new technologies, new theory results require better algorithms, both from the mathematical and computer-algebraic side, and new techniques in quantum field theory. The central software package for perturbative calculations, FORM, now has a new major release, FORM 5. Progress has also been achieved in integration-by-parts reduction, which is of central importance for reducing to a much smaller set of master integrals. New developments were also reported in analytic and numerical Feynman-diagram integration using Mellin–Barnes techniques, new compact function classes such as Feynman–Fox integrals, and modern summation technologies and methods to establish and solve gigantic recursions and differential equations of degree 4000 and order 100. The latest results on elliptic integrals and progress on the correct treatment of the γ_5-problem in real dimensions were also presented. These technologies ▷ allow the calculation of processes up to five loops and in the presence of more scales at two- and three-loop order. New results for single-scale quantities like quark condensates and the ρ-parameter were also reported.

In the loop

Measurements at future colliders will depend on the precise knowledge of parton distribution functions, the strong coupling constant $\alpha_s(M_Z)$ and the heavy-quark masses. Experience suggests that going from one loop order to the next in the massless and massive cases takes 15 years or more, as new technologies must be developed. By now, most of the space-like four-loop splitting functions governing scaling violations are known with a good precision, as well as new results for the three-loop time-like splitting functions. The massive three-loop Wilson coefficients for deep-inelastic scattering are now complete, requiring far larger and different integral spaces compared with the massless case. Related to this are the Wilson coefficients of semi-inclusive deep-inelastic scattering at next-to-next-to leading order (NNLO), which will be important to tag individual flavours at the EIC. For the $\alpha_s(M_Z)$ measurement at low-scale processes, the correct treatment of renormalon contributions is necessary. Collisions at high energies also allow the detailed study of scattering processes in the forward region of QCD. Other long-term projects concern NNLO corrections for jet-production at e^+e^- and hadron colliders, and other related processes like Higgs-boson and top-quark production, in some cases with a large number of partons in the final state. This also includes the use of effective Lagrangians.

Many more steps lie ahead if we are to match the precision of measurements at high-luminosity colliders

The complete calculation of difficult processes at NNLO and beyond always drives the development of term-reduction algorithms and analytic or numerical integration technologies. Many more steps lie ahead in the coming years if we are to match the precision of measurements at high-luminosity colliders. Some of these will doubtless be reported at Loopsummit-3 in summer 2027.

Johannes Blümlein *and* **Peter Marquard** *DESY.*

UPCs 2025

Ultra-peripheral physics in the ultraperiphery

In June 2025, physicists met at Saariselkä, Finland to discuss recent progress in the field of ultra-peripheral collisions (UPCs). All the major LHC experiments measure UPCs – events where two colliding nuclei miss each other, but nevertheless interact via the mediation of photons that can propagate long distances. In a case of life imitating science, almost 100 delegates propagated to a distant location in one of the most popular hiking destinations in northern Lapland to experience 24-hour daylight and discuss UPCs in Finnish saunas.

In the ultraperiphery *Almost 100 physicists travelled to Saariselkä to discuss UPCs amidst the peacefully coexisting reindeer.*

UPC studies have expanded significantly since the first UPC workshop in Mexico in December 2023. The opportunity to study scattering processes in a clean photon–nucleus environment at collider energies has inspired experimentalists to examine both inclusive and exclusive scattering processes, and to look for signals of collectivity and even the formation of quark–gluon plasma (QGP) in this unique environment.

For many years, experimental activity in UPCs was mainly focused on exclusive processes and QED phenomena including photon–photon scattering. This year, fresh inclusive particle-production measurements gained significant attention, as well as various signatures of QGP-like behaviour observed by different experiments at RHIC and at the LHC. The importance of having complementing experiments to perform similar measurements was also highlighted. In particular, the ATLAS experiment joined the ongoing activities to measure exclusive vector-meson photoproduction, finding a cross section that disagrees with the previous ALICE measurements by almost 50%. After long and detailed discussions, it was agreed that different experimental groups need to work together closely to resolve this tension before the next UPC workshop.

Experimental and theoretical developments very effectively guide each other in the field of UPCs. This includes physics within and beyond the Standard Model (BSM), such as nuclear modifications to the partonic structure of protons and neutrons, gluon-saturation phenomena predicted by QCD (*CERN Courier* January/February 2025 p31), and precision tests for BSM physics in photon–photon collisions. The expanding activity in the field of UPCs, together with the construction of the Electron Ion Collider (EIC) at Brookhaven National Laboratory in the US, has also made it crucial to develop modern Monte Carlo event generators to the level where they can accurately describe various aspects of photon–photon and photon–nucleus scatterings.

As a photon collider, the LHC complements the EIC. While the centre-of-mass energy at the EIC will be lower, there is some overlap between the kinematic regions probed by these two very different collider projects thanks to the varying energy spectra of the photons. This allows the theoretical models needed for the EIC to be tested against UPC data, thereby reducing theoretical uncertainty on the predictions that guide the detector designs. This complementarity will enable precision studies of QCD phenomena and BSM physics in the 2030s.

Ilkka Helenius *and* **Heikki Mäntysaari** *University of Jyväskylä.*

EUROPE'S COLLIDER STRATEGY TAKES SHAPE

How are community inputs and debates shaping the ongoing update to the European strategy for particle physics? The *Courier* consults two scientists tasked with representing CERN Member States and the high-energy-physics community.

A community-driven process is building consensus

CERN Council president **Costas Fountas** sums up the vision of CERN's Member States.

In March 2024, the CERN Council called on the particle-physics community to develop a visionary and concrete plan that greatly advances human knowledge in fundamental physics through the realisation of the next flagship project at CERN. This community-driven strategy will be submitted to the CERN Council in March 2026, leading to discussions among CERN Member States. The CERN Council will update the European strategy for particle physics (ESPP) based on these deliberations, with a view to approving CERN's next flagship collider in 2028.

This third update to the ESPP builds on a process initiated by the CERN Council in 2006 and updated in 2013 and 2020. It is designed to convey to the CERN Council the views of the community on strategic questions that are key to the future of high-energy physics (HEP). The process involves all CERN Member States and Associate Member States, with the goal of developing a roadmap for the field for many years to come. The CERN Council asked that the newly updated ESPP should take into account the status of implementation of the 2020 ESPP, recent accomplishments at the LHC and elsewhere, progress in the construction of the High-Luminosity LHC (HL-LHC), the outcome of the Future Circular Collider (FCC) Feasibility Study, recent technological developments in accelerator, detector and computing technology, and the international landscape of the field. Scientific inputs were requested from across the community.

On behalf of the CERN Council, I would like to thank the high-energy community for understanding that this is a critical time for our field and participating very actively. Throughout this time, the various national groups have held a large number of meetings to debate which would be the best accelerator to be hosted at CERN after the HL-LHC. They also discussed and proposed alternative options as requested by the CERN Council, which followed the process closely.

By June 2025 we were delighted to hear from the ESPP secretariat that the participation of the community had been overwhelming and that a very large number of proposals had been submitted (*CERN Courier* May/June 2025 p8). These submissions show a broad consensus that CERN should be maintained as the global centre for collider physics through the realisation of a new flagship project. Europe's strategy

M Brice, CERN

Costas Fountas *has served as president of the CERN Council since his appointment in January this year, and as the Greek scientific delegate to the Council since 2016. A professor of physics at the University of Ioannina and longstanding member of the CMS collaboration, he previously served as vice-president of the Council from 2022 to 2024.*

should be ambitious, innovative and forward looking. An overwhelming majority of the communities from CERN Member States express their strong support for the FCC programme, starting with an electron–positron collider (FCC-ee) as a first stage. Their strong support is largely based on its superb physics potential and its long-term prospects, given the potential to explore the energy frontier with a hadron collider (FCC-hh) following a precision era at FCC-ee.

This strategy coherently develops the vision of ESPP 2020, which recommended to the CERN Council that an electron–positron Higgs factory be the highest-priority next collider. The 2020 ESPP update further recommended that Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron–positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next strategy update.

Based on ESPP 2020, the CERN Council mandated the CERN management to undertake a feasibility study for the FCC and approved an initial budget of CHF 100 million over a five-year period. Throughout the past five years, the FCC

On behalf of the CERN Council, I would like to thank the high-energy community for understanding that this is a critical time for our field and participating very actively

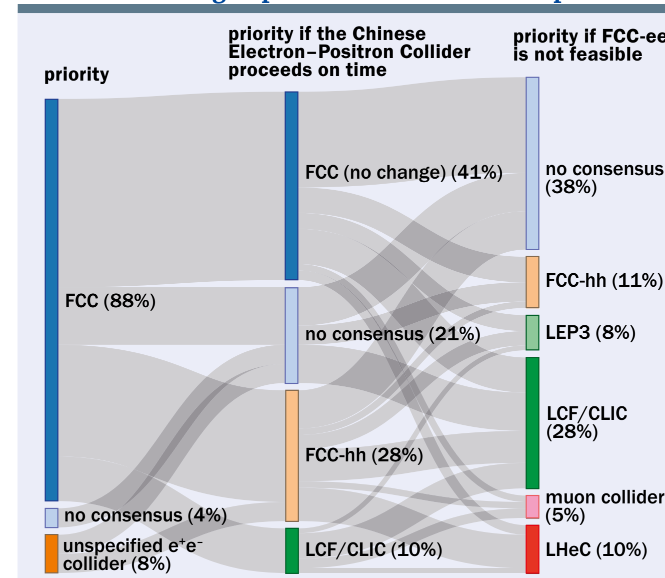
feasibility study was undertaken by CERN management under the oversight of the CERN Council. Council heard presentations on its progress at every session and carefully scrutinised a very successful mid-term review (*CERN Courier* March/April 2024 p25). The FCC collaboration completed the FCC feasibility study ahead of schedule and summarised the results of the study in a three-volume report that was released in March 2025 (*CERN Courier* May/June 2025 p8). The results are currently under review by panels which will scrutinise both the scientific aspects of the project as well as its budget estimates. The project will be presented to the Scientific Policy and Finance committees in September 2025 and to the CERN Council in November 2025.

It is rewarding to see that the scientific opinion of the community is in sync with ESPP 2020, the decision of the CERN Council to initiate the FCC feasibility study, and the efforts of CERN management to steer and complete it. This is a sign of the strength of the HEP community. While respecting a healthy diversity of opinion, a clear consensus has emerged across the community that the FCC is the highest priority project.

Crucially, however, the CERN Council requested that the community provide not only the scientifically most attractive option, but also hierarchically ordered alternative options. Specifically, the Council requested that the strategy update should include the preferred option for the next collider at CERN and prioritised alternative options to be pursued if the chosen preferred plan turns out not to be feasible or competitive. No consensus has yet been reached here, however two projects have the required readiness to be candidates for alternative programmes: the Linear Collider Facility (LCF, 250 GeV) and the Compact Linear Collider (CLIC, 380 GeV), with additional R&D required in the latter case. A third proposal, LEP3, also requires further study, but could be a promising candidate for a Higgs factory in the existing LEP/LHC tunnel, albeit at a significantly reduced luminosity relative to FCC-ee.

The R&D for several of these projects has been supported by CERN for a long time. Research on linear colliders has been an active programme for the past 30 years and has received significant support, not only ensuring their readiness for consideration as future HEP facilities, but also sparking an exceptional R&D programme in the applications of fundamental research, for example in accelerators for cancer treatment (*CERN Courier* July/August 2024 p46). Over the past five years, CERN has also invested in muon colliders and hosts the International Muon Collider Collaboration. CERN also leads research into the application of plasma-wakefield acceleration for fundamental physics, having supported the AWAKE experiment for 10 years now (*CERN Courier* May/June 2024 p25).

CERN's future flagship collider – Member State preferences



Based on an unofficial analysis by *CERN Courier* of national submissions to the 2026 update to the European strategy for particle physics. Each national submission is accorded equal weight, with that weight divided equally when multiple options are specified. With the deadline for national submissions passing before Slovenia acceded as CERN's 25th Member State, 24 national submissions are included. These data are not endorsed by the authors, the CERN Council, the strategy secretariat or CERN management.

The next milestone for updating the ESPP is 14 November: the deadline for submission of the final national inputs. The final drafting session of the strategy update will then take place from 1 to 5 December 2025 at Monte Verità Ascona, where the community recommendations will be finalised. These will be presented to the CERN Council in March 2026 and discussed at a dedicated meeting of the CERN Council in May 2026 in Budapest.

Meanwhile, a key milestone for community deliberations recently passed. The full spectrum of community inputs was presented and debated at an Open Symposium held in Venice in June. As strategy secretary Karl Jakobs reports on the following pages, the symposium was a smashing success with lively discussions and broad participation from our community. On behalf of Council, I would like to convey my sincere thanks to the Italian delegation for the superb organisation of the symposium. ●

CERNCOURIER

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Venice symposium debates decades of collider strategy

Strategy secretary **Karl Jakobs** reports from a vibrant Open Symposium in Venice.

K Jakobs

Karl Jakobs *is the secretary of the 2026 update to the European strategy for particle physics. A professor at the University of Freiburg, Jakobs served as spokesperson of the ATLAS collaboration from 2017 to 2021 and as chairman of the European Committee for Future Accelerators from 2021 to 2023.*

The Open Symposium of the European Strategy for Particle Physics (ESPP) brought together more than 600 physicists from almost 40 countries in Venice, Italy, from 23 to 27 June, to debate the future of European particle physics. In the focus was the discussion on the next large-scale accelerator project at CERN to follow the HL-LHC, which is scheduled to operate until the end of 2041. The strategy update should – according to the remit defined by the CERN Council – define a preferred option for the next collider and prioritised alternative options to be pursued if the preferred plan turns out not to be feasible or competitive. In addition, the strategy update should indicate areas of priority for exploration complementary to colliders and other experiments to be considered at CERN and at other European laboratories, as well as for participation in projects outside Europe.

The Open Symposium is an important step in the strategy process. The aim is to involve the full community in discussions of the 266 scientific contributions that had been submitted by the community to the ESPP process before the symposium (*CERN Courier* May/June 2025 p8).

In the opening session of the symposium CERN Director-General Fabiola Gianotti summarised the impressive achievements of the CERN community in the implementation of the recommendations from the 2020 update to the ESPP. Eric Laenen (Nikhef) stressed that the outstanding questions in particle physics require a broad and diverse experimental programme, including the HL-LHC, a new flagship collider, and a wide variety of other experiments including those in neighbouring fields. A broad consensus emerged that a future collider programme should be realised that can fully leverage both precision and energy, covering the widest range of observables at different energy scales. To match experimental precision, significant progress on the theoretical side is also required, in particular regarding higher-order calculations.

An important part of the symposium was devoted to presentations of possible future large-scale accelerator projects. Detailed presentations were given on the FCC-ee and FCC-hh colliders, either in the integrated FCC programme or proceeding directly to FCC-hh as a standalone realisation at an earlier time. Linear colliders were presented as alternative options, with a Linear Collider Facility (LCF) based on the design of the International Linear Collider (ILC) and CLIC both considered. In addition, smaller collider options were presented, based on re-using the LHC/LEP tunnel. A first proposal, LEP3, suggests accelerating electrons and positrons up to energies of 230 GeV, while a second proposal, LHeC, proposes the realisation of electron–proton collisions in one interaction point of the LHC. LHeC would require the construction of an additional new energy-recovery linac for the acceleration of electrons.

Moving focus from the precision frontier to the energy frontier, several ways to reach the 10 TeV "parton scale" were presented. (Comparisons between the energy reach of hadron and lepton colliders must discuss parton–parton centre-of-mass energies, where partons refer to the pointlike constituents of hadrons, as only a fraction of the energy of collisions between composite particles can be used to probe the existence of new particles and fields.) If FCC-ee is realised, a natural path is to proceed with proton–proton collisions with proton–proton centre-of-mass energies in the range of 85 to 120 TeV, depending on the available high-field magnet technology. As an alternative, a muon collider could provide a path towards high-energy lepton collisions, however, demonstrations of how to address the significant technological challenges, such as six-dimensional cooling in transverse and longitudinal phase space, and other items associated with the various acceleration steps, need to be achieved. Likewise, plasma-based acceleration techniques for electrons and positrons capable of exceeding the 1 TeV energy scale are yet to be demonstrated.

A broad consensus emerged that a future collider programme should be realised that can fully leverage both precision and energy

The symposium was organised to foster strong engagement by the community in discussion sessions. Six physics topics – covering electroweak physics, strong interactions, flavour physics, physics beyond the Standard Model, neutrino physics and cosmic messengers, and dark matter and the dark sector, as well as the three technology areas on accelerators, detectors and computing, were summarised in rapporteur talks, followed by 45-minute discussions, where the people present in Venice strongly engaged.

INFN

Open symposium *More than 600 physicists converged on Venice from 23 to 27 June to debate the future of European particle physics.*

For the study of precision Higgs measurements, the performance of all the considered electron–positron (e^+e^-) colliders is comparable. While a sub-percent precision can be reached in several measurements of Higgs couplings to fermions and bosons, HL-LHC measurements would prevail for rare processes. On the determination of the important Higgs-boson (H) self-coupling, the precision obtained at the HL-LHC will prevail until either e^+e^- linear colliders can improve it in direct HH production measurements at collision energies above 500 GeV, or before precisions at the level of a few percent can be reached at FCC-hh or a muon collider. It was further stressed that precision measurements in the Higgs, electroweak (Z, W, top) and flavour physics constitute three facets for indirect discoveries and that their synergy is essential to maximise the discovery potential of future colliders. Due to its high luminosity at low energies and its four experiments, the FCC-ee shows a superior physics performance in the electroweak programme.

In flavour physics, a lot of progress will be achieved in the coming decade by the LHCb and Belle-II experiments. While the tera-Z production at a future FCC-ee would provide a major step forward, the giga-Z data samples available at linear colliders do not seem to be a good option for flavour physics. The FCC-ee and LHeC would also achieve high precision on QCD measurements, leading, for example, to a per-mille level determination of the strong coupling constant α_s. The important investigations of the quark-gluon plasma at the HL-LHC could be continued in parallel to an e^+e^- collider operation at CERN at the SPS fixed target programme, before FCC-hh would eventually allow for novel studies in the high-temperature QCD domain.

Keeping diversity in the particle-physics programme was also felt to be essential: the next collider project should not come at the expense of a diverse scientific programme in Europe. Given that we do not know where new physics will show up, ensuring a diverse and comprehensive physics programme is vital, including fixed-target, neutrino, flavour, astroparticle and nuclear-physics experiments. Experiments in these areas have the potential for ground-breaking discoveries.

At the technology frontier, essential work on accelerator R&D, such as on high-field and high-temperature superconducting magnets and RF systems, remain a high priority and appropriate investments must be made. R&D on advanced acceleration concepts should continue with adequate effort to prepare future projects. In the detector area, the establishment of the Detector Research & Development (DRD) collaborations as a result of the implementation of the recommendations of the 2020 ESPP update were considered to provide a solid basis to tackle the challenges related to the developments for high-performing detectors for future colliders and beyond. It is also expected that the required software and computing challenges for future colliders can be mastered, provided that adequate person power and funding are available and adaptations to new technologies, in particular GPUs, AI and – on a longer timescale – quantum computing, can be made.

The discussions in Venice revealed a community united in its desire for a future flagship collider at CERN

The discussions in Venice revealed a community united in its desire for a future flagship collider at CERN. Over the past years, very significant progress has been made in this direction, and the discussions on the prioritisation of collider options will continue over the next months. In addition to the FCC-ee, linear colliders (LCF, CLIC) present mature options for a Higgs factory at CERN. LEP3 and LHeC could alternatively be considered as intermediate collider projects, followed by a larger accelerator capable of exploring the 10 TeV parton scale.

The differences in the physics potential between the various collider options will be documented in the *Physics Briefing Book* that will be released by the Physics Preparatory Group by the end of September. In parallel, the technical readiness, risks, timescales and costs will be reviewed by the European Strategy Group (ESG). Alongside the final national inputs, these assessments will provide the foundation for the final recommendations to be drafted by the ESG in early December 2025. ●

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NINETEEN SIXTY-FOUR

Michael Riordan surveys the extraordinary events of 1964 – a year that witnessed the birth of the quark model, the invention of the Higgs mechanism, the discovery of CP violation and the first observation of the cosmic microwave background.

In the history of elementary particle physics, 1964 was truly an *annus mirabilis*. Not only did the quark hypothesis emerge – independently from two theorists half a world apart – but a multiplicity of theorists came up with the idea of spontaneous symmetry breaking as an attractive method to generate elementary particle masses. And two pivotal experiments that year began to alter the way astronomers, cosmologists and physicists think about the universe.

Some of the insights published in 1964 were first conceived in 1963. Caltech theorist Murray Gell-Mann had been ruminating about quarks ever since a March 1963 luncheon discussion with Robert Serber at Columbia University. Serber was exploring the possibility of a triplet of fundamental particles that in various combinations could account for mesons and baryons in Gell-Mann's SU(3) symmetry scheme, dubbed "the Eightfold Way". But Gell-Mann summarily dismissed his suggestion, showing him on a napkin how any such fundaments would have to have fractional charges of –2/3 or 1/3 the charge on an electron, which seemed absurd.

From the ridiculous to the sublime

Still, he realised, such ridiculous entities might be allowable if they somehow never materialised outside of the hadrons. For much of the year, Gell-Mann toyed with the idea in his musings, calling such hypothetical entities by the nonsense word "quarks", until he encountered the famous line in *Finnegans Wake* by James Joyce, "Three quarks for Muster Mark." He even discussed it with his old MIT thesis adviser, then CERN Director-General Victor Weisskopf, who chided him not to waste their time talking about such nonsense on an international phone call.

In late 1963, Gell-Mann finally wrote the quark idea up for publication and sent his paper to the newer European journal *Physics Letters* rather than the (then) more prestigious *Physical Review Letters*, in part because he thought it would be rejected there. "A schematic model of baryons and mesons", published on 1 February 1964, is brief and to the point. After a few preliminary remarks, he noted that "a simpler, more elegant scheme can be constructed if we allow non-integral values for the charges ... We then refer to the members u(2/3), d(–1/3) and s(–1/3) of the triplet as 'quarks'." But toward the end, he hedged his bets, ▷

Annus mirabilis *(right) A timeline of the key 1964 milestones; discoveries that laid the groundwork for the Standard Model of particle physics and continue to be actively studied and refined today. (Images: N Eskandari, A Epshtein)*

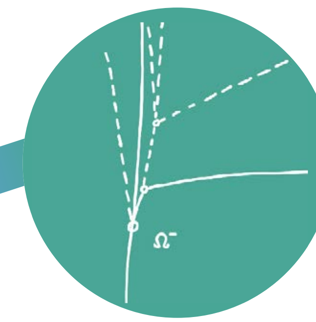
4 January

Murray Gell-Mann submits "A schematic model of baryons and mesons" to *Physics Letters* (published 1 February), proposing the existence of quarks.

17 January

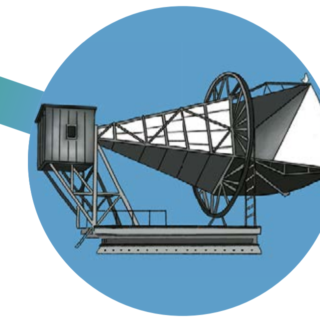
George Zweig publishes "An SU(3) model for strong interaction symmetry and its breaking" as CERN report number CERN-TH-412, independently proposing the existence of quarks (or aces).

11 February



A **Brookhaven National Laboratory** team submits "Observation of a hyperon with strangeness minus three" to *Physical Review Letters*, providing compelling evidence for SU(3) symmetry.

May

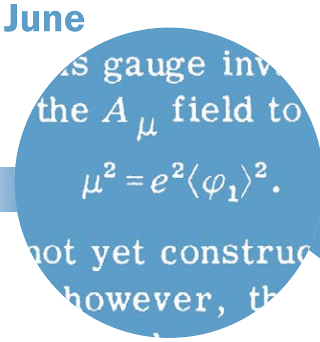


Arno Penzias and **Robert Wilson** first observe an isotropic radio signal later identified as cosmic microwave background radiation.

19 June

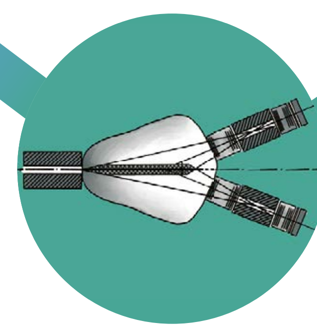
James Bjorken and **Sheldon Glashow** submit "Elementary particles and SU(4)" to *Physics Letters*, introducing the charm quantum number.

26 June



Robert Brout and **François Englert** submit "Broken symmetry and the mass of gauge vector mesons" to *Physical Review Letters* (published 31 August), showing that the spontaneous breaking of gauge symmetries can give mass to gauge bosons without introducing physical Goldstone bosons.

10 July

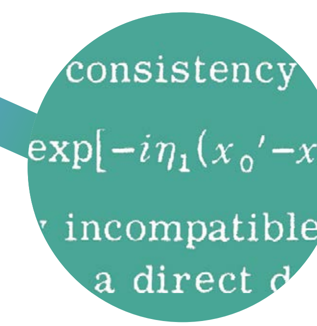


Jim Cronin and **Val Fitch** submit "Evidence for the 2π decay of the K_2^0 meson" to *Physical Review Letters*, discussing their team's discovery of CP violation.

27 July

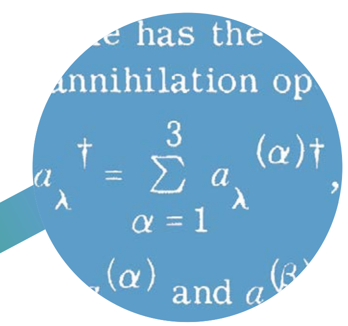
Peter Higgs submits "Broken symmetries, massless particles and gauge fields" to *Physics Letters* (published 15 September), showing that the spontaneous breaking of gauge symmetries can give mass to gauge bosons, and implying the existence of a massive scalar boson.

12 October

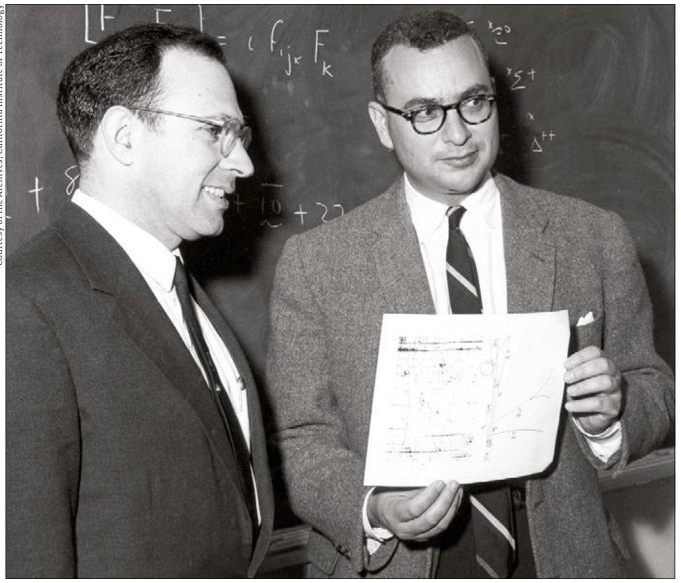


Gerald Guralnik, Richard Hagen and **Tom Kibble** submit "Global conservation laws and massless particles" to *Physical Review Letters* (published 16 November), providing a formal proof that Goldstone's theorem is inapplicable to gauge symmetries.

27 October



Oscar Greenberg submits "Spin and unitary-spin independence in a paraquark model of baryons and mesons" to *Physical Review Letters* (published November 16), effectively introducing the colour quantum number.



Strong interactions *Murray Gell-Mann (right) in 1964, showing a Brookhaven Labs bubble-chamber photograph of the Ω^- baryon, whose discovery confirmed his theory of SU(3) flavour symmetry. He is pictured next to Yuval Ne'eman.*

The charm quark they had predicted in 1964 was the central player in the November Revolution that led to widespread acceptance of the Standard Model

warning readers not to take the existence of these quarks too seriously: "A search for stable quarks of charge +2/3 or −1/3 ... at the highest-energy accelerators would help to reassure us of the non-existence of real quarks."

As often happens in the history of science, the idea of quarks had another, independent genesis – at CERN in 1964. George Zweig, a CERN postdoc who had recently been a Caltech graduate student with Richard Feynman and Gell-Mann, was wondering why the ϕ meson lived so long before decaying into a pair of K mesons. A subtle conservation law must be at work, he figured, which led him to consider a constituent model of the hadrons. If the ϕ were somehow composed of two more fundamental entities, one with strangeness +1 and the other with −1, then its great preference for kaon decays over other, energetically more favourable possibilities, could be explained. These two strange constituents would find it difficult to "eat one another," as he later put it, so two individual, strange kaons would be required to carry each of them away.

Late in the fall of 1963, Zweig discovered that he could reproduce the meson and baryon octets of the Eightfold Way from such constituents if they carried fractional charges of 2/3 and −1/3. Although he at first thought this possibility artificial, it solved a lot of other problems, and he began working feverishly on the idea, day and night. He wrote up his theory for publication, calling his fractionally charged particles "aces" – in part because he figured there would be four of them. Mesons, built from pairs of these aces, formed the "deuces" and baryons the "treys" in his deck of cards. His theory first appeared as a long CERN report in mid-January 1964, just as Gell-Mann's quark paper was awaiting publication at *Physics Letters*.

As often happens in the history of science, the idea of quarks had another, independent genesis

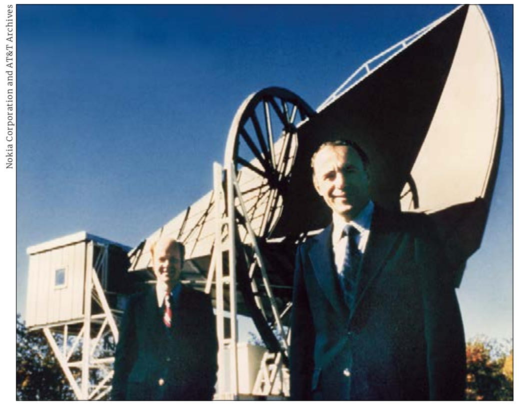
As chance would have it, there was an intensive activity going on in parallel that January – an experimental search for the Ω^- baryon that Gell-Mann had predicted just six months earlier at a Geneva particle-physics conference. With negative charge and a mass almost twice that of the proton, it had to have strangeness −3 and would sit atop a 10-fold decuplet of heavy baryons predicted in his Eightfold Way. Brookhaven experimenter Nick Samios was eagerly seeking evidence of this very strange particle in the initial run of the 80 inch bubble chamber that he and colleagues had spent years planning and building. On 31 January 1964, he finally found a bubble-chamber photograph with just the right signatures. It might be the "gold-plated event" that could prove the existence of the Ω^- baryon.

After more detailed tests to make sure of this conclusion, the Brookhaven team delivered a paper with the unassuming title "Observation of a hyperon with strangeness minus three" to *Physical Review Letters*. With 33 authors, it reported only one event. But with that singular event, any remaining doubt about SU(3) symmetry and Gell-Mann's Eightfold Way evaporated.

A fourth quark for Muster Mark?

Later in spring 1964, James Bjorken and Sheldon Glashow crossed paths in Copenhagen, on leave from Harvard and Stanford, working at Niels Bohr's Institute for Theoretical Physics. Seeking to establish lepton–hadron symmetry, they needed a fourth quark because a fourth lepton – the muon neutrino – had been discovered in 1962 at Brookhaven. Bjorken and Glashow were early adherents of the idea that hadrons were made of quarks, but based their arguments on SU(4) symmetry rather than SU(3). "We called the new quark flavour 'charm,' completing two weak doublets of quarks to match two weak doublets of leptons, and establishing lepton–quark symmetry, which holds to this day," recalled Glashow (*CERN Courier* January/February 2025 p35). Their *Physics Letters* article appeared that summer, but it took another decade before solid evidence for charm turned up in the famous J/ψ discovery at Brookhaven and SLAC. The charm quark they had predicted in 1964 was the central player in the so-called November Revolution a decade later that led to widespread acceptance of the Standard Model of particle physics.

In the same year, Oscar Greenberg at the University of Maryland was wrestling with the difficult problem of how to confine three supposedly identical quarks within a volume hardly larger than a proton. According to the sacrosanct Pauli exclusion principle, identical spin-1/2 fermions could never occupy the exact same quantum state. So how, for example, could one ever cram three strange quarks inside an Ω^- baryon?



Background noise *Robert W Wilson (left) and Arno Penzias (right) with the Holmdel horn they used to discover the cosmic microwave background radiation.*

Lifelong friendship *Robert Brout (left) and François Englert (right) identified a mechanism to generate particle masses using spontaneous symmetry breaking in non-Abelian gauge theories.*

One possible solution, Greenberg realised, was that quarks carry a new physical property that distinguished them from one another so they were not in fact identical. Instead of a single quark triplet, that is, there could be three distinct triplets of what he dubbed "paraquarks", publishing his ideas in November 1964, and capping an extraordinary year of insights into hadrons. We now recognise his insight as anticipating the existence of "coloured" quarks, where colour is the source of the relentless QCD force binding them within mesons and baryons.

The origin of mass

Although it took more than a decade for experiments to verify them, these insights unravelled the nature of hadrons, revealing a new family of fermions and hinting at the nature of the strong force. Yet they were not necessarily the most important ideas developed in particle physics in 1964. During that summer, three theorists – Robert Brout, François Englert and Peter Higgs – formulated an innovative technique to generate particle masses using spontaneous symmetry breaking of non-Abelian Yang-Mills gauge theories – a class of field theories that would later describe the electroweak and strong forces in the Standard Model.

Inspired by successful theories of superconductivity, symmetry-breaking ideas had been percolating among those few still working on quantum field theory, then in deep decline in particle physics, but they foundered whenever masses were introduced "by hand" into the theories. Or, as Yoichiro Nambu and Peter Goldstone realised in the early 1960s, massless bosons appeared in the theories that did not correspond to anything observed in experiments.

If they existed, the W (and later, Z) bosons carrying the short-range weak force had to be extremely massive (as is now well known). Brout and Englert – and independently Higgs – found they could generate the masses of such vector bosons if the gauge symmetry governing their behaviour was instead spontaneously broken, preserving the underlying symmetry while allowing for distinctive, asymmetric particle states. In solid-state physics, for example, magnetic domains will spontaneously align along a single direction, breaking the underlying symmetry of the electromagnetic field. Brout and Englert published their solution in June 1964, while Higgs followed suit a month later (after his paper was rejected by *Physics Letters*). Higgs subsequently showed that this symmetry breaking required a scalar boson to exist that was soon named after him. Dubbed the "Higgs mechanism," this mass-generating process became a crucial feature of the unification of the weak and electromagnetic forces a few years later by Steven Weinberg and Abdus Salam. And after their electroweak theory was shown in 1971 to be renormalisable, and hence calculable, the theoretical floodgates opened wide, leading to today's dominant Standard Model paradigm.

Besides the quark model and the Higgs mechanism, 1964 witnessed two surprising discoveries that would light up almost any other year in the history of science

Surprise, surprise!

Besides the quark model and the Higgs mechanism, 1964 witnessed two surprising discoveries that would light up almost any other year in the history of science. That summer saw the publication of an epochal experiment leading to the discovery of CP violation in the decays of long-lived neutral mesons. Led by Princeton physicists Jim Cronin and Val Fitch, their Brookhaven experiment had discerned a small but non-negligible fraction – 0.2% – of two-body decays into a pair of pions, instead of into the dominant CP-conserving three-body decays. For months, the group wrestled with trying to understand this surprising result before publishing it that July in *Physical Review Letters*.

It took almost another decade before Japanese theorists Makoto Kobayashi and Toshihide Maskawa proved that such a small amount of CP violation was the natural result of the Standard Model if there were three quark-lepton families instead of the two then known to exist. Whether this phenomenon has any causal relation to the dominance of matter in the universe is still up for grabs decades later. "Indeed, it is almost certain that the CP violation observed in the K-meson system is not directly responsible for the matter dominance of the universe," wrote Cronin in the early 1990s, "but one would wish that it is related to whatever the mechanism was that created [this] matter dominance."

Another epochal 1964 observation was not published until

1965, but it deserves mention here because of its tremendous significance for the subsequent marriage of particle physics and cosmology. That summer, Arno Penzias and Robert W Wilson of Bell Telephone Labs were in the process of converting a large microwave antenna in Holmdel, NJ, for use in radio astronomy. Shaped like a giant alpenhorn lying on its side, the device had been developed for early satellite communications. But the microwave signals that it was receiving included a faint, persistent "hiss" no matter the direction in which the horn was pointed; they at first interpreted the hiss as background noise – possibly due to some smelly pigeon droppings that had accumulated inside, which they removed. Still it persisted. Penzias and Wilson were at a complete loss to explain it.

Cosmological consequences

It so happened that a Princeton group led by Robert Dicke and James Peebles was just then building a radiometer to search for the uniform microwave radiation that should suffuse the universe had it begun in a colossal fireball, as a few cosmologists had been arguing for decades. In the spring of 1965, Penzias read a preprint of a paper by Peebles on the subject and called Dicke to suggest he come to Holmdel to view their results. After arriving and realising they had been scooped, the Princeton physicists soon confirmed the Bell Labs results using their own rooftop radiometer.

The results were published as back-to-back letters in the *Astrophysical Journal* on 7 May 1965. The Princeton group wrote extensively about the cosmological consequences of the discovery, while Penzias and Wilson submitted just a brief, dry description of their work, "A measurement of excess antenna temperature at 4080 Mc/s" – ruling out other possible interpretations of the uniform signal corresponding to the radiation expected from a 3.5 K blackbody.

Subsequent measurements at many other frequencies have established that this is indeed the cosmic background radiation expected from the Big Bang birth of the universe, confirming that it had in fact occurred. That was an incredibly brief, hot, dense phase of its existence, which has prodded many particle physicists to take up the study of its evolution and remnants. This discovery of the cosmic background radiation therefore serves as a fitting capstone on what was truly a pivotal year for particle physics. ●

THE AUTHOR

Michael Riordan *is author of* The Hunting of the Quark *and co-author of* The Shadows of Creation: Dark Matter and the Structure of the Universe *and* Tunnel Visions: The Rise and Fall of the Superconducting Super Collider. *He was awarded the 2025 Abraham Pais Prize for the History of Physics by the American Physical Society.*

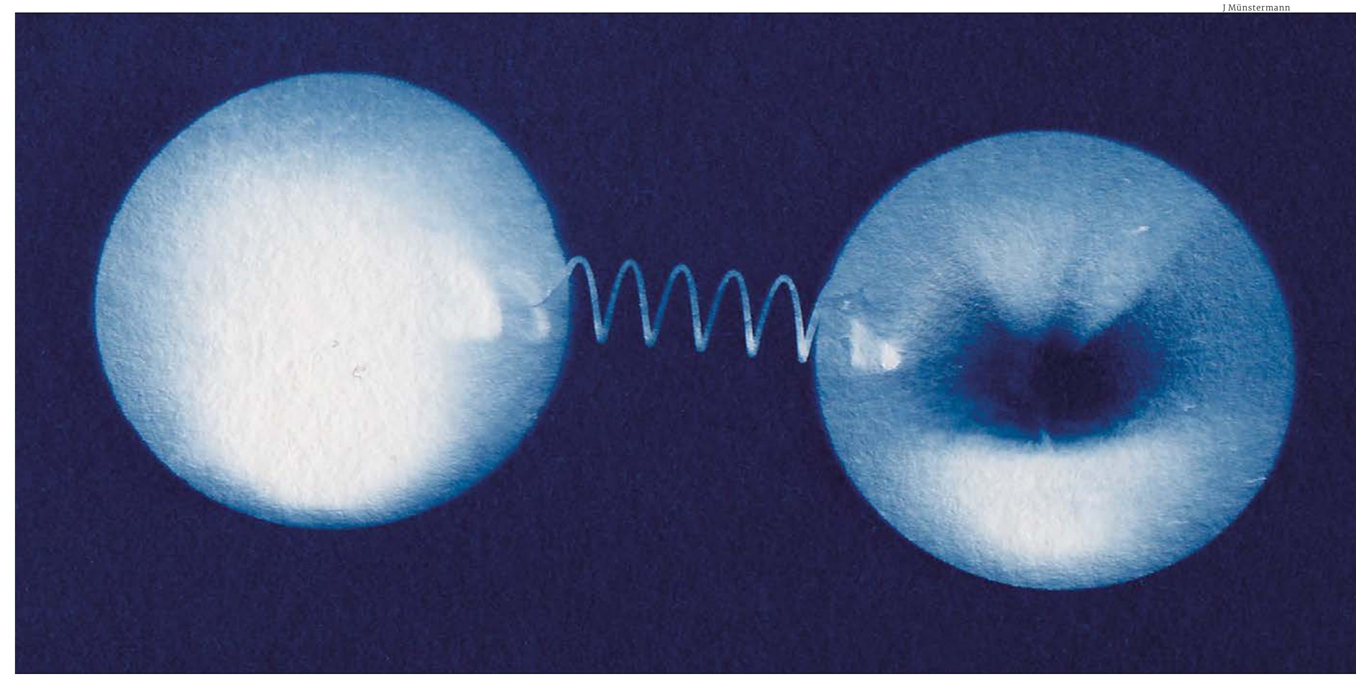
Further reading

F Close 2022 *Elusive: How Peter Higgs Solved the Mystery of Mass* (New York: Basic Books).

R P Crease and C C Mann 1996 *The Second Creation: Makers of the Revolution in 20th-Century Physics* (New Brunswick, NJ, Rutgers University Press).

M Riordan 1987 *The Hunting of the Quark: A True Story of Modern Physics* (New York: Simon & Schuster).

J Münstermann



Toponium *Artist's impression of the fleeting binding by gluons of a top quark and its antiparticle before one of the pair decays weakly into b-jets.*

MEMORIES OF QUARKONIA

With the story of quarkonia entering its final chapter, John Ellis shares personal recollections of five decades of discoveries and debates about the simplest composite object in QCD, whose history is inextricable from the development of particle physics.

The world of particle physics was revolutionised in November 1974 by the discovery of the J/ψ particle. At the time, most of the elements of the Standard Model of particle physics had already been formulated, but only a limited set of fundamental fermions were confidently believed to exist: the electron and muon, their associated neutrinos, and the up, down and strange quarks that were thought to make up the strongly interacting particles known at that time. The J/ψ proved to be a charm–anticharm bound state, vindicating the existence of a quark flavour first hypothesised by Sheldon Glashow and James Bjorken in 1964 (*CERN Courier* January/February 2025 p35). Its discovery eliminated any lingering doubts regarding the quark model of 1964 (see p30) and sparked the development of the Standard Model into its modern form.

This new "charmonium" state was the first example of quarkonium: a heavy quark bound to an antiquark of the same flavour. It was named by analogy to positronium, a bound state of an electron and a positron, which decays by mutual annihilation into two or three photons. Composed of unstable quarks, bound by gluons rather than photons, and decaying mainly via the annihilation of their constituent quarks, quarkonia have fascinated particle physicists ever since.

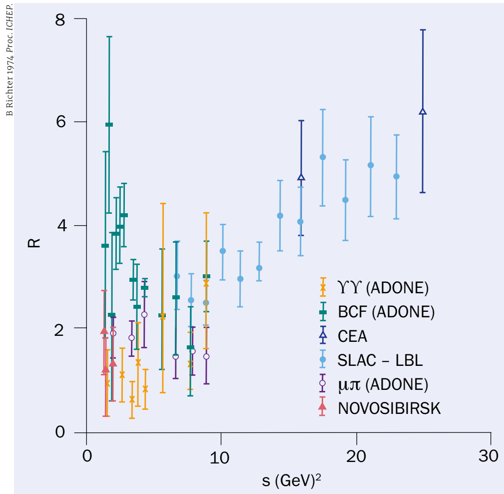
The charmonium interpretation of the J/ψ was cemented

THE AUTHOR

John Ellis *King's College London.*

The story of quarkonium can be thought to have begun in 1963 with the discovery of the ϕ meson

B Richter 1974 Proc. ICHEP



Why is R rising? *Measurements of the ratio, R, of the cross-sections for $e^+e^- \to$ hadrons and $e^+e^- \to \mu^+\mu^-$, presented by Burton Richter at the 17th International Conference on High-Energy Physics, held in London in July 1974. In hindsight, and notwithstanding resonances, the data are compatible with a rise in R from 2 to 10/3 as charm production opens up at s ~ 14 GeV², reflecting the appearance of a new quark flavour with charge +2/3 and three colours.*

by the subsequent discovery of a spectrum of related $c\bar{c}$ states, and ultimately by the observation of charmed particles in 1976. The discovery of charmonium was followed in 1977 by the identification of bottomonium mesons and particles containing bottom quarks. While toponium – a bound state of a top quark and antiquark – was predicted in principle, most physicists thought that its observation would have to wait for the innate precision of a next-generation e^+e^- collider following the LHC, in view of the top quark's large mass and exceptionally rapid decay, more than 10^{12} times quicker than the bottom quark. The complex environment at a hadron collider, where the composite nature of protons precludes knowledge of the initial collision energy of pairs of colliding partons within them, would make toponium particularly difficult to identify at the LHC.

However, in the second half of 2024, the CMS collaboration reported an enhancement near the threshold for $t\bar{t}$ production at the LHC, which is now most plausibly interpreted as the lowest-lying toponium state. The existence of this enhancement has recently been corroborated by the ATLAS collaboration (see p9).

Here are the personal memories of an eyewitness who followed these 50 years of quarkonium discoveries firsthand.

Strangeonium?

In hindsight, the quarkonium story can be thought to have begun in 1963 with the discovery of the ϕ meson. The ϕ was an unexpectedly stable and narrow resonance, decaying mainly into kaons rather than the relatively light pions, despite lying only just above the $K\bar{K}$ threshold. Heavier quarkonia cannot decay into a pair of mesons containing single heavy quarks, as their masses lie below the energy threshold for such "open flavour" decays.

The preference of the ϕ to decay into kaons was soon interpreted by Susumu Okubo as a consequence of approximate SU(3) flavour symmetry, developing mathematical ideas based on unitary 3 × 3 matrices with a determinant one. At the beginning of 1964, quarks were proposed and George Zweig suggested that the ϕ was a bound state of a strange quark and a strange anti-quark (or aces as he termed them). After 1974, the portmanteau word "strangeonium" was retrospectively applied to the ϕ and similar heavier $s\bar{s}$ bound states, but the name has never really caught on.

In the year or so prior to the discovery of the J/ψ in November 1974, there was much speculation about data from the Cambridge Electron Accelerator (CEA) at Harvard and the Stanford Positron–Electron Asymmetric Ring (SPEAR) at SLAC. Data from these e^+e^- colliders indicated a rise in the ratio, R, of cross-sections for hadron and $\mu^+\mu^-$ production (see "Why is R rising?" figure). Was this a failure of the parton model that had only recently found acceptance as a model for the apparently scale-invariant internal structure of hadrons observed in deep-inelastic scattering experiments? Did partons indeed have internal structure? Or were there "new" partons that had not been seen previously, such as charm or coloured quarks? I was asked on several occasions to review the dozens of theoretical suggestions on the market, including at the ICHEP conference in the summer of 1974. In preparation, I toted a large Migros shopping bag filled with dozens of theoretical papers around Europe. Playing the part of an objective reviewer, I did not come out strongly in favour of any specific interpretation, however, during talks that autumn in Copenhagen and Dublin, I finally spoke out in favour of charm as the best-motivated explanation of the increase in R.

November revolution

Then, on 11 November 1974, the news broke that two experimental groups, one working at BNL under the leadership of Sam Ting and the other at SLAC led by Burt Richter, had discovered, in parallel, the narrow vector boson that bears the composite name J/ψ (see "Charmonium" figure). The worldwide particle-physics community went into convulsions (*CERN Courier* November/December 2024 p41) – and the CERN Theory Division was no exception. We held informal midnight discussion sessions around an open-mic phone with Fred Gilman in the SLAC theory group, who generously shared with us the latest J/ψ news. Away from the phone, like many groups around the world, we debated the merits and demerits of many different theoretical ideas. Rather than write a plethora of rival papers about these ideas, we decided to bundle our thoughts into a collective preprint. Instead of taking individual responsibility for our trivial thoughts, the preprint was anonymous, the place of the authors' names being taken by a mysterious "CERN Theory Boson Workshop". Eagle eyes will spot that the equations were handwritten by Mary K Gaillard (*CERN Courier* July/August 2025 p47). Informally, we called ourselves Co-Co, for communication collective. With "no pretentions to originality or priority," we explored five hypotheses: a hidden charm vector meson, a coloured vector meson, an intermediate vector boson, a Higgs meson and narrow resonances in strong interactions.

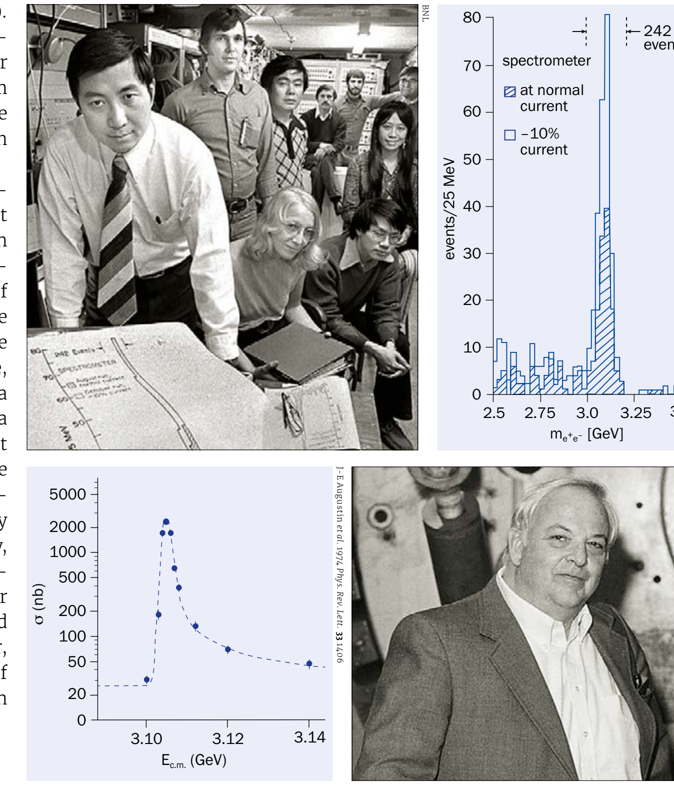
My immediate instinct was to advocate the charmonium interpretation of the J/ψ, and this was the first interpretation to be described in our paper. This was on the basis of the Glashow–Iliopoulos–Maiani (GIM) mechanism, which accounted for the observed suppression of flavour-changing neutral currents by postulating the existence a charm quark with a mass around 2 GeV (see *CERN Courier* July/August 2024 p30), and the Zweig rule, which suggested phenomenologically that quarkonia do not easily decay by quark–antiquark annihilation via gluons into other flavours of quarks. So I was somewhat surprised when one of the authors of the GIM paper wrote a paper proposing that it might be an intermediate electroweak vector boson. A few days after the J/ψ discovery came the news of the (almost equally narrow) ψ′ discovery, which I was told as I was walking along the theory corridor to my office one morning. My informant was a senior theorist who was convinced that this discovery would kill the charmonium interpretation of the J/ψ. However, before I reached my office I realised that an extension of the Zweig rule would also suppress ψ′ → J/ψ + light meson decays, so the ψ′ could also be narrow.

Keen competition

The charmonium interpretation of the J/ψ and ψ′ states predicted that there should be intermediate P-wave states (with one unit of orbital angular momentum) that could be detected in radiative decays of the ψ′. In the first half of 1975 there was keen competition between teams at SLAC and DESY to discover these states. That summer I was visiting SLAC, where I discovered one day under the cover of a copying machine, before their discovery was announced, a sheet of paper with plots showing clear evidence for the P-wave states. I made a copy, went to Burt Richter's office and handed him the sheet of paper. I also asked whether he wanted my copy. He graciously allowed me to keep it, as long as I kept quiet about it, which I did until the discovery was officially announced a few weeks later.

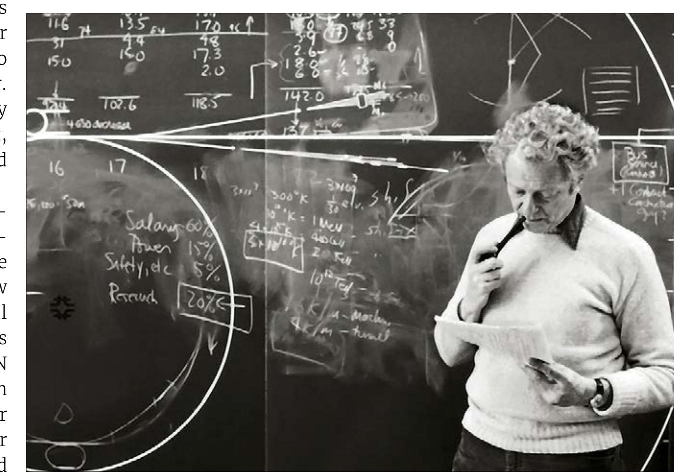
Discussion about the interpretation of the new particles, in particular between advocates of charm and Han–Nambu coloured quarks – a different way to explain the new particles' astounding stability by giving them a new quantum number – rumbled on for a couple of years until the discovery of charmed particles in 1976. During this period we conducted some debates in the main CERN auditorium moderated by John Bell. I remember one such debate in particular, during which a distinguished senior British theorist spoke for coloured quarks and I spoke for charm. I was somewhat taken aback when he described me as representing the "establishment", as I was under 30 at the time.

Over the following year, my attention wandered to grand



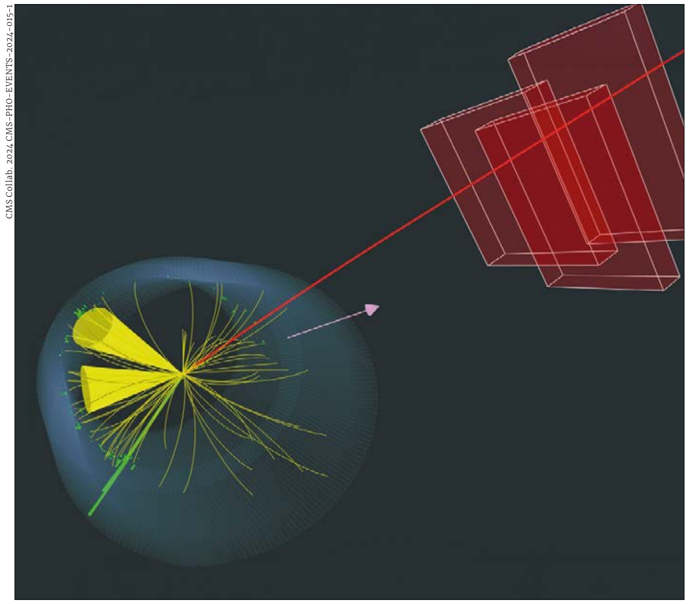
Charmonium *Sam Ting (top left) and Burton Richter (bottom right) led teams who discovered a remarkably stable charmonium resonance in e^+e^- collisions in the November Revolution of 1974, naming it J (top right) and ψ (bottom left), respectively. While the J is plotted as a raw mass spectrum, the ψ is plotted as the estimated cross section for multi-hadron production and compared to a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes (dashed line).*

Fermilab



Bottomonium *Leon Lederman and his E288 collaboration observed the 9.5 GeV ϒ resonance in the background-subtracted invariant-mass spectrum of muon pairs created in proton nucleus collisions.*

CERNCOURIER
Volume 65 Number 5 September/October 2025


CMS Collab. 2024 CMS-PHO-EVENTS-2024-015-1

Toponium? *The event display of a candidate top-quark pair event in the CMS experiment. Each top quark decays to a bottom quark and a W boson. The yellow cones represent the two b-tagged jets, with one W boson decaying into an electron (green line) and one W boson decaying into a muon (red line) and a neutrino. Missing transverse energy from the unobservable neutrinos is represented by the magenta arrow.*

unified theories, and my first paper on the subject was with Michael Chanowitz and Mary K Gaillard, which we completed in May 1977. We realised while writing this paper that simple grand unified theories – which unify the electroweak and strong interactions – would relate the mass of the τ heavy lepton that had been discovered in 1975 to the mass of the bottom quark, which was confidently expected but whose mass was unknown. Our prediction was $m_b/m_\tau = 2$ to 5, but we did not include it in the abstract. Shortly afterwards, while our paper was in proof, the discovery of the Υ state (or states) by a group at Fermilab led by Leon Lederman (see "Bottomonium" figure) became known, implying that $m_b \sim 4.5$ GeV. I added our successful mass prediction by hand in the margin of the corrected proof. Unfortunately, the journal misunderstood my handwriting and printed our prediction as $m_b/m_\tau = 2605$, a spectacularly inaccurate postdiction! It remains to be seen whether the idea of a grand unified theory is correct: it also predicted successfully the electroweak mixing angle θ_W and suggested that neutrinos might have mass, but direct evidence, such as the decay of the proton, has yet to be found.

Peak performance

Meanwhile, buoyed by the success of our prediction for m_b, Mary K Gaillard, Dimitri Nanopoulos, Serge Rudaz and I set to work on a paper about the phenomenology of the top and bottom quarks. One of our predictions was that the first two excited states of the Υ, the Υ' and Υ'', should be detectable by the Lederman experiment because the Zweig rule would suppress their cascade decays to lighter bottomonia via light-meson emission. Indeed, the Lederman experiment found that the Υ bump was broader than the experimental resolution, and the bump was eventually resolved into three bottomonium peaks.

It was in the same paper that we introduced the terminology of "penguin diagrams", wherein a quark bound in a hadron changes flavour not at tree level via W-boson exchange but via a loop containing heavy particles (like W bosons or top quarks), emitting a gluon, photon or Z boson. Similar diagrams had been discussed by the ITEP theoretical school in Moscow, in connection with K decays, and we realised that they would be important in B-hadron decays. I took an evening off to go to a bar in the Old Town of Geneva, where I got involved in a game of darts with the experimental physicist Melissa Franklin. She bet me that if I lost the game I had to include the word "penguin" in my next paper. Melissa abandoned the darts game before the end, and was replaced by Serge Rudaz, who beat me. I still felt obligated to carry out the conditions of the bet, but for some time it was not clear to me how to get the word into the b-quark paper that we were writing at the time. Then, another evening, after working at CERN, I stopped to visit some friends on my way back to my apartment, where I inhaled some (at that time) illegal substance. Later, when I got home and continued working on our paper, I had a sudden inspiration that the famous Russian diagrams look like penguins. So we put the word into our paper, and it has now appeared in almost 10,000 papers.

What of toponium, the last remaining frontier in the world of quarkonia? In the early 1980s there were no experimental indications as to how heavy the top quark might be, and there were hopes that it might be within the range of existing or planned e^+e^- colliders such as PETRA, TRISTAN and LEP. When the LEP experimental programme was being devised, I was involved in setting "examination questions" for candidate experimental designs that included asking how well they could measure the properties of toponium. In parallel, the first theoretical papers on the formalism for toponium production in e^+e^- and hadron–hadron collisions appeared.

But the top quark did not appear until the mid-1990s at the Tevatron proton–antiproton collider at Fermilab, with a mass around 175 GeV, implying that toponium measurements would require an e^+e^- collider with an energy much greater than LEP, around 350 GeV. Many theoretical studies were made of the cross section in the neighbourhood of the $e^+e^- \to t\bar{t}$ threshold, and how precisely the top quark mass, electroweak and Higgs couplings could be measured.

Meanwhile, a smaller number of theorists were calculating the possible toponium signal at the LHC, and the LHC experiments ATLAS and CMS started measuring $t\bar{t}$ production with high statistics. CMS and ATLAS embarked on programmes to search for quantum-mechanical correlations in the final-state decay products of the top quarks and antiquarks, as should occur if the $t\bar{t}$ state were to be produced in a specific spin-parity state. They both found decay correlations characteristic of $t\bar{t}$ production in a pseudoscalar state: it was the first time such

a quantum correlation had been observed at such high energies.

The CMS collaboration used these studies to improve the sensitivities of dedicated searches they were making for possible heavy Higgs bosons decaying into $t\bar{t}$ final states, as would be expected in many extensions of the Standard Model. Intriguingly, hints of a possible excess of events around the $t\bar{t}$ threshold with the type of correlation expected from a pseudoscalar $t\bar{t}$ state began to emerge in the CMS data, but initially not with high significance.

Pseudoscalar states

I first heard about this excess at an Asia–CERN physics school in Thailand, and started wondering whether it could be due to the lowest-lying toponium state, which would decay predominantly into unstable top quarks and antiquarks rather than via their annihilation, or to a heavy pseudoscalar Higgs boson, and how one might distinguish between these hypotheses. A few years previously, Abdelhak Djouadi, Andrei Popov, Jérémie Quevillon and I had studied in detail the possible signatures of heavy Higgs bosons in $t\bar{t}$ final states at the LHC, and shown that they would have significant interference effects that would generate dips in the cross-section as well as bumps.

The significance of the CMS signal subsequently increased to over 5σ, showing up in a tailored search for new pseudoscalar states decaying into $t\bar{t}$ pairs with specific spin correlations, and recently this CMS discovery has been confirmed by the ATLAS Collaboration, with a significance over 7σ. Unfortunately, the experimental resolution in the $t\bar{t}$ invariant mass is not precise enough to see any dip due to pseudoscalar Higgs production, and Djouadi, Quevillon and I have concluded that it is not yet possible to discriminate between the toponium and Higgs hypotheses on purely experimental grounds.

However, despite being a fan of extra Higgs bosons, I have to concede that toponium is the more plausible interpretation of the CMS threshold excess. The mass is consistent with that expected for toponium, the signal strength is consistent with theoretical calculations in QCD, and the $t\bar{t}$ spin correlations are just what one expects for the lowest-lying pseudoscalar toponium state that would be produced in gluon–gluon collisions.

Caution is still in order. The pseudoscalar Higgs hypothesis cannot (yet) be excluded. Nevertheless, it would be a wonderful golden anniversary present for quarkonium if, some 50 years after the discovery of the J/ψ, the appearance of its last, most massive sibling were to be confirmed.

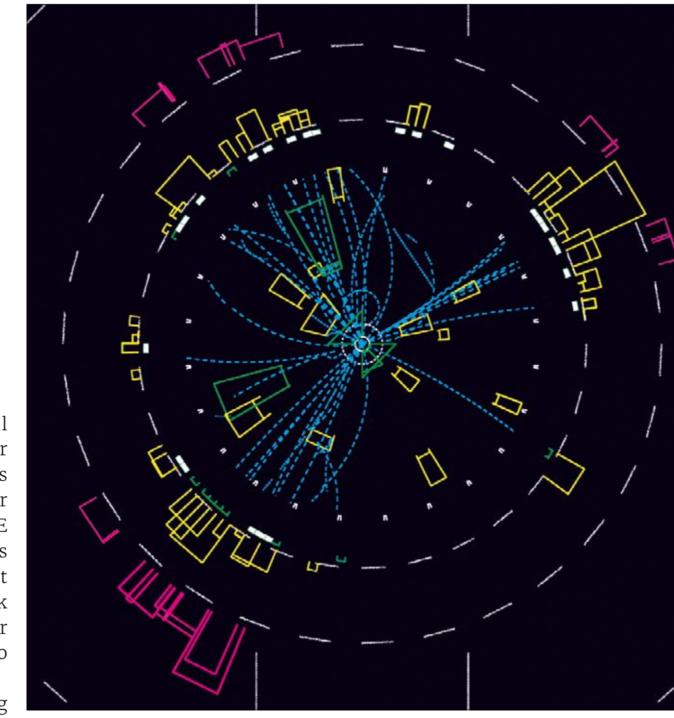
Toponium will be a very interesting target for future e^+e^- colliders

Toponium will be a very interesting target for future e^+e^- colliders, which will be able to determine its properties with much greater accuracy than a hadron collider could achieve, making precise measurements of the mass of the top quark and its electroweak couplings possible. The quarkonium saga is far from over. ●

CERNCOURIER
Volume 65 Number 5 September/October 2025

HIDDEN TREASURES

As the LHC surpasses one exabyte of stored data – the largest scientific data set ever accumulated – Cristinel Diaconu and Ulrich Schwickerath call for new collaborations to join a global effort in data preservation, to allow future generations to unearth the hidden treasures.



OPAL collaboration

Data resurrection *DELPHI and OPAL (above) have resurrected their full software stacks, including event displays, thanks to the revival of the CERNLIB software library.*

In 2009, the JADE experiment had been inoperational for 23 years. The PETRA electron–positron collider that served it had already completed a second life as a pre-accelerator for the HERA electron–proton collider and was preparing for a third life as an X-ray source. JADE and the other PETRA experiments were a piece of physics history, well known for seminal measurements of three-jet quark–quark–gluon events, and early studies of quark fragmentation and jet hadronisation. But two decades after being decommissioned, the JADE collaboration was yet to publish one of its signature measurements.

At high energies and short distances, the strong force becomes weaker. Quarks behave almost like free particles. This "asymptotic freedom" is a unique hallmark of QCD. In 2009, as now, JADE's electron–positron data was unique in the low-energy range, with other data sets lost to history. When reprocessed with modern next-to-next-to-leading-order QCD and improved simulation tools, the DESY experiment was able to rival experiments at CERN's higher-energy Large Electron–Positron (LEP) collider for precision on the strong coupling constant, contributing to a stunning proof of QCD's most fundamental behaviour. The key was a farsighted and original initiative by Siggi Bethke to preserve JADE's data and analysis software.

New perspectives

This data resurrection from JADE demonstrated how data can be reinterpreted to give new perspectives decades after an experiment ends. It was a timely demonstration. In 2009, HERA and SLAC's PEP-II electron–positron collider had been recently decommissioned, and Fermilab's Tevatron proton–antiproton collider was approaching the end of its operations. Each facility nevertheless had a strong analysis programme ahead, and CERN's Large Hadron Collider (LHC) was preparing for its first collisions. How could all this data be preserved?

The uniqueness of these programmes, for which no upgrade or followup was planned for the coming decades, invited the consideration of data usability at horizons well beyond a few years. A few host labs risked a small investment, with dedicated data-preservation projects beginning, for example, at SLAC, DESY, Fermlilab, IHEP and CERN (see "Data preservation" dashboard). To exchange data-preservation concepts, methodologies and policies, and to ensure the long-term preservation of HEP data, the Data Preservation in High Energy Physics (DPHEP) group was created in 2014. DPHEP is a global initiative under the supervision of the International Committee for Future Accelerators (ICFA), with strong support from CERN from the beginning. It actively welcomes new collaborators and new partner experiments, to ensure a vibrant and long-term future for the precious data sets being collected at present and future colliders.

At the beginning of our efforts, DPHEP designed a four-level classification of data abstraction. Level 1 corresponds to the information typically found in a scientific publication or its associated HEPData entry (a public

THE AUTHORS

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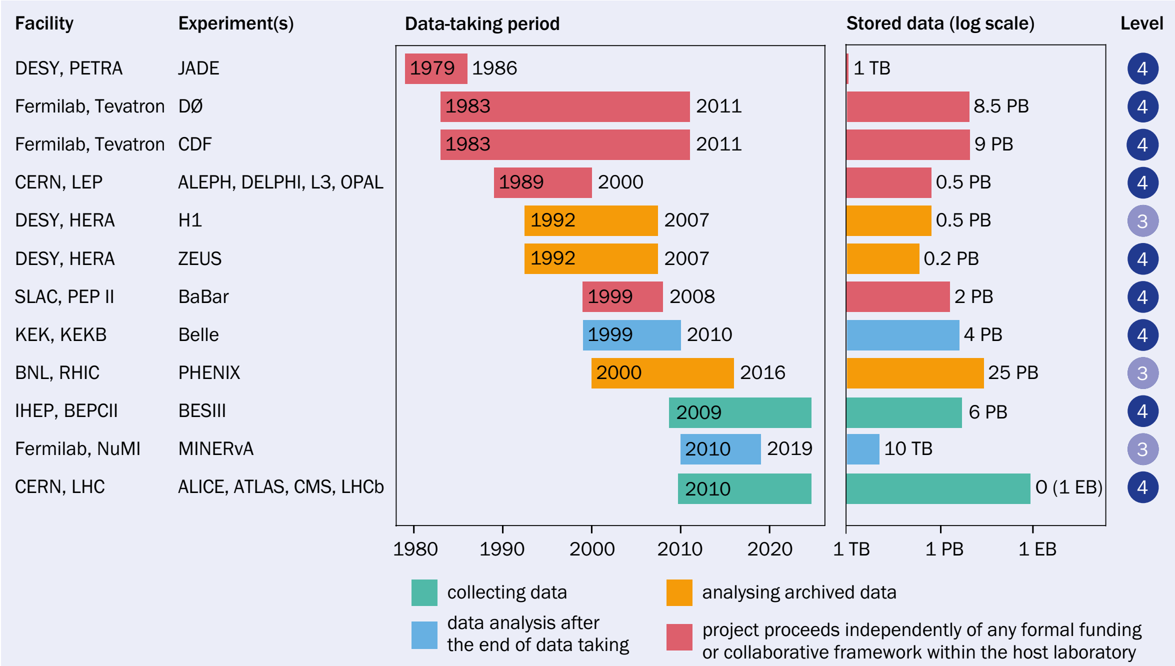
CERNCOURIER

Volume 65 Number 5 September/October 2025



Data preservation *High-energy-physics experiments collaborating with the DPHEP initiative, ordered by the start of operations. The amount of stored data is plotted on a logarithmic scale alongside DPHEP's four-fold classification level of the quality of data abstraction. Experiments are colour coded according to the data-preservation status reported at the most recent DPHEP meeting in late 2024.*

repository for high-energy physics data tables). Level 4 includes all inputs necessary to fully reprocess the original data and simulate the experiment from scratch.

The concept of data preservation had to be extended too. Simply storing data and freezing software is bound to fail as operating systems evolve and analysis knowledge disappears. A sensible preservation process must begin early on, while the experiments are still active, and take into account the research goals and available resources. Long-term collaboration organisation plays a crucial role, as data cannot be preserved without stable resources. Software must adapt to rapidly changing computing infrastructure to ensure that the data remains accessible in the long term.

Return on investment

But how much research gain could be expected for a reasonable investment in data preservation? We conservatively estimate that for dedicated investments below 1% of the cost of the construction of a facility, the scientific output increases by 10% or more. Publication records confirm that scientific outputs at major experimental facilities continue long after the end of operations (see "Publications per year, during and after data taking" panel). Publication rates remain substantial well beyond the "canonical" five years after the end of the data taking, particularly for experiments that pursued dedicated data-preservation programmes. For some experiments, the lifetime of the preservation system is by now comparable with the data-taking period, illustrating the need to carefully define collaborations for the long term.

Publication records confirm that scientific outputs at major experimental facilities continue long after the end of operations

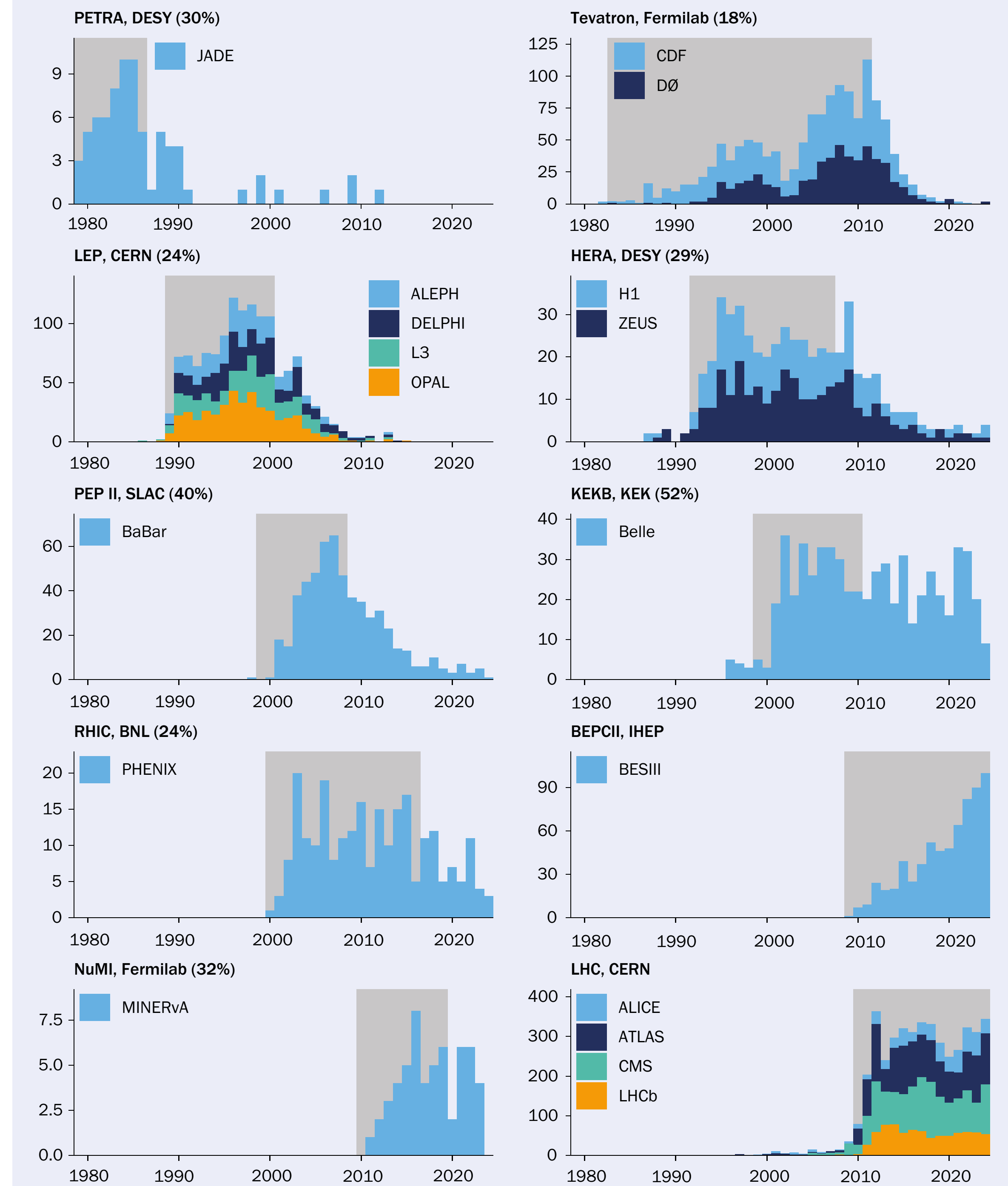
The most striking example is BaBar, an electron–positron-collider experiment at SLAC that was designed to investigate the violation of charge-parity symmetry in the decays of B mesons, and which continues to publish using a preservation system now hosted outside the original experiment site. Aging infrastructure is now presenting challenges, raising questions about the very-long-term hosting of historical experiments – "preservation 2.0" – or the definitive end of the programme. The other historical b-factory, Belle, benefits from a follow-up experiment on site.

HERA, an electron– and positron–proton collider that was designed to study deep inelastic scattering (DIS) and the structure of the proton, continues to publish and even to attract new collaborators as the community prepares for the Electron Ion Collider (EIC) at BNL, nicely demonstrating the relevance of data preservation for future programmes. The EIC will continue studies of DIS in the regime of gluon saturation (*CERN Courier* January/February 2025 p31), with polarised beams exploring nucleon spin and a range of nuclear targets. The use of new machine-learning algorithms on the preserved HERA data has even allowed aspects of the EIC physics case to be explored: an example of those "treasures" not foreseen at the end of collisions.

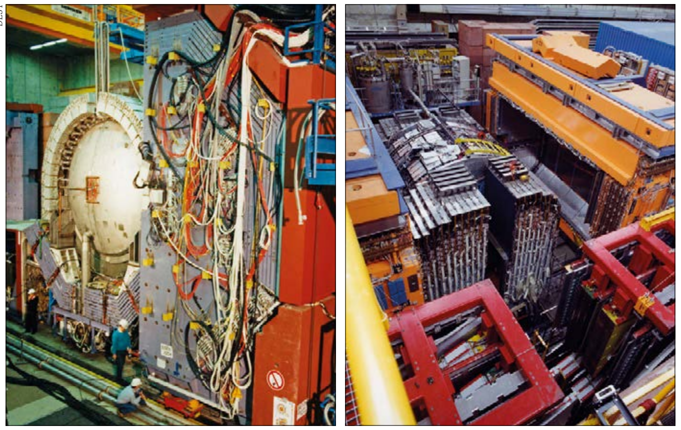
IHEP in China conducts a vigorous data-preservation programme around BESIII data from electron–positron collisions in the BEPCII charm factory. The collaboration is considering using artificial intelligence to rank data priorities and user support for data reuse.

Publications per year, during and after data taking

The publication record at experiments associated with the DPHEP initiative. Data-taking periods of the relevant facilities are shaded, and the fraction of peer-reviewed articles published afterwards is indicated as a percentage for facilities that are not still operational. The data, which exclude conference proceedings, were extracted from Inspire-HEP on 31 July 2025.



CERNCOURIER
Volume 65 Number 5 September/October 2025



Treasure chest *The H1 (left) and ZEUS (right) detectors at HERA/DESY recorded billions of collisions from 1992 until 2007, and still continue to deliver physics publications based on dedicated data-preservation systems.*

In the past 10 years, data preservation has grown in prominence in parallel with open science

Remarkably, LEP experiments are still publishing physics analyses with archived ALEPH data almost 25 years after the completion of the LEP programme on 4 November 2000. The revival of the CERNLIB collection of FORTRAN data-analysis software libraries has also enabled the resurrection of the legacy software stacks of both DELPHI and OPAL, including the spectacular revival of their event displays (see "Data resurrection" figure). The DELPHI collaboration revised their fairly restrictive data-access policy in early 2024, opening and publishing their data via CERN's Open Data Portal.

Some LEP data is currently being migrated into the standardised EDM4hep (event data model) format that has been developed for future colliders. As well as testing the format with real data, this will ensure data preservation and support software development, analysis training and detector design for the electron–positron collider phase of the proposed Future Circular Collider using real events.

The future is open

In the past 10 years, data preservation has grown in prominence in parallel with open science, which promotes free public access to publications, data and software in community-driven repositories, and according to the FAIR principles of findability, accessibility, interoperability and reusability. Together, data preservation and open science help maximise the benefits of fundamental research. Collaborations can fully exploit their data and share its unique benefits with the international community.

The two concepts are distinct but tightly linked. Data preservation focuses on maintaining data integrity and usability over time, whereas open data emphasises accessibility and sharing. They have in common the need for careful and resource-loaded planning, with a crucial role played by the host laboratory.

Data preservation and open science both require clear policies and a proactive approach. Beginning at the very start of an experiment is essential. Clear guidelines on copyright, resource allocation for long-term storage, access strategies and maintenance must be established to address the challenges of data longevity. Last but not least, it is crucially important to design collaborations to ensure smooth international cooperation long after data taking has finished. By addressing these aspects, collaborations can create robust frameworks for preserving, managing and sharing scientific data effectively over the long term.

Today, most collaborations target the highest standards of data preservation (level 4). Open-source software should be prioritised, because the uncontrolled obsolescence of commercial software endangers the entire data-preservation model. It is crucial to maintain all of the data and the software stack, which requires continuous effort to adapt older versions to evolving computing environments. This applies to both software and hardware infrastructures. Synergies between old and new experiments can provide valuable solutions, as demonstrated by HERA and EIC, Belle and Belle II, and the Antares and KM3NeT neutrino telescopes.

From afterthought to forethought

In the past decade, data preservation has evolved from simply an afterthought as experiments wrapped up operations into a necessary specification for HEP experiments. Data preservation is now recognised as a source of cost-effective research. Progress has been rapid, but its implementation remains fragile and needs to be protected and planned.

The benefits will be significant. Signals not imagined during the experiments' lifetime can be searched for. Data can be reanalysed in light of advances in theory and observations from other realms of fundamental science. Education, training and outreach can be brought to life by demonstrating classic measurements with real data. And scientific integrity is fully realised when results are fully reproducible.

The LHC, having surpassed an exabyte of data, now holds the largest scientific data set ever accumulated. The High-Luminosity LHC will increase this by an order of magnitude. When the programme comes to an end, it will likely be the last data at the energy frontier for decades. History suggests that 10% of the LHC's scientific programme will not yet have been published when collisions end, and a further 10% not even imagined. While the community discusses its strategy for future colliders, it must therefore also bear in mind data preservation. It is the key to unearthing hidden treasures in the data of the past, present and future. ●

Further reading

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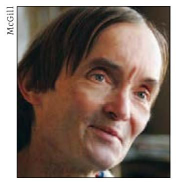
LHC Reinterpretation Forum 2025 arXiv:2504.00256.
DPHEP Collab. 2023 *Eur. Phys. J. C* **83** 795.
CERN Open Data Portal: opendata.cern.ch.

OPINION VIEWPOINT

Four reasons dark energy should evolve with time

Robert Brandenberger argues that the unchanging cosmological constant of the ΛCDM model is theoretically problematic.

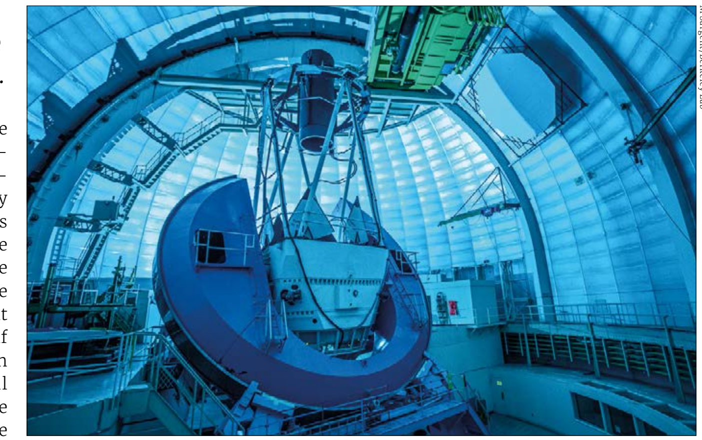
McGill



Robert H Brandenberger *is a Swiss–Canadian theoretical cosmologist at McGill University, best known for co-founding string–gas cosmology and for research on the early universe.*

In the late 1990s, observational evidence accumulated that the universe is currently undergoing an accelerating expansion. Its cause remains a major mystery for physics. The term "dark energy" was coined to explain the data, however, we have no idea what dark energy is. All we know is that it makes up about 70% of the energy density of the universe, and that it does not behave like regular matter – if it is indeed matter and not a modification of the laws of gravity on cosmological scales. If it is matter, then it must have a pressure density close to $p = -\rho$, where ρ is its energy density. The cosmological constant in Einstein's equations for spacetime acts precisely this way, and a cosmological constant has therefore long been regarded as the simplest explanation for the observations. It is the bedrock of the prevailing ΛCDM model of cosmology – a setup where dark energy is time-independent. But recent observations by the Dark Energy Spectroscopic Instrument provide tantalising evidence that dark energy might be time-dependent, with its pressure slightly increasing over time (*CERN Courier* May/June 2025 p11). If upcoming data confirm these results, it would require a paradigm shift in cosmology, ruling out the ΛCDM model.

M Sargent/Berkeley Lab



Galaxies and quasars *Measurements by the Dark Energy Spectroscopic Instrument hint that dark energy may be time-dependent rather than a cosmological constant.*

Mounting evidence

From the point of view of fundamental theory, there are at least four good reasons to believe that dark energy must be time-dependent and cannot be a cosmological constant.

Recent observations provide tantalising evidence that dark energy might be time-dependent

The first piece of evidence is well known: if there is a cosmological constant induced by a particle-physics description of matter, then its value should be 120 orders of magnitude larger than observations indicate. This is the famous cosmological constant problem.

A second argument is the "infrared instability" of a spacetime induced by a cosmological constant. Alexander Polyakov (Princeton) has forcefully argued that inhomogeneities on very large length scales would gradually mask a preexisting cosmological constant, making it appear to vary over time.

Recently, other arguments have been put forwards indicating that dark energy must be time-dependent. Since quantum matter generates a large cosmological constant when treated as an effective field theory, it should be expected that the cosmological constant problem can only be addressed in a quantum theory of all forces. The best candidate we have is superstring theory. There is mounting evidence that – at least in the regions of the theory under mathematical control – it is impossible to obtain a positive cosmological constant corresponding to the observed accelerating expansion. But one can obtain time-dependent dark energy, for example in quintessence toy models.

The final reason is known as the trans-Planckian censorship conjecture. As the nature of dark energy remains a complete mystery, it is often treated as an effective field theory. This means that one expands all fields in Fourier modes and quantises each field as a harmonic oscillator. The modes one uses have wavelengths that increase in proportion to the scale of space. This creates a theoretical headache at the highest energies. To avoid infinities, an "ultraviolet cutoff" is required at or below the Planck mass. This must be at a fixed physical wavelength. In order to maintain this cutoff in an expanding space, it is necessary to continuously create new modes at the cutoff scale as the wavelength of the previously present modes increases. This implies a violation of unitarity. If dark energy were a cosmological constant, then modes with wavelength equal to the cutoff scale at the present time would become classical at some time in the future, and the violation of unitarity would be visible in hypothetical future observations. To avoid this problem, we conclude that dark energy must be time-dependent.

Because of its deep implications for fundamental physics, we are eagerly awaiting new observational results that will shine more light on the issue of the time-dependence of dark energy.

Further reading

R Brandenberger 2025 arXiv:2503.17659.

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OPINION REVIEWS

The history of heavy ions

Hans Joachim Specht: Scientist and Visionary

Edited by Sanja Damjanovic, Volker Metag, Jürgen Schukraft and Hans Joachim Specht

Springer Nature

Across a career that accompanied the emergence of heavy-ion physics at CERN, Hans Joachim Specht was often a decisive voice in shaping the experimental agenda and the institutional landscape in Europe. Before he passed away last May, he and fellow editors Sanja Damjanovic (GSI), Volker Metag (University of Giessen) and Jürgen Schukraft (Yale University) finalised the manuscript for *Scientist and Visionary* – a new biographical work that offers both a retrospective on Specht's wide-ranging scientific contributions and a snapshot of four decades of evolving research at CERN, GSI and beyond.

Brainchild *Components of the CERES detector (left) were constructed in Heidelberg, before being transported and installed at CERN (right).*

Precision and rigour

Specht began his career in nuclear physics under the mentorship of Heinz Maier-Leibnitz at the Technische Universität München. His early work was grounded in precision measurements and experimental rigour. Among his most celebrated early achievements were the discoveries of superheavy quasi-molecules and quasi-atoms, where electrons can be bound for short times to a pair of heavy ions, and nuclear-shape isomerism, where nuclei exhibit long-lived prolate or oblate deformations. These milestones significantly advanced the understanding of atomic and nuclear structure. Around 1979, he shifted focus, joining the emerging efforts at CERN to explore the new frontier of ultra-relativistic heavy-ion collisions, which was started five years earlier at Berkeley by the GSI–LBL collaboration. It was Bill Willis, one of CERN's early advocates for high-energy nucleus–nucleus collisions, who helped draw Specht into this developing field. That move proved foundational for both Specht and CERN.

From the early 1980s through to 2010, Specht played leading roles in four CERN nuclear-collision experiments: R807/808 at the Intersecting Storage Rings, and HELIOS, CERES/NA45 and NA60 at the Super Proton Synchrotron (SPS). As the book describes, he was instrumental, and not only in their scientific goals, namely to search for the highest temperatures of the newly formed hot, dense QCD matter, exceeding the well established Hagedorn limiting hadron fluid temperature of roughly 160 MeV. The overarching aim was to establish that quasi-thermalised gluon matter and even quark–gluon matter can be created at the SPS. Specht was also involved in the design and execution of these detectors. At the Universität Heidelberg, he built a heavy-ion research group and became a key voice in securing German support for CERN's heavy-ion programme.

CERES was Specht's brainchild, and stood out for its bold concept

As spokesperson of the HELIOS experiment from 1984 onwards, Specht gained recognition as a community leader. But it was CERES, his brainchild, that stood out for its bold concept: to look for thermal dileptons using a hadron-blind detector – a novel idea at the time that introduced the concept of heavy-ion collision experiments. Despite considerable scepticism, CERES was approved in 1989 and built in under two years. Its results on sulphur-gold collisions became some of the most cited of the SPS era, offering strong evidence for thermal lepton-pair production, potentially from a quark–gluon plasma – a hot and deconfined state of QCD matter then hypothesised to exist at high temperatures and densities, such as in the early universe. Such high temperatures, above the hadrons' limiting Hagedorn temperature of 160 MeV, had not yet been experimentally demonstrated at LBNL's Bevalac and Brookhaven's Alternating Gradient Synchrotron.

Advising ALICE

In the early 1990s, while CERES was being upgraded for lead–gold runs, Specht co-led a European Committee for Future Accelerators working group that laid the groundwork for ALICE, the LHC's dedicated heavy-ion experiment. His Heidelberg group formally joined ALICE in 1993. Even after becoming scientific director of GSI in 1992, Specht remained closely involved as an advisor.

Specht's next major CERN project was NA60, which collided a range of nuclei in a fixed-target experiment at the SPS and pushed dilepton measurements to new levels of precision. The NA60 experiment achieved two breakthroughs: a nearly perfect thermal spectrum consistent with blackbody radiation of temperatures ▷

240 to 270 MeV, some hundred MeV above the previous highest hadron Hagedorn temperature of 160 MeV. Clear evidence of in-medium modification of the ρ meson was observed, due to meson collisions with nucleons and heavy baryon resonances, showing that this medium is not only hot, but also that its net baryon density is high. These results were widely seen as strong confirmation of the lattice–QCD-inspired quark–gluon plasma hypothesis. Many chapter authors, some of whom were direct collaborators, others long-time interpreters of heavy-ion signals, highlight the impact NA60 had on the field. Earlier claims, based on competing hadronic signals for deconfinement, such as strong collective hydrodynamic flow, J/ψ melting and quark recombination, were often also described by hadronic transport theory, without assuming deconfinement.

Specht didn't limit himself to fundamental research. As director of GSI, he oversaw Europe's first clinical ion-beam cancer therapy programme using carbon ions. The treatment of the first 450 patients at GSI was a breakthrough moment for medical physics and led to the creation of the Heidelberg Ion Therapy centre in Heidelberg, the first hospital-based hadron therapy centre in Europe. Specht later recalled the first successful treatment as one of the happiest moments of his career. In their essays, Jürgen Debus, Hartmut Eickhoff and Thomas Nilsson outline how Specht steered GSI's mission into applied research without losing its core scientific momentum.

Specht was also deeply engaged in institutional planning, helping to shape the early stages of the Facility for Antiproton and Ion Research, a new facility to study heavy ion collisions, which is expected to start operations at GSI at the end of the decade. He also initiated plasma-physics programmes, and contributed to the development of detector technologies used far beyond CERN or GSI. In parallel, he held key roles in international science policy, including within the Nuclear Physics Collaboration Committee, as a founding board member of the European Centre for Theoretical Studies in Nuclear Physics in Trento, and at CERN as chair of the Proton Synchrotron and Synchro-Cyclotron Committee, and as a decade-long member of the Scientific Policy Committee.

The book doesn't shy away from more unusual chapters either. In later years, Specht developed an interest in the neuroscience of music. Collaborating with Hans Günter Dosch and Peter Schneider, he explored how the brain processes musical structure – an example of his lifelong intellectual curiosity and openness to interdisciplinary thinking.

Importantly, *Scientist and Visionary* is not a hagiography. It includes a range of

Springer Nature

perspectives and technical details that will appeal to both physicists who lived through these developments and younger researchers unfamiliar with the history behind today's infrastructure. At its best, the book serves as a reminder of how much experimental physics depends not just on ideas, but on leadership, timing and institutional navigation.

That being said, it is not a typical scientific biography. It's more of a curated mosaic, constructed through personal reflections and contextual essays. Readers looking for deep technical analysis will find it in parts, especially in the sections on CERES and NA60, but its real value lies in how it tracks the development of large-scale science across different fields, from high-energy physics to medical applications and beyond.

For those interested in the history of CERN, the rise of heavy-ion physics, or the institutional evolution of European science, this is a valuable read. And for those who knew or worked with Hans Specht, it offers a fitting tribute – not through nostalgia, but through careful documentation of the many ways Hans shaped the physics and the institutions we now take for granted.

Horst Stöcker *FIAS and ITP, Goethe Universität Frankfurt and GSI Helmholtzzentrum für Schwerionenphysik GmbH, Darmstadt.*

Two takes on the economics of big science

Big Science, Innovation & Societal Contributions: The Organisations and Collaborations in Big Science Experiments

Edited by Shantha Liyanage, Markus Nordberg and Marilena Streit-Bianchi

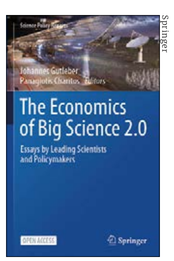
Oxford University Press

Oxford University Press

The Economics of Big Science 2.0: Essays by Leading Scientists and Policymakers

Edited by Johannes Gutleber and Panagiotis Charitos

Springer



Springer

At the 2024 G7 conference on research infrastructure in Sardinia, participants were invited to think about the potential socio-economic impact of the Einstein Telescope. Most physicists would have no expectation that a deeper knowledge of gravitational waves will have any practical usage in the foreseeable future. What, then, will be the economic impact of building a gravitational-wave detector hundreds of metres underground in some abandoned mines? What will be the societal impact of several kilometres of lasers and mirrors?

Such questions are strategically important for the future of fundamental science, which is increasingly often big science. Two new books tackle its socio-economic impacts head on, though with quite different approaches, one more qualitative in its research, and the other more quantitative. What are the pros and cons of qualitative versus quantitative analysis in social sciences? Personally, as an economist, at a certain point I would tend to say show me the figures! But, admittedly, when assessing the socio-economic impact of large-scale research infrastructures, if good statistical data is not available, I would always prefer a fine-grained qualitative analysis to quantitative models based on insufficient data.

Big Science, Innovation & Societal Contributions, edited by Shantha Liyanage (CERN), Markus Nordberg (CERN) and Marilena Streit-Bianchi (vice president of ARSCIENCIA), takes the qualitative route – a journey into mostly uncharted territory, asking difficult questions about the socio-economic impact of large-scale research infrastructures.

Some figures about the book may be helpful: the three editors were able to collect 15 chapters, with about 100 figures and tables, to involve 34 authors, to list more than 700 references, and to cover a wide range of scientific fields, including particle physics, astrophysics, medicine and computer science. A cursory reading of the list of about 300 acronyms, from AAI (Architecture Adaptive Integrator) to ZEPLIN (ZonEd Proportional scintillation in Liquid Noble gas detector), would be a good test to see how many research infrastructures and collaborations you already know.

After introducing the LHC, a chapter ▷ on new accelerator technologies explores a remarkable array of applications of accelerator physics. To name a few: CERN's R&D in superconductivity is being applied in nuclear fusion; the CLOUD experiment uses particle beams to model atmospheric processes relevant to climate change (*CERN Courier* January/February 2025 p5); and the ELISA linac is being used to date Australian rock art, helping determine whether it originates from the Pleistocene or Holocene epochs (*CERN Courier* March/April 2025 p10).

The authors go on to explore innovation with a straightforward six-step model: scanning, codification, abstraction, diffusion, absorption and impacting. This is a helpful compass to build a narrative. Other interesting issues discussed in this part of the book include governance mechanisms and leadership of large-scale scientific organisations, including in gravitational-wave astronomy. No chapter better illustrates the impact of science on human wellbeing than the survey of medical applications by Mitra Safavi-Naeini and co-authors, which covers three major domains of applications in medical physics: medical imaging with X-rays and PET; radiotherapy targeting cancer cells internally with radioactive drugs or externally using linacs; and more advanced but expensive particle-therapy treatments with beams of protons, helium ions and carbon ions. Personally, I would expect that some of these applications will be enhanced by artificial intelligence, which in turn will have an impact on science itself in terms of digital data interpretation and forecasting.

Sociological perspectives

The last part of the book takes a more sociological perspective, with discussions about cultural values, the social responsibility to make sure big data is open data, and social entrepreneurship. In his chapter on the social responsibility of big science, Steven Goldfarb stresses the importance of the role of big science for learning processes and cultural enhancement. This topic is particularly dear to me, as my previous work on the cost–benefit analysis of the LHC revealed that the value of human capital accumulation for early-stage researchers is among the biggest contributions to the machine's return on investment.

I recommend *Big Science, Innovation & Societal Contributions* as a highly informative, non-technical and updated introduction to the landscape of big science, but I would suggest complementing it with another very recent book,


SARAO/MeerKAT

Big science *Large projects such as the South African Radio Astronomy Observatory (pictured) present unique challenges to economists.*

A wide-ranging exploration of how large-scale research infrastructures generate socio-economic value

The Economics of Big Science 2.0, edited by Johannes Gutleber and Panagiotis Charitos, both currently working at CERN. Charitos was also the co-editor of the volume's predecessor, *The Economics of Big Science*, which focuses more on science policy, as well as public investment in science.

Why a "2.0" book? There is a shift of angle. *The Economics of Big Science 2.0* builds upon the prior volume, but offers a more quantitative perspective on big science. Notably, it takes advantage of a larger share of contributions by economists, including myself as co-author of a chapter about the public's perception of CERN.

It is worth clarifying that economics, as a domain within the paradigm of social sciences more generally, has its rules of the game and style. For example, the social sciences can be used as an umbrella encompassing sociology, political science, anthropology, history, management and communication studies, linguistics, psychology and more. The role of economics within sociology is to build quantitative models and to test them with statistical evidence, a field also known as econometrics.

Here, the authors excel. *The Economics of Big Science 2.0* offers a wide-ranging exploration of how large-scale research infrastructures generate socio-economic value, primarily driven by quantitative analysis. The authors explore a diverse range of empirical methods, from forming cost–benefit analyses to evaluating econometric modelling, allowing them to assess the tangible effects of big science across multiple fields. There is a unique challenge for applied economics here, as big science centres by definition do not come in large numbers, however the authors involve large numbers of stakeholders, allowing for a statistical analysis of impacts, and the estimation of expected values, standard errors and confidence intervals.

Societal impact

The Economics of Big Science 2.0 examines the socio-economic impact of ESA's space programmes, the local economic benefits from large-scale facilities and the efficiency benefits from open science. The book measures public attitudes toward and awareness of science within the context of CERN, offering insights into science's broader societal impacts. It grounds its analyses in a series of focused case studies, including particle colliders such as the LHC and FCC, synchrotron light sources like ESRF and ALBA, and radio telescopes such as SARAO, illustrating the economic impacts of big science through a quantitative lens. In contrast to the more narrative and qualitative approach of *Big Science, Innovation & Societal Contributions*, *The Economics of Big Science 2.0* distinguishes itself through a strong reliance on empirical data.

Massimo Florio *University of Milan and CSIL.*

CERNCOURIER
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PEOPLE
CAREERS

Becoming T-shaped

IBM's head of science and technology urges early-career researchers to proactively involve industry in their research.

For Heike Riel, IBM fellow and head of science and technology at IBM Research, successful careers in science are built not by choosing between academia and industry, but by moving fluidly between them. With a background in semiconductor physics and a leadership role in one of the world's top industrial research labs, Riel learnt to harness the skills she picked up in academia, and now uses them to build real-world applications. Today, IBM collaborates with academia and industry partners on projects ranging from quantum computing and cybersecurity to developing semiconductor chips for AI hardware.

"I chose semiconductor physics because I wanted to build devices, use electronics and understand photonics," says Riel, who spent her academic years training to be an applied physicist. "There's fundamental science to explore, but also something that can be used as a product to benefit society. That combination was very motivating."

Hands-on mindset

For experimental physicists, this hands-on mindset is crucial. But experiments also require infrastructure that can be difficult to access in purely academic settings. "To do experiments, you need cleanrooms, fabrication tools and measurement systems," explains Riel. "These resources are expensive and not always available in university labs." During her first industry job at Hewlett-Packard in Palo Alto, Riel realised just how much she could achieve if given the right resources and support. "I felt like I was then the limit, not the lab," she recalls.

This experience led Riel to proactively combine academic and industrial research in her PhD with IBM, where cutting-edge experiments are carried out towards a clear, purpose-driven goal within a structured research framework, leaving lots of leeway for creativity. "We explore scientific questions, but always with an application in mind," says Riel. "Whether we're improving a product or solving a practical problem, we aim to create knowledge and turn it into impact."


IBM Research

Heike Riel *is an IBM fellow and head of science and technology.*

Academic research is often driven by curiosity and knowledge gain, while industrial research is shaped by application

Shifting gears

According to Riel, once you understand the foundations of fundamental physics, and feel as though you have learnt all the skills you can leach from it, then it's time to consider shifting gears and expanding your skills with economics or business. In her role, understanding economic value and organisational dynamics is essential. But Riel advises against independently pursuing an MBA. "Studying economics or an MBA later is very doable," she says. "In fact, your company might even financially support you. But going the other way – starting with economics and trying to pick up quantum physics later – is much harder."

Riel sees university as a precious time to master complex subjects like quantum mechanics, relativity and statistical physics – topics that are difficult to revisit later in life. "It's much easier to learn theoretical physics as a student than to go back to it later," she says. "It builds something more important than just knowledge: it builds your tolerance for frustration, and your capacity for deep logical thinking. You become extremely analytical and much better at breaking down problems. That's something every employer values."

In demand

High-energy physicists are even in high demand in fields like consulting, says Riel. A high-achieving academic has a really good chance at being hired, as long as they present their job applications effectively. When scouring applications, recruiters look for specific key words and transferable skills, so regardless of the depth or quality of your academic research, the way you present yourself really counts. Physics, Riel argues, teaches a kind of thinking that's both analytical and resilient. With experimental physics, your application can be tailored towards hands-on experience and understanding tangible solutions to real-world problems. For theoretical physicists, your application should demonstrate logical problem-solving and thinking outside of the box. "The winning combination is having aspects of both," says Riel.

On top of that, research in physics increases your "frustration tolerance". Every physicist has faced failure at one point during their academic career. But their determination to persevere is what makes them resilient. Whether this is through constantly thinking on your feet, or coming up with new solutions to the same problems, this resilience is what can make a physicist's application pierce through the others. "In physics, you face problems every day that don't have easy answers, and you learn how to deal with that," explains Riel. "That mindset is incredibly useful, whether you're solving a semiconductor design problem or managing a business unit."

Riel champions the idea of the "T-shaped person": someone with deep expertise in one area (the vertical stroke of the T) and broad knowledge across fields (the horizontal bar of the T). "You start by going deep – becoming the go-to person for something," says Riel. This deep knowledge builds your credibility in your desired field: you become the expert. But after that, you need to broaden your scope and understanding.

That breadth can include moving between fields, working on interdisciplinary projects, or applying physics in new domains. "A T-shaped person brings something unique to every conversation," adds Riel. "You're able to connect dots that others might not even see, and that's where a lot of innovation happens."

Adding the bar on the T means that you can move fluidly between different fields, including through academia and industry. For this reason, Riel believes that the divide between academia and industry is less rigid than people assume, especially in large research organisations like IBM. "We sit in that middle ground," she explains. "We publish papers. We work with universities on fundamental problems. But we also push toward real-world solutions, products and economic value."

The difficult part is making the leap from academia to industry. "You need the confidence to make the decision, to choose between working in academia or industry," says Riel. "At some point in your PhD, your first post-doc, or maybe even your second, you need to start applying your practical skills to industry." Companies like IBM offer internships, PhDs, research opportunities and temporary contracts for physicists all the way from masters students to high-level post-docs. These are ideal ways to get your foot in the door of a project, get work published, grow your network and garner some of those industry-focused practical skills, regardless of the stage you are at in your academic career. "You can learn from your colleagues about economy, business strategy and ethics on the job," says Riel. "If your team can see you using your practical skills and engaging with the business, they will be eager to help you up-skill. This may mean supporting you through further study, whether it's an online course, or later an MBA."

Applied knowledge

Riel notes that academic research is often driven by curiosity and knowledge gain, while industrial research is shaped by application. "US funding is often tied to applications, and they are much stronger at converting research into tangible products, whereas in Europe there is still more of a divide between knowledge creation and the next step to turn this into products," she says. "But personally, I find it most satisfying when I can apply what I learn to something meaningful."

That applied focus is also cyclical, she says. "At IBM, projects to develop hardware often last five to seven years. Software development projects have a much faster turnaround. You start with an idea, you prove the concept, you innovate the path to solve the engineering challenges and eventually it becomes a product. And then you start again with something new." This is different to most projects in academia, where a researcher contributes to a small part of a very long-term project. Regardless of the timeline of the project, the skills gained from academia are invaluable.

For early-career researchers, especially those in high-energy physics, Riel's message is reassuring: "Your analytical training is more useful than you think. Whether you stay in academia, move to industry, or float between both, your skills are always relevant. Keep learning and embracing new technologies."

The key, she says, is to stay flexible, curious and grounded in your foundations. "Build your depth, then your breadth. Don't be afraid of crossing boundaries. That's where the most exciting work happens."

Interview by Alex Epshtein *CERN.*

Appointments and awards

Kavli IPMU

Symmetry-breaking insight

Hitoshi Murayama, founding director of the Kavli IPMU Tokyo and currently based at UC Berkley, has been awarded the 2025 Particle Physics Medal by the Japan Particle and Nuclear Theory Forum. The prize recognises Murayama's foundational theoretical work, joint with Haruki Watanabe, on a unified framework for the Nambu–Goldstone theorem in systems without Lorentz invariance. This research offers new insights into symmetry breaking in non-relativistic systems, with implications for both particle physics and condensed-matter theory.

CERN management 2026–2030

The CERN Council has approved the senior leadership structure presented by Director-General Designate Mark Thomson in June. When Thomson's five-year term commences in January, Oliver Brüning will head the accelerators and technology sector, leading the teams through Long Shutdown 3 of the LHC, starting in July 2026, to prepare for the start of the High-Luminosity LHC. Current CMS spokesperson Gautier Hamel de Monchenault will be director for research and computing, taking charge of the experimental physics, information technology (IT) and theoretical physics departments. Ursula Bassler, former CERN Council president, will lead the new stakeholder relations sector, which will replace the current international relations sector, with a somewhat broader scope to reflect key activities towards the realisation of the FCC, should it be prioritised by the ongoing update to the European strategy. Jan-Paul Brouwer has been appointed director for finance and human resources, while Mar Capeáns will head the newly created site operations sector, responsible for civil engineering and cross-organisational activities including business continuity and crisis management, as well as health and safety. Enrica Porcari will serve as CERN's first chief information officer, steering IT strategy, governance and policy in areas including cybersecurity and AI.

2025 Simon Memorial Prize

Ady Stern, professor at the Weizmann Institute of Science, has received the 2025 Simon Memorial Prize for his theoretical contributions to the physics of the quantum Hall effect and topological phases of matter. Stern's work has helped establish the concept of topological order and anyonic quasiparticles, advancing the field's understanding of strongly correlated systems. His research has influenced both condensed matter and theoretical physics, particularly in the context of fractional statistics and quantum computation.

A Stern

Markov Prize awards

The Markov Prize of 2025 has been awarded to Andrei Kataev, Sergey Larin and Konstantin Chetyrkin, all from the Institute for Nuclear Research of the Russian Academy of Sciences, for fundamental contributions to the development of perturbative methods for multi-loop computations in quantum field theory. Their results include: refinements to the integration-by-parts method in Feynman integrals; the calculation of three-loop corrections to electron–positron annihilation to hadrons and tau–lepton decay to hadrons; the calculation of three-loop corrections to the Bjorken sum rule; foundational contributions to four-loop and five-loop beta functions in QCD; and four-loop calculations relevant to Z-boson and tau–lepton decays.

New Jefferson Lab director

Jens Dilling has been appointed director of the US Department of Energy's Thomas Jefferson National Accelerator Facility, effective 30 June. Previously, Dilling served as associate laboratory director for neutron sciences at Oak Ridge National Laboratory (ORNL), where he oversaw the High Flux Isotope Reactor and Spallation Neutron Source. Dilling began his career at TRIUMF in Canada, leading its isotope science programme and building the TRIUMF Ion Trap for Atomic and Nuclear Science before moving into leadership roles at ORNL. Dilling is also a fellow of the American Physical Society and a DOE Oppenheimer leadership fellow.

Altarelli Award for 2025

Each year, the Guido Altarelli Award honours two outstanding early-career particle physicists for work relevant to deep inelastic scattering (DIS). This year's theoretical award goes to René Poncelet (left), of the Polish Academy of Sciences, for high-precision calculations of top-quark and Higgs-boson processes that have made a substantial impact on LHC data analysis. In the experimental category, Miguel Arratia (right) of UC Riverside is recognised for advancing DIS jet studies and developing high-granularity calorimetry technologies for the upcoming Electron–Ion Collider at BNL.

T Hobbs

Dougherty is Astronomer Royal

Michele Dougherty, from Imperial College London, has been appointed as the UK's next Astronomer Royal. The prestigious honorary post dates back to 1675, when it was established by Charles II, and marks Dougherty as the official astronomical advisor to King Charles III, succeeding Martin Rees who held the post for 30 years. Dougherty was the principal investigator of the magnetometer on NASA's Cassini mission, where her team discovered water vapour plumes on Saturn's moon Enceladus, and currently serves as the principal investigator on ESA's JUICE mission exploring Jupiter's icy moons. As executive chair of STFC and upcoming president of the Institute of Physics, she brings leadership across science funding, outreach and astrophysics. Dougherty will be the first woman Astronomer Royal in the post's 350 year history.

Imperial College London

ECR award in PET

Ekaterina Shanina, a PhD student in biomedical engineering at UC Davis, has been recognised for her development of a novel, activity-painting-based brain phantom for positron emission tomography (PET), called PICASSO. Her study was chosen by *Physics in Medicine & Biology*'s editorial board as the best paper in the journal's Early Career Researcher Focus Collection 2024. PICASSO enables realistic static and dynamic neuroimaging simulations without the limitations of conventional models, such as cold walls or air bubbles, and offers precise quantitative assessment of high-resolution PET scanners like NeuroEXPLORER. Her innovative approach significantly advances PET scanner evaluation and calibration.

CERNCOURIER
Volume 65 Number 5 September/October 2025

PEOPLE OBITUARIES

César Gómez 1954–2025

A rich life in theory

César Gómez, whose deep contributions to gauge theory and quantum gravity were matched by his scientific leadership, passed away on 7 April 2025 after a short fight against illness, leaving his friends and colleagues with a deep sense of loss.

César gained his PhD in 1981 from Universidad de Salamanca, where he became professor after working at Harvard, the Institute for Advanced Study and CERN. He held an invited professorship at the Université de Genève between 1987 and 1991, and in this same year, he moved to Consejo Superior de Investigaciones Científicas (CSIC) in Madrid, where he eventually became a founding member of the Instituto de Física Teórica (IFT) UAM–CSIC. He became emeritus in 2024.

Among the large number of topics he worked on during his scientific career, César was initially fascinated by the dynamics of gauge theories. He dedicated his postdoctoral years to problems concerning the structure of the quantum vacuum in QCD, making some crucial contributions.

Focusing in the 1990s on the physics of two-dimensional conformal field theories, he used his special gifts to squeeze physics out of formal structures, leaving his mark in works ranging from superstrings to integrable models, and co-authoring with Martí Ruiz-Altaba and Germán Sierra the book *Quantum Groups in Two-Dimensional Physics* (Cambridge University Press, 1996). With the new century and the rise of holography, César returned to the topics of his youth: the renormalisation group and gauge theories, now with a completely different perspective.

Far from settling down, in the last decade we discover a very daring César, plunging together with Gia Dvali and other collaborators into a radical approach to understand symmetry breaking in gauge theories, opening new avenues in the study of black holes and the emergence of spacetime in quantum gravity. The magic of von Neumann algebras inspired him to propose an elegant, deep and original understanding of inflationary universes and their quantum properties. This research programme led him to one of his most fertile and productive periods, sadly truncated by his unexpected passing at a time when he was bursting with ideas and projects.


IFT archives

César Gómez had a thought-provoking personality.

César's influence went beyond his papers. After his arrival at CSIC as an international leader in string theory, he acted as a pole of attraction. His impact was felt both through the training of graduate students, as well as by the many courses he imparted that left a lasting memory on the new generations.

Contrasting with his abstract scientific style, César also had a pragmatic side, full of vision, momentum and political talent. A major part of his legacy is the creation of the IFT, whose existence would be unthinkable without César among the small group of theoretical physicists from Universidad Autónoma de Madrid and CSIC who made a dream come true. For him, the IFT was more than his research institute, it was the home he helped to build.

Philosophy was a true second career for César, dating back to his PhD in Salamanca and strengthened at Harvard, where he started a lifelong friendship with Hilary Putnam. The philosophy of language was one of his favourite subjects for philosophical musings, and he dedicated to it an inspiring book in Spanish in 2003.

Cesar's impressive and eclectic knowledge of physics always transformed blackboard discussions into a delightful and fascinating experience, while his extraordinary ability to establish connections between apparently remote notions was extremely motivating at the early stages of a project. A regular presence at seminars and journal clubs, and always conspicuous by his many penetrating and inspiring questions, he was a beloved character among graduate students, who felt the excitement of knowing that he could turn every seminar into a unique event.

César was an excellent scientist with a remarkable personality. He was a wonderful conversationalist on any possible topic, encouraging open discussions free of prejudice, and building bridges with all conversational partners. He cherished his wife Carmen and daughters Ana and Pepa, who survive him.

Farewell, dear friend. May you rest in peace, and may your memory be our blessing.

Luis Álvarez-Gaumé *SCGP, State University of New York and CERN*, **José L F Barbón** *IFT UAM–CSIC*, **Agustín Sabio Vera** *Universidad Autónoma de Madrid and IFT UAM–CSIC and* **Miguel Á Vázquez-Mozo** *Universidad de Salamanca.*

Jonathan L Rosner 1941–2025

A master of bridging theory and experiment

Jonathan L Rosner, a distinguished theoretical physicist and professor emeritus at the University of Chicago, passed away on 24 May 2025. He made profound contributions to particle physics, particularly in quark dynamics and the Standard Model.

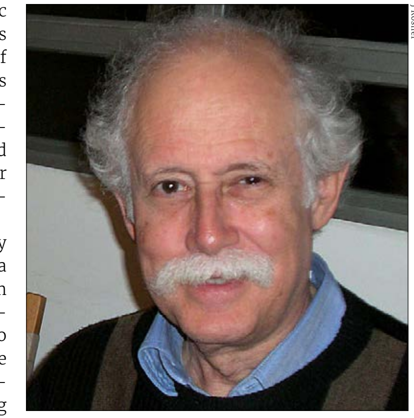
Born in New York City, Rosner grew up in Yonkers, NY. He earned his Bachelor of Arts in Physics from Swarthmore College in 1962 and completed his PhD at Princeton University in 1965 with Sam Treiman as his thesis advisor. His early academic appointments included positions at the University of Washington and Tel Aviv University. In 1969 he joined the faculty at the University of Minnesota, where he served until 1982. That year, he became a professor at the University of Chicago, where he remained a central figure in the Enrico Fermi Institute and the Department of Physics until his retirement in 2011.

Rosner's research spanned a broad spectrum of topics in particle physics, with a focus on the properties and interactions of quarks and leptons in the Standard Model and beyond.

In a highly influential paper in 1969, he ▷

pointed out that the duality between hadronic s-channel scattering and t-channel exchanges could be understood graphically, in terms of quark worldlines. Approximately three months before the "November revolution", i.e. the experimental discovery of charm–anticharm particles, together with the late Mary K Gaillard and Benjamin W Lee, Jon published a seminal paper predicting the properties of hadronic states containing charm quarks.

He made significant contributions to the study of mesons and baryons, exploring their spectra and decay processes. His work on quarkonium systems, particularly the charmonium and bottomonium states, provided critical insights into the strong force that binds quarks together. He also made masterful use of algebraic methods in predicting and analysing CP-violating observables.


J Rosner

Jon Rosner was a distinguished theoretician who made profound contributions to particle physics.

In more recent years, Jon focused on exotic combinations of quarks and antiquarks, tetraquarks and pentaquarks. In 2017 he co-authored a *Physical Review Letters* paper that provided the first robust prediction of a $bb\bar{u}\bar{d}$ tetraquark that would be stable under the strong interaction (*CERN Courier* November/December 2024 p33).

What truly set Jon apart was his rare ability to seamlessly integrate theoretical acumen with practical experimental engagement. While primarily a theoretician, he held a deep appreciation for experimental data and actively participated in the experimental endeavour. A prime example of this was his long-standing involvement with the CLEO collaboration at Cornell University.

He also collaborated on studies related to the detection of cosmic-ray air showers and contributed to the development of prototype systems for detecting radio pulses associated with these high-energy events. His interdisciplinary approach bridged theoretical predictions with experimental observations, enhancing the coherence between theory and practice in high-energy physics.

Unusually for a theorist, Jon was a high-level expert in electronics, rooted through his deep life-long interest in amateur short-wave radio. As with everything else, he did it very thoroughly, from physics analysis to travelling to solar eclipses to take advantage of the increased propagation range of the electromagnetic waves caused by changes in the ionosphere. Rosner was also deeply committed to public service within the scientific community. He served as chair of the Division of Particles and Fields of the American Physical Society in 2013, during which he played a central role in organising the "Snowmass on the Mississippi" conference. This event was an essential part of the long-term strategic planning for the US high-energy physics programme. His leadership and vision were widely recognised and appreciated by his peers.

Throughout his career, Rosner received numerous accolades. He was a fellow of the American Physical Society and was awarded fellowships from the Alfred P. Sloan Foundation and the John Simon Guggenheim Memorial Foundation. His publication record includes more than 500 theoretical papers, reflecting his prolific and highly impactful career in physics. He is survived by his wife, Joy, their two children, Hannah and Benjamin, and a granddaughter, Sadie.

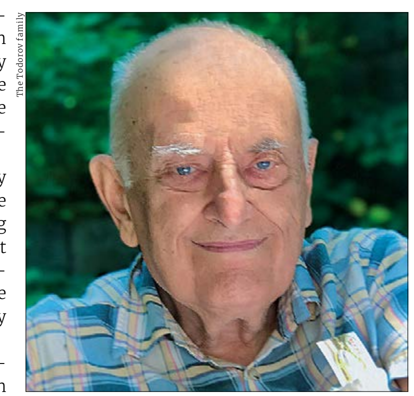
Marek Karliner *Tel Aviv University and* **Fred Gilman** *Carnegie Mellon University.*

Ivan Todorov 1933–2025

Advancements in quantum field theory

Ivan Todorov, theoretical physicist of outstanding academic achievements and a man of remarkable moral integrity, passed away on 14 February in his hometown of Sofia. He is best known for his prominent works on the group-theoretical methods and the mathematical foundations of quantum field theory.

Ivan was born on 26 October 1933 into a family of literary scholars who played an active role in Bulgarian academic life. After graduating from the University of Sofia in 1956, he spent several years at JINR in Dubna and at IAS Princeton, before joining INRNE in Sofia. In 1974 he became a full member of the Bulgarian Academy of Sciences.


The Todorov family

Ivan Todorov made prominent contributions to the mathematical foundations of quantum field theory.

Ivan contributed substantially to the development of conformal quantum field theories in arbitrary dimensions

Ivan contributed substantially to the development of conformal quantum field theories in arbitrary dimensions. The classification and the complete description of the unitary representations of the conformal group have been collected in two well known and widely used monographs by him and his collaborators. Ivan's research on constructive quantum field theories and the books devoted to the axiomatic approach have largely influenced modern developments in this area. His early scientific results related to the analytic properties of higher loop Feynman diagrams have also found important applications in perturbative quantum field theory.

The scientifically highly successful international conferences and schools organised in Bulgaria during the Cold War period under the guidance of Ivan served as meeting grounds for leading Russian and East European theoretical physicists and their West European and American colleagues. They were crucial for the development of theoretical physics in Bulgaria.

Everybody who knew Ivan was impressed by his vast culture and acute intellectual curiosity. His profound and deep knowledge of modern mathematics allowed him to remain constantly in tune with new trends and ideas in theoretical physics. Ivan's courteous and smiling way of discussing physics, always peppered with penetrating comments and suggestions, was inimitable. His passing is a great loss for theoretical physics, especially in Bulgaria, where he mentored a generation of researchers.

His friends and colleagues.

CERNCOURIER

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BACKGROUND

Notes and observations from the high-energy physics community

Observatory online


NSF–DOE Vera C. Rubin Observatory

The Vera Rubin Observatory released its first images on 23 June, featuring the Virgo Cluster and Trifid Nebula (pictured). Its 3.2 gigapixels dwarf the 100 megapixels in high-end cameras and the roughly 500 megapixels sometimes quoted as the effective performance of the human eye. Located in Chile, and named for Vera Rubin (1928–2016), who provided compelling evidence for the existence of dark matter in the 1970s, the observatory aims to map the southern sky over the next 10 years.

2100 Asteroids found by the Vera Rubin Observatory in its first seven nights of observations

Media corner

"It is an amazing measurement. Baryons containing b-quarks are relatively hard to produce, and CP violation is very delicate and hard to study."

Edward Witten, theoretical physicist at the Institute for Advanced Study, on the first observation of CP violation in baryons at the LHC (*Scientific American*, 16 July).

"Given current budget constraints and the significant budget cuts proposed by the administration, we are pleased the Senate Appropriations Committee was able to maintain funding at current levels for both the National Science Foundation and NASA."

Barbara Snyder, president of the 71-member Association of American Universities, in *Science* (10 July).

"We need women and other under-represented groups in physics to be encouraged into the field to ensure a diverse range of ideas."

Tanusri Saha-Dasgupta (S. N. Bose National Centre for Basic Sciences) and **Rupamanjari Ghosh** (Jawaharlal Nehru University) on the "second quantum revolution" (*Physics World*, 15 July).

"The Big Bang only made hydrogen and helium and lithium. Here we see how calcium, sulphur or iron are made and dispersed back into the host galaxy, a cosmic cycle of matter."

Ivo Seitenzahl (Australian National University in Canberra) on the first observation of a "double detonation" type 1a supernova, by ESO's Very Large Telescope in Chile (*Japan News*, 10 July).

"This may be one of the first you see cancelled, but I don't think it'll be the last."

Bill Madia, former director of Pacific Northwest National Laboratory and Oak Ridge National Laboratory, on the cancellation of the CMB-S4 project (*Science*, 12 July).

From the archive: September/October 1985

Physics data at your fingertips


CERN PhotoLab

Theory meets experiment: Nobel laureate Abdus Salam, left, raises a glass in 1979 to Paul Musset of the Gargamelle collaboration.

For many years high-energy physicists have carried around the famous *Particle Data Booklet*. This indispensable pocket 'database' produced by the Particle Data Group at Berkeley is now just one of several databases of high-energy physics accessible to an increasing number of physicists. The modern way to provide up-to-date information rapidly and efficiently is through the computer, and with the growth of networks in Europe and the US it is possible for users at many universities and laboratories to get the data they require from their own terminal.

The initiative to compile computer databases of high-energy physics reactions was taken over 10 years ago at Durham University in the UK, in conjunction with the group at Berkeley. This project (HEPData) now involves physicists at CERN, DESY and Serpukhov. These databases contain information on scattering distributions and structure functions from a wide range of experiments.

This information, together with data on particle properties and experimental details and proposals, resides on the central computers at the Rutherford Appleton Laboratory and SLAC. Implementation is also underway so that the data can be retrieved directly from the new CERN CMS (interactive operating) system. Users at institutes that can access these machines directly, or through networks, can quickly obtain a host of particle-physics data.

● Text adapted from *CERN Courier* October 1985 p339.

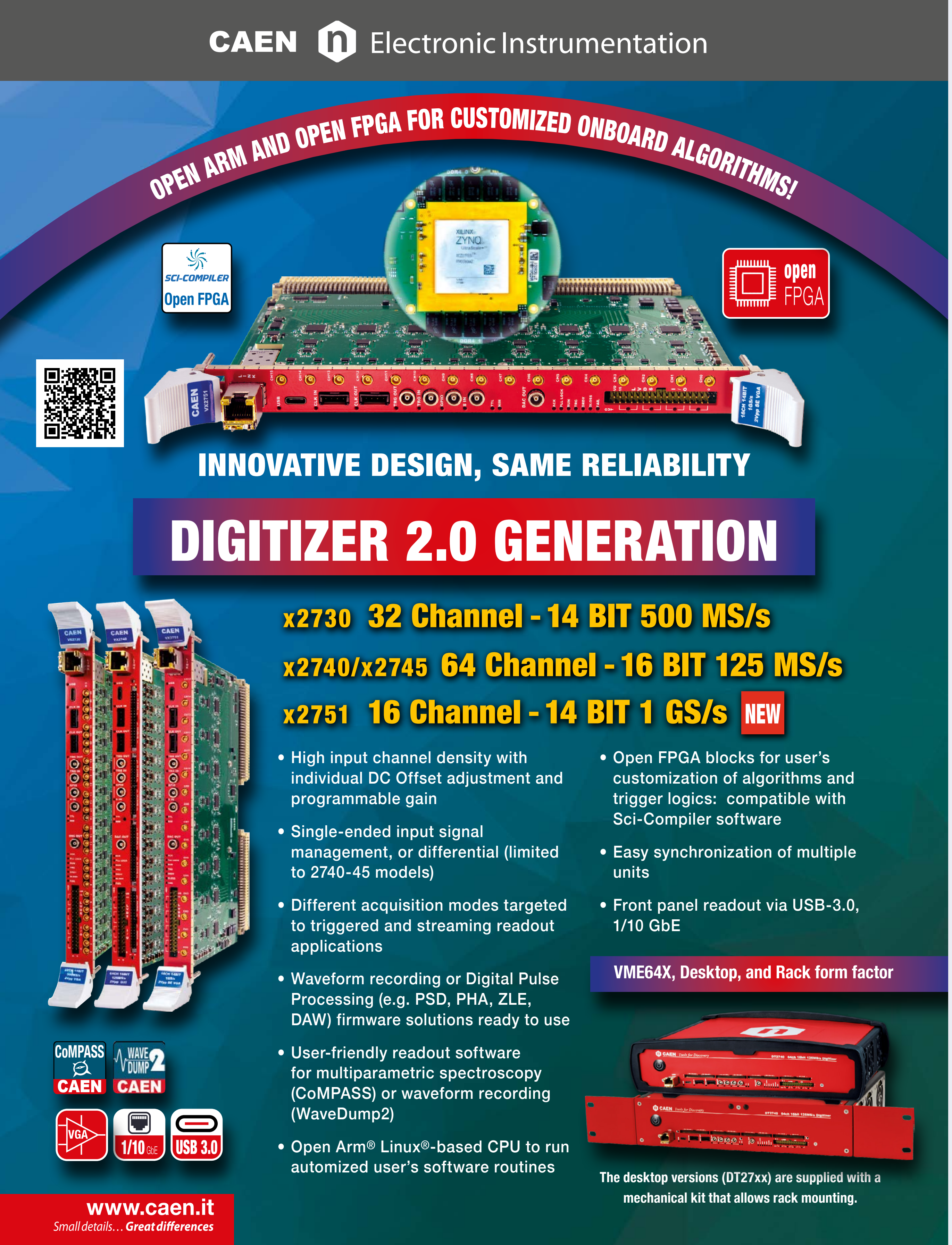
Compiler's note

September 1985 saw the sad loss of Paul Musset in a mountaineering accident. In 1979 Abdus Salam shared the Nobel Prize in Physics for work on electroweak unification; he toasted Musset in recognition of Gargamelle's 1973 discovery of neutral currents that showed the theory was on the right track. Data from Gargamelle later contributed to the HEPData database, which went live around 1980, before becoming interactive as described here. Nowadays HEPData comprises data related to thousands of publications and classifies as Level 1 (publication related) in the context of data preservation (see p41).

Betelbuddy for Betelgeuse


Gemini Observatory/NOIRLab/NSF/AURA/M Zamani

References to Betelgeuse may date as far back as Chinese court astronomer Sima Qian, writing circa 100 BCE. Though the red supergiant is Orion's shoulder, its name derives from mistranscriptions of the Arabic Yad al-Jawzā', meaning the hand of al-Jawzā'. Astronomers from the Gemini North Telescope in Hawaii may now have discovered her bracelet, the companion star Siwarha – or indeed the Betelbuddy, as others have dubbed it. Siwarha may explain Betelgeuse's dramatic dimming in 2019 and 2020.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